UNDERSTANDING ROBUSTNESS AS AN IMAGE OF SUSTAINABLE AGRICULTURE

Douwe M. de Goede

Thesis committee

Promotor
Prof. Dr H.G.J. Gremmen
Professor of Ethics of Life Sciences
Wageningen University

Co-promotor
Dr M. Blom-Zandstra
DLO researcher
Plant Research International (PRI)

Other members
Prof. Dr F.W.A. Brom, Utrecht University
Prof. Dr P.H. Feindt,Wageningen University
Dr K.H. de Greef, Wageningen University
Prof. Dr E.T. Lammerts van Bueren, Wageningen University

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Preface and acknowledgements

My attempts to get grip on the concept robustness were regularly parried with counter-questions: “what do *you* mean with robustness?” or “how should I *interpret* robustness?” Some gave long descriptions of sustainability problems and suggested that these *‘could perhaps be seen as not robust’*, while others were far more explicit: *“an apple that does not bruise when I let it fall”*. Some were utmost clear, but nevertheless made me doubt: *“Robustness? I assume you mean resilience?”*, and, at the time Q-fever harassed goat keepers in the Netherlands *“Why don’t you grab her udders firmly and feel for yourself what robust means!”* I have used these, and many other answers to write this thesis, and I am grateful to all that were willing to share their understanding of robustness with me.

It was not easy to move from a collection of different understandings of robustness to a ‘robust’ understanding of these differences. I have benefitted from the help, support and criticism of many others and my thanks goes to all of them and some in particular.

It is obvious that this thesis would not have looked the same without the supervision of my promotor Bart Gremmen, and co-promotor Greet Blom. I enjoyed working with you very much. Bart, despite your busy agenda, you were actually always available for discussion. Looking back on how constructive and enlightening our discussions were, I realise that I have probably not used these opportunities enough. You usually saw the best way forward before I did, but had the pleasant patience to join me on my detours. Greet, during this largely conceptual study, you watched over the relation to practice. When necessary you protected me from misunderstandings, and where possible you encouraged me to continue, by setting examples from practice. Both your enthusiasm and clarifying questions have added to the quality of this thesis.

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to fill holes, rather than tearing them open may have seemed an open door, but appeared an eye-opener when writing the discussion.
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Finally, this study was financially supported by TransForum, initiated and partly funded by the Dutch government to contribute to a more sustainable and innovative knowledge infrastructure in agriculture. A financial contribution from the chair group Philosophy for printing this thesis is gratefully acknowledged.

Wageningen, March 26th 2014
Douwe de Goede

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General introduction

Background of the research project

During the last three decades, sustainability has been one of the most multi-interpretable criteria by which agriculture has ever been evaluated. At the same time, farm crops and livestock have increasingly been raised artificially, notably to contribute to reliable production. This ongoing agricultural industrialisation has added to social concerns that have by now initiated innumerable research programs towards more sustainable agriculture. Most of these concerns are closely connected to the consequences of technology-driven agricultural expansions after World War II, which, although successful in terms of huge production, have made agriculture much more vulnerable to unwanted fluctuations.
In reaction to this experienced vulnerability, it has been suggested that agricultural systems should be made more robust (Ten Napel et al., 2006). The basic idea behind the introduction of the concept of robustness is that not only production systems but also (traditional) breeding of livestock and crops used in these productions systems needs to change its focus. Ten Napel et al. do not define robustness, but connect it loosely to an Adaptation Model, suggesting a kind of flexibility: 'returning to the original position after a disturbance'. It remains unclear whether, and if so why, the existing systems are really non-robust because suitable indicators to assess a system's robustness are missing.
This research is part of the TransForum Scientific Program (van Latesteijn and Andeweg, 2011) that was initiated in 2004 to stimulate Agro innovation for sustainable development. As an innovation program TransForum aimed to provide better sustainability perspectives for the Dutch agro-sector, for example by searching for new value propositions. The scientific programme consisted of four themes, that were meant to follow a cyclic innovation process (Veldkamp et al., 2009):

I. Images of sustainable development;
II. Inventions for sustainable development;
III. Organisation of innovations and transitions;
IV. Mobilisation of demand for sustainable products, services and experiences.

This research forms part of theme II and was set up in connection with three other research projects within that theme. I will briefly describe theme II of the TransForum scientific programme and the research projects in the remainder of this chapter, after having discussed the problem definition and research objectives.

Problem definition and research objectives

Ten Napel et al. (2006) argue that developing robustness as a characteristic for production systems is a way to achieve both sustainable and social acceptable agriculture. However, a uniform definition of robustness is missing, making robustness a malleable concept. As a consequence, for different kinds of problems both societal stakeholders and scientists may have varying conceptualisations (or production chain specific translations) of robustness. Still, in setting the research agenda for agriculture, especially in plant- and animal sciences robustness has

rapidly become a key concept to criticise the existing scientific practice and to stimulate the transfer of agricultural production towards a sustainable and social acceptable production system.
The general aim of the research described in this thesis is to contribute to a better understanding of the conceptualisation of robustness in agricultural science as well as its relevance to sustainability. This project has three main research questions:

1. What is robustness and how is it approached in different fields of science? How do these approaches relate to sustainability?
2. Which conceptualisation(s) are being worked out in agriculture? Which conceptualisation(s) are dominant and which have potential?
3. What is the relevance of robust agriculture vis-à-vis sustainable agriculture?

Methodology

To achieve a better understanding of different approaches to robustness in general, and conceptualisations of robustness in relation to sustainable agriculture in particular, I adopted a conceptual analysis (Foley, 1999). Despite its popularisation within 20th century analytic philosophy as a method to analyse concepts and propositions (Heil, 1999), the conceptual analysis is poorly described as a research methodology. As Furner (2004) argued, the conceptual analysis *"involves precisely defining the meaning of a given concept by identifying and specifying the conditions under which any definition or phenomenon is (or could be) classified under the concept in question"*. It is generally used to contribute to our understanding of the way in which concepts are or could be used to communicate ideas about certain fields (Furner, 2004; Jackson, 2000). By adopting the conceptual approach as a research methodology, I assumed that it is possible to reach some agreement about the meaning(s) of robustness in the context of agriculture. Moreover I assumed that a clarification of the meaning(s) given to robustness is useful to fully understand its relation to sustainable agriculture.
For the empirical part of my study, I used three TransForum cases and the Houden van Hennen case. In this section I describe the research methods and the case selection.

Research method

The conceptual analysis was done by a desk-study into literature on robustness, and related terms. As a first step I collected definitions and descriptions of robustness in different fields of science to roughly map the field of robustness-thinking. Not only did I encounter multiple and sometimes conflicting interpretations of the term, I also found that these interpretations appear to be used loosely in different contexts.

With the purpose of structuring and reconstructing the interpretations and usages of robustness, I determined which organising principles account for different interpretations, and used these principles to develop a conceptual framework by which robustness conceptualisations in selected cases could be categorised. I derived the organising principles from literature. The first organising principle relates to different stability views, i.e. efficiency of function and persistence of functionality, the differences between which have particularly been emphasised in ecology and resilience theory. The second organising principle distinguishes two bipolar views of the ability of systems to cope with disturbances, i.e. is the system able to cope with disturbances independently, or are additional control measures needed.

I used cases to study the conceptualisation of robustness in practice. Case study is a qualitative research method that provides a systemic way of looking at carefully selected issues. The conceptual framework that is presented in chapter 3 is used to categorise robustness conceptualisations in selected cases. In line with the conceptual approach, I selected scientific projects that had the objective to develop more robust production systems to increase sustainability, but had not yet, or only implicitly conceptualised robustness. I selected unique cases that covered a wide range of agricultural practices, but were nevertheless typical in their ambitions to realise inventions that could contribute to more sustainable agricultural production through robustness (see Case selection). I use the cases to determine whether, and if so which, robustness conceptualisations are dominant and useful in relation to sustainable agriculture.

A second case is adopted to study the phenomenon of complexity/robustness spiralling. For this purpose I selected a finished project that has explicitly aimed to operationalise robustness in an agricultural production system. In this case I studied coping strategies that were expressed in design criteria for a new laying hen husbandry system. As one of the immediate causes of the project was growing discontent about existing coping strategies, I expected that this casus would uncover a preference for alternative robustness strategies.

Zooming in on animal welfare as a point of special interest related to robustness in animal sciences, I combine insights gathered in the conceptual analysis and case studies in a suggestion for implementation of robustness thinking in animal husbandry systems to reduce the conditions under which damaging behaviour occurs.

The conceptual study is presented in chapters 2 and 3, and the operationalisation of robustness in practice is discussed in chapters 4 and 5. The cases provided empirical data for the conceptualisation and operationalisation of robustness in chapters 3 and 4 respectively (see figure 1). Research question 1 is addressed and answered in chapter 2. Research question 2 is approached from different perspectives in chapters 3, 4 and 5, while research question 3 is addressed in chapter 3, chapter 5 and in the general discussion (chapter 6).

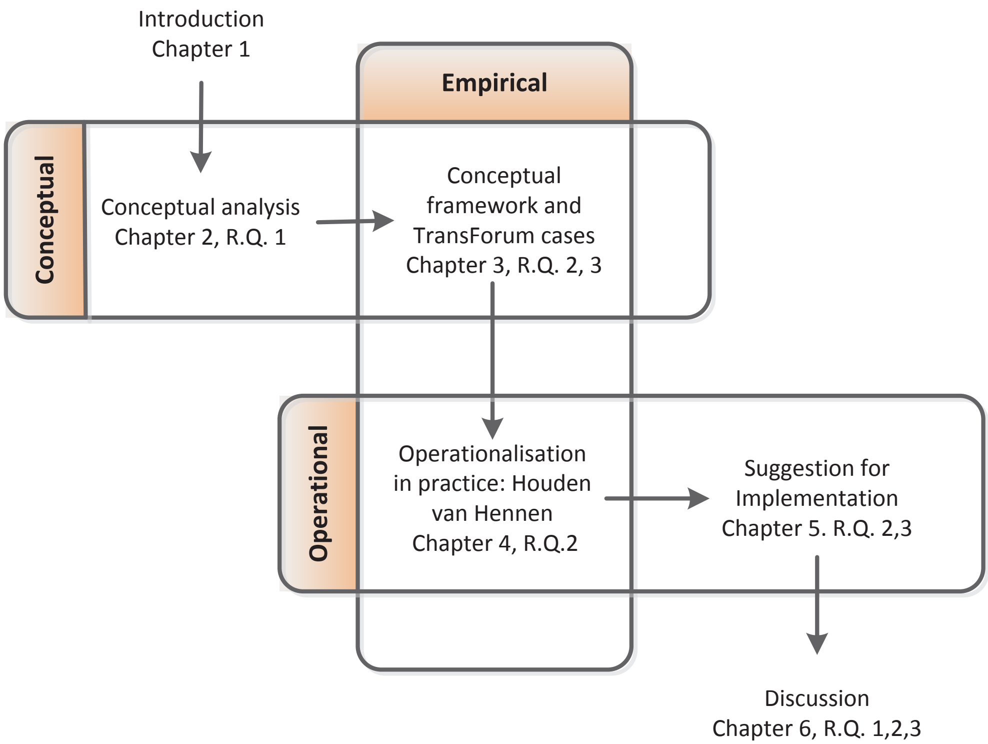

Figure 1. Schematic visualisation of the research methods in relation to the outline of this thesis and their contribution to answering the research questions (R.Q.).

Case selection

For the empirical part of the research, four cases were used. Three TransForum cases were selected as part of the conceptualisation analysis (chapter 3), while the Houden van Hennen case was used for the analysis of practical operationalisation (chapter 4).
In both analyses I used the cases as empirical data to clarify the conceptualisation process of robustness in practice.
The TransForum cases were selected to study the potential of robustness as an image of sustainability. These cases all came from the TransForum Scientific Program (van Latesteijn and Andeweg, 2011). The TransForum Program, of which this research is also part, consisted of four separate themes. Theme II, named *'Inventions related to the sustainable development of agriculture and green space'*, included three scientific projects that had the objective to develop more robust production systems. I designed my project, the fourth in this theme, to elaborate on robustness conceptualisations in these scientific projects. Each of the projects concentrated on specific agricultural sectors, namely animal production, greenhouse farming, and pip-fruit production. The projects started shortly before my conceptual study into robustness got off the ground. As the deliverables of the three TransForum projects became available during my own research, I studied the conceptualisation process while the projects were

still running. In chronological order, the three projects are: “Stacking functionally expressed apple genes for durable resistance to apple scab”, “SynErgy: Monitoring and control system for conditioning of plants and greenhouse”, and “Robustness of animal production systems: concept and application”. I shall first describe the three TransForum cases before turning to the Houden van Hennen case that I used for my analysis of operationisation of robustness in practice.

Stacking functionality expressed apple genes for durable resistance to apple scab
The aim of this project (Joshi, 2010) is the development of high quality apple varieties that have a durable resistance to apple scab (*Venturia inaequalis*). The dominant idea behind this project is that durable resistance to apple scab allows a strong reduction in fungicide usage in apple growing (Schouten et al., 2009). This contributes to a sustainable development of apple production in north-western Europe and makes it possible to position apple production in or near urban areas, where city dwellers can enjoy the beauty of flowering and fruiting orchards.
To achieve durable resistance, the project aimed to stack two resistance genes isolated from resistant apple plants that have an insufficient fruit quality, and introducing them into elite high quality varieties by means of cisgenesis, genetic modification with species specific genes only (Jacobsen and Schouten, 2008; Joshi, 2009; Schouten and Jacobsen, 2008). It is argued that durable resistance at plant level requires at least two functionally expressed resistance genes, stacked in a variety (Erdin et al., 2006). This is called gene pyramiding, or gene stacking (Erdin et al., 2006; Halpin, 2005; Taverniers, 2008). The project uses genetic modification to stack two apple scab resistance genes in susceptible elite cultivars with superior fruit quality to provide these varieties with durable resistance to scab. It is argued that stacking genes through genetic modification to create durable resistance is an innovative approach, that can be applied to all other crops, without the necessity of time-consuming breeding programs (Schouten et al., 2009).

SynErgy: Monitoring and control system for conditioning of plants and greenhouse
This project (Dieleman et al., 2010) aimed to remove barriers that obstruct the development of energy-producing greenhouses, with the intention to create an innovative agro system that reduces the energy use by the greenhouse industry while achieving an optimal production of vegetables, cut flowers and pot plants. The cause for this project goes back to the 1990’s, when energy crises and subsequent price-rises, increased environmental consciousness and sharpened up laws with regard to energy consumption of the Dutch glasshouse industry, gave rise to the development of so called ‘closed greenhouses’, equipped with aquifers in which surplus energy is stored during the summer and from which required energy is taken in winter (Bot, 2001; De Gelder, 2012; Opdam, 2005). Between 1998 and 2003, a new concept for an integrated climate and energy system that allowed a permanent closure of the greenhouse ventilation window as developed and tested (De Gelder, 2005). Closed greenhouses were expected to realise higher CO2 concentrations and higher humidity levels, to reduce temperature fluctuations and realise more constant plant development, to minimise the risk of diseases and reduce evaporation levels. The expectations after the first tests in 2002 were so high (De Gelder, 2005; Opdam, 2005),

that the greenhouse was further developed even before its potentials were clear and the optimal conditions on crop level were known. The use of closed and semi-closed greenhouses has been investigated since with the dual aims of saving energy and optimising the production climate (Bakker et al., 2009; Elings, 2011; Heuvelink, 2008; Hoes, 2008). Indeed, climate conditions in (semi-(closed) greenhouses were found to differ significantly from those in conventional greenhouses (Qian, 2011). In practice this meant that the new technical system made it possible to control growth conditions, of which the optimum states, their interactions and possible trade-offs were for the greater part unknown. The technical 'solution' had, in other words, given the originally energy-related problem of greenhouse farming, a plant physiological dimension (Marcelis, 2006; Schmidt, 2011). The closed greenhouse was developed as a means to reduce energy, but its additional advantages made the optimisation of its use a goal in itself. For this purpose, the optimal conditioning regime has to be redefined to optimise plant performance, while saving or producing energy. The TransForum project *SynErgy: Monitoring and control system for conditioning of plants and greenhouse*, compares plant physiological processes under different conditioning regimes to create a cropping system that, by continuous monitoring and adapting, optimises production in energy producing greenhouses.

Robustness of animal production systems: concept and application

This project aimed to develop new market concepts for the laying hen in husbandry system, pig meat production chain and dairy farming, new chains around these concepts, and innovative keeping systems in these chains (ten Napel and Groot Koerkamp, 2010). The project tries to reach a breakthrough in animal welfare and to gain societal acceptance by establishing new alliances.

The starting point for the scientific project '*Robustness of animal production systems: concept and application* was the TransForum working paper called utilizing intrinsic robustness in agricultural production systems (Ten Napel et al., 2006). Their paper discusses two approaches for dealing with unwanted fluctuations, the so called Control Model and the Adaptation Model. The prevailing Control Model uses protection and intervention to keep balance. It has been successful in improving productivity enormously in a relatively short period by controlling external disturbances. In order to control these external disturbances strict controlling measures (preventive drug use, repellents, high hygiene etcetera) are necessary. However, a number of problems concerning efficiency and negative side-effects became apparent (Rauw et al., 1998). For example freak accidents, but also chronic stress and overburdening of animals, soil degradation, an emerging pest, weed and disease problems may have dramatic consequences. Most of these side-effects have unwanted societal, environmental, economic and animal welfare consequences (Bos, 2004; Ten Napel et al., 2006; Ten Napel et al., 2011).

Under the Adaptation Model production systems and processes are designed for stable performance in the normal bandwidth of sources of variation. The Adaptation Model tries to reduce the consequences by returning to the original position after a disturbance. Rather than eliminating the sources of variation, the management of these sources is important. This is done by designing a robust production system. The project approach is inspired by quality control in engineered systems, such as 'Robust design', 'Robust engineering' and Taguchi methods as applied in the production of cars and microchips (Dehnad, 1989; Phadke, 1989; Taguchi, 2004).

Houden van Hennen

For my analysis of the practical operationalisation of robustness I selected the Houden van Hennen case (Wageningen UR Projectteam Houden van Hennen, 2004c). This project was at the forefront of operationalising robustness in new system designs. The Houden van Hennen (HvH) project was part of the Dutch programme Verantwoorde Veehouderij (Responsible Animal Husbandry) that was executed under the authority of the Dutch Government in 2004, shortly after the 2003 outbreak of avian influenza and just before two far reaching European regulations, concerning bans on trimming beaks (2006) and the use of cages (2012), would come into effect. The project's objective was the delivery of concepts that would initiate transitions towards sustainability and resulted in two designs for socially responsible laying-hen husbandry systems (Bos, 2008; Groot Koerkamp and Bos, 2008). The project adopted an approach of Reflexive Interactive Design (RIO) in which it tried to maximise the influence and participation of diverse groups of actors on the goals and values embedded in the project. A considerable part of the design approach was dedicated to analysis of system, environment, stakeholders demands and problem definitions (Groot Koerkamp and Bos, 2008). One of the main challenges was to articulate the concepts of robustness and naturalness, both identified as playing a central role in societal debates (Wageningen UR Projectteam Houden van Hennen, 2004c). I could relate this project, which started with the formulation of an extensive program of demands, to the implicit aim to stop spiralling complexity in animal husbandry systems and study whether designing for robustness can break through spiralling complexity.

Thesis outline

Chapter 2 is a general conceptual analysis of robustness, concentrating on its relation to vulnerability and stability theory. In this chapter I describe that robustness should not be seen as a clear-cut system feature, but that it is best understood as a flip side of vulnerability. I introduce the term robustness state to refer to an intermediate sphere between vulnerability aspects and their opposite stability images. As an inherent property of the system, robustness can refer to a system's resistance to change, or to its capacity to recover after being disturbed. As a relational property, robustness relates to a capacity to avoid exposure.

In chapter 3 the conceptual analysis from chapter 2 is narrowed down to a framework of robustness conceptualisations and the potential of these conceptualisations as images of sustainability are evaluated. The three Transforum projects are assessed on the basis of this framework and it is argued that robustness is narrowly understood in relation to control and efficiency, while other potential conceptualisations are largely ignored.

The conceptualisation process itself is described in chapter 4 with an analysis of the Houden van Hennen project, which explicitly aimed to operationalise and design robustness in a new laying hen husbandry system. The Houden van Hennen project carefully collected stakeholder demands and combined them in a Programme of

Demands in a time where trust and believe in further optimisation and higher efficiency was at rock bottom and the demand for radical change was high. Chapter 4 illustrates that designing for robustness should be seen as a next step in on-going complexity/robustness spiralling.

Chapter 5 is a plea for an integrated, holistic approach to robustness and provides a suggestion for implementation of robustness thinking in animal husbandry systems to reduce damaging behaviour. The capacity of animals to cope with various perturbations and fluctuations can be influenced at many different levels. It is not a matter of avoiding exposure or breeding more vigorous animals. If geared to one another, small changes in system design and production methods, robust technologies and carefully chosen breeding programmes including social traits can reduce damaging behaviour and contribute to other robustness traits.

Chapter 6 is a general discussion, in which I return to the three main research questions. I build on the conceptual analysis (chapters 2 and 3) to describe three main robustness approaches that are relevant for agricultural systems and their sustainability. It is argued that inherent robustness at crop or animal level increasingly derives its relevance from the instrumentalisation of biological systems within otherwise technology driven agricultural systems as agricultural systems are pulled along in spiralling complexity. I relate this subordination of the biological approach to robustness to shifting understandings of system vulnerability, sustainability images and mechanisms underlying the complexity of agricultural systems. A more holistic approach is needed to understand robust agriculture. The chapter ends with some concluding remarks and suggestions for future research.

The balance between vulnerability and stability

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Abstract

The impression that agricultural systems are increasingly vulnerable to unwanted environmental fluctuations has created an urge for robustness in agriculture. However, the meaning of robustness and its relation to sustainable agriculture remain unclear. Considering two related concepts, i.e., vulnerability and stability, this article analyses different conceptualisations of robustness and their applications in agricultural production systems. It is argued that robustness should not be seen as a clear-cut system feature, and that it only exists in the absence of stability and by the grace of disruptions that could possibly harm the system structurally or functionally. The article introduces the term robustness state to refer to an intermediate sphere between vulnerable and stable, in which a system's capacity to cope with both ordinary and occasional disturbances is optimised. We distinguish three robustness states that differ in the degree by which systems are allowed or inclined to follow environmental changes: (1) a state of avoiding exposure, (2) a state of inherent resistance, and (3) a state of response and recovery after being disrupted. In addition to cardinal questions inevitably related to robustness, namely the specification of both system and perturbation, this article discusses the issue in what way a system feature is robust. This issue may help to clarify the actual meaning given to robustness and appears particularly relevant when discussing the desirability of different strategies to cope with aspects of vulnerability. Different rationales behind recent calls to make agricultural systems more robust are discussed with a view to agricultural developments related to sustainability of agricultural practices and the questioned necessity of external control measures.

An urge for robustness?

The impression that technology driven expansions after World War II have made agricultural systems extremely vulnerable to unwanted environmental fluctuations has created an urge for 'robust agriculture'. For several reasons this urge for robustness is remarkable. Indeed, during the last two decades crops and livestock have increasingly, and successfully, been raised in a high-tech manner, notably to contribute to reliable, uniform and stable production. Agricultural production systems have been further optimised to withstand common perturbations and new system designs have integrated 'anticipated disturbances' from the start. This high level of optimisation against anticipated disturbances has gone at the expense of diversity, which causes a potential threat when confronted with unexpected disruptions. In other words, the functional requirements of agricultural systems to answer societal expectations challenge the structural organisation that is needed to maintain sufficient capacity to cope with the unexpected. Robustness relates to a system's capacity to cope with both anticipated and unexpected events, their interconnectedness, and trade-offs between them. In this chapter we explore the meaning of robustness as a balance between vulnerability to some, and stability against other disturbances. More specifically, we will describe robustness as an intermediate state between different aspects of vulnerability and their opposing images of stability.

Robustness is indeed rapidly gaining attention as a possible solution for a variety of problems that characterise modern agriculture. The Dutch innovation programme 'Transforum', which aims to develop a more sustainable perspective for the Dutch agri-sector considers robustness an important societal value that needs to be developed (Ten Napel et al., 2006). For this purpose we consider two related concepts, the elaborations of which have resulted in different conceptualisations of robustness, namely vulnerability and stability. On the one hand robustness is used to refer to the opposites of various aspects of vulnerability, on the other hand to denote a system's capacity to maintain stability despite occurring irregularities. In this chapter we will first shortly describe the usage of robustness in general, before going into a full consideration of different conceptualisations of robustness in relation to system vulnerability and stability. We present the idea that robustness is a state rather than a clear-cut system feature and argue that, in addition to cardinal questions concerning the system and its disturbance, this state should be taken into account when discussing the robustness of systems and the desirability of robustness strategies.

What is robustness?

Although more or less defined in different fields of science, the term robustness is loosely being used in various contexts and has been given equally diverse meanings[1]. Generally, robustness is understood as being a feature of complex systems, related to the capacity to maintain structure and/or functionality despite internal and external

[1] *It is impossible to be comprehensive, but for an overview of some definitions given to robustness in different fields of science see appendix 1.*

perturbations. Different and sometimes conflicting interpretations of robustness are found in biology (de Visser et al., 2003; Wagner, 2005), ecology (Walker et al., 2005), economics (Leeson and Subrick, 2006), technology and systems engineering (Frey et al., 2007; Fricke and Schulz, 2005; Ross et al., 2008), as well as operational research and decision-support (Rosenhead et al., 1972; Roy, 2010), to name a few. The increasing attraction of robustness and robust design to the agricultural community is probably due to successes reached in diverse industries that have applied Taguchi's robust engineering methodologies (Dehnad, 1989; Taguchi, 1986; Taguchi et al., 1999; Taguchi, 2004), most notably automobiles and electronics. However, long before the current revival of interest in robustness, work had already been going on to develop robust agricultural products. Already in the 1940s, robust products, i.e., products that grew uniformly to assure maximum yield despite different weather and soil conditions, were being developed (Nair et al., 1992). Robinson et al. even argue that these early studies formed the groundwork for later robust engineering methodologies (Robinson et al., 2004). Nonetheless, even if robustness thinking has its origins in agriculture, the various interpretations that have subsequently been given to robustness have obscured its meaning and application in agricultural systems. Different applications in crop farming include performance under poor production conditions (Sall et al., 1998), strategic decision-making in the context of unknown futures (Cittadini et al., 2008) or capacities to respond to crop failures (Lien et al., 2007b). Applications of robustness have particularly been discussed in animal husbandry where it is mainly considered at animal level in relation to physiological, behavioural and immunological performance, health conditions and production potentials under a wide variety of environmental conditions (Knap, 2005). While in animal husbandry robustness is generally considered at the level of the individual animal, in crop production it is the robustness of the population that counts. This illustrates that also within agricultural sciences, robustness is being related to different system levels. To be meaningful, it is important to specify the system level at which robustness is being considered, i.e. define the boundary, inside and environment of the system (Jen, 2003). In this chapter we use the word system to refer to physical systems, either natural or human-made, unless stated otherwise. We use the word subsystem to refer to specified system levels that are elements of larger systems.

Robustness as a flip side of system vulnerability

Robustness appears an intuitively attractive, yet ambiguous concept. Intentions to develop more robust agricultural systems signify a desire to improve the systems in any matter or form. This is why the characterisation of a system as robust presupposes the existence of the opposite; a non-robust system. Indeed, robust systems exist merely by the grace of disruptions that could possibly "queer the pitch", causing system failures, performance losses or even regime shifts. So we can only classify a system as robust to specific disruptions once we have defined its non-robust, vulnerable state, i.e., once we have specified the nature of its vulnerability. It has therefore been argued that robustness is the opposite, or the 'flip side', of vulnerability (Asbjornslett and Rausand, 1999; Gallopín, 2006). For this reason it is not surprising that robustness has gained the attention of agricultural scientists, whose subject of research has been afflicted by increased vulnerabilities to external disturbances over the last few decades. This also means that assessments of system robustness, let alone attempts to develop robustness, must coincide with vulnerability analyses. More precisely, robustness claims have meaning only, when the vulnerability of the system is made explicit. We therefore believe that an analysis of the notion of vulnerability is essential for a better understanding of robustness.

Vulnerability is most often conceptualised as a multidimensional concept that refers to a system's defencelessness or susceptibility to damage or disruption. It is used to describe a system's limited ability to withstand exposure to threats and survive stochastic events. As a concept, vulnerability has been used and developed in various contexts and research traditions. Although conceptual frameworks with different characterisations of vulnerability have meanwhile been presented (Adger, 2006; Chambers, 2006; Luers, 2005; Moser, 1998; Turner et al., 2003), these approaches have some terms in common. Vulnerability is generally considered to be constituted by one or more vulnerability components, and most definitions include at least one of the three main aspects: exposure, sensitivity, and non-resilience, i.e., the incapacity to absorb and recover from disturbances and possibly adapt to environmental changes (Adger, 2006; Luers, 2005; Moser, 1998; Turner et al., 2003). This chapter refers to vulnerability aspects, rather than vulnerability components, since it is not being suggested that vulnerability only exists when all its supposed components are present. Without intending to interfere in discussions whether or not exposure should be externalised from vulnerability, we do recognise a qualitative difference between exposure on the one hand and sensitivity and resilience on the other. While exposure refers to a relationship between a system and its environment, sensitivity and resilience are system attributes that exist prior to perturbations and thus are separate from exposure. For the purpose of this chapter it suffices to shortly discuss exposure, sensitivity and non-resilience as separate aspects of vulnerability.

Exposure

Exposure is the degree, duration, and extent to which a system is subjected to a perturbation (Adger, 2006). Because exposure concerns a relationship between a system and its surroundings rather than a system attribute, it has been called the 'external' side of vulnerability (Chambers, 2006), as opposed to a system's 'internal' lack of the means to cope with disturbances without loss. This suggestion of a double structure of vulnerability is based on a distinction between vulnerability as: (1) a system property that is revealed when the system is exposed to a disturbance (coping capacity), and (2) a relational property of a system and the disturbance together. The external side of vulnerability is increasingly being recognised as a constituting element of vulnerability (Moser, 1998), which, as Gallopín correctly argued, would classify systems as non-vulnerable only because exposures to perturbations are long in coming (Gallopín, 2006). An apparent obvious solution to reduce vulnerability would then be to prevent perturbations from occurring, i.e., to control the relational property of systems with their environment.

Sensitivity

Sensitivity is the degree to which a system is, or will be affected by perturbations. In agriculture, sensitivity of crops and animals to environmental disturbances is frequently seen as a threat to the production capacity. Reducing sensitivity is believed to help organisms to maintain homeostasis under a wider range of environmental conditions. In animal sciences, it is precisely this thought that explains recent attempts to 'breed for robustness', i.e., to select for low sensitivity to external stimuli that challenge homeostasis. This instantiation of robustness is concerned with the range within which overall performance is satisfactory. Breeding strategies in animal husbandry increasingly include robustness traits as integral aspects of overall performance, rather than as secondary to production requirements. Suggested robustness traits include for instance high fertility and low calving intervals, low maintenance, easy calving and longevity (Pryce et al., 2009), temperament (Lawrence et al., 2009) as well as insensitivity to temperature fluctuations and changing feed quality (Pryce et al., 2009; Star, 2008). These traits are particularly relevant as a reply to societal concerns, as well as due to their economic value. A commonly suggested trade-off between performance and robustness supports this. Systems that have evolved, or have been designed to perform specific tasks under given environmental conditions, show increased sensitivity to environmental changes. For instance, a study by Bytyqi et al. has indicated increased environmental sensitivity of cattle breeds with higher genetic potential for milk production (Bytyqi et al., 2007). On the contrary, less sensitive systems display a relatively low performance, but under a much wider range. At animal and crop level, selective breeding for robustness is therefore believed to lead to generalists, rather than specialists (Ten Napel et al., 2009). This is particularly true if robustness against disturbances at animal or crop level replaces control measures, such as preventive drug use, repellents and climate control, which would otherwise have been provided externally. All in all, it appears that the potential of robustness as a breeding goal is largely determined by its economic value (de Vries and Cole, 2009; Star, 2008).

Non-resilience

The third aspect of vulnerability is non-resilience: the lack or insufficiency of resilience. Resilience may refer to two different system features, namely: the capability of returning to an equilibrium steady state after a disturbance, and: having sufficient absorbing capacity to prevent structural changes. The first is known as engineering resilience, measured by the time needed to recover from a disturbance (Holling, 1996; Pimm, 1984; Tilman and Downing, 1994), whereas the second has been termed ecosystem resilience, or ecological resilience (Gunderson, 2000; Holling, 1996; Holling and Meffe, 1996), measured by the maximum magnitude of disturbance that a system can absorb before it collapses. Although the term non-resilience is not commonly used, references to low or decreasing levels of resilience are made to describe a system's incapacity to return to an equilibrium steady state, or to the lack of absorbing capacity to prevent structural changes. In this chapter we will refer to engineering resilience as the elasticity conceptualisation of robustness, and distinguish it from an amplitude conceptualisation of robustness, which refers to ecosystem resilience (see figure 2). Descriptions of robustness as elasticity often relate to regulatory systems and their capacity to regain *efficiency of function*. In dairy farming, consider the rate of return to a positive energy balance after energy balance nadir (lowest energy balance) during early lactation, which was found to affect a cow's luteal activity and day of first heat (Berry et al., 2009; Pollott and Coffey, 2009; Wall et al., 2009). In crop farming, the recovery times of photosynthetic efficiency after low temperature stress are measured to assess the robustness of chilling sensitive plants in different climates (Sowinski et al., 2005).

Note that these examples do not imply that slowly recovering animals or plants are more susceptible to disturbances. Susceptibility to, and ability to recover from disturbances are two separate system features. In other words, robust systems in terms of elasticity are not necessarily less sensitive to the disturbances from which they easily recover.

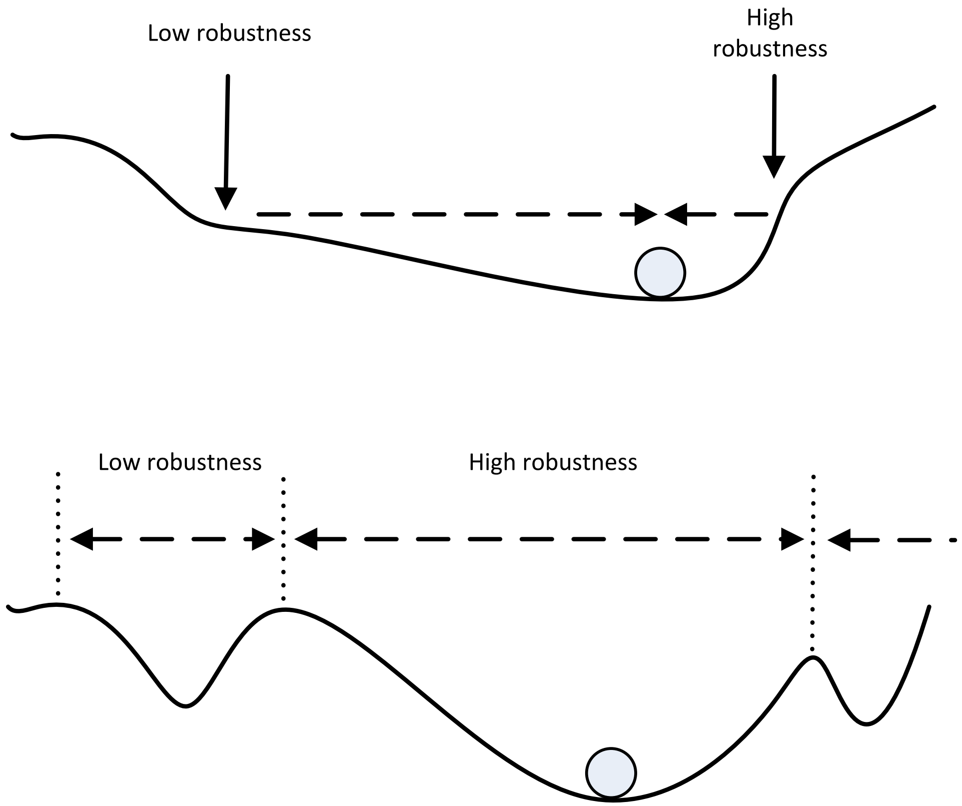

Figure 2. Resilience may refer to two different system features. *Engineering resilience, or the elasticity conceptualisation of robustness (above) is measured by the time needed to recover from a disturbance; ecosystem resilience, or the amplitude conceptualisation of robustness (below) is measured by the magnitude of disturbance that a system can absorb without being changed structurally.*

Ecosystem resilience measures the amount of space in which a particular configuration can persist, or its susceptibility to being transformed to an alternative configuration by stochastic events. This is why we refer to amplitude conceptualisations of robustness when robustness is used to describe this capacity. An amplitude conceptualisation of robustness is only relevant if stability landscapes are believed to consist of more than one stable equilibrium. That is, the dynamics that structurally define a system can radically change when disturbances are strong enough to initiate transitions to alternative steady states. The amplitude conceptualisation of robustness is particularly relevant in the study of alternative steady states and regime shifts in ecological systems and extends to describing the stamina and adaptive capacity of social systems in dynamic, multi-equilibrium stability landscapes (Gunderson, 2000; Gunderson and Holling, 2002; Levin and Lubchenco, 2008; Scheffer, 2009; Scheffer et al., 1993; Walker et al., 2005). In relation to social-ecological systems, adaptive capacity might be considered as a specific and distinct system feature that denotes the ability to learn in response to disturbances. In general, adaptation refers either to an evolutionary process of increasing adaptedness, i.e., the status of being adapted to a specific environment, or to what has been called a system's adaptability, i.e., its capacity to adapt to changes in environment. While the first is an indication of a system's functional optimisation to the relative stability of a specific niche, the latter represents a system's capacity to keep multiple options open. However, despite successful development of ecosystem resilience in ecology, its applicability to designed systems and social systems is still under discussion (Adger, 2000; Anderies et al., 2004; Carpenter et al., 2001).

Robustness as a notion of system stability

Above we have argued that robustness appears as a flip side of aspects of vulnerability. Robustness is also used to describe a system's stability. Three different notions of stability can be distinguished: constancy, resistance to change and resilience (Hansson and Helgesson, 2003), each referring to static and ideal situations. we will refer to them as stability images; images that may be strived after by means of strategic decision-making, yet practically unattainable. we will discuss them below and describe how robustness has been used to refer to each of these notions of stability.

Constancy

Constancy, a situation with little or no change, is observed ex post and refers to a period without perturbations, rather than to the strength of a system. It describes system performance, regardless of the presence of disturbing factors or existing vulnerabilities of the system under consideration. According to this notion, stability and the capacity to cope with disturbances when they occur are two separate things. The distinction made here resembles the distinction between internal and external sides of vulnerability. Similar to exposure, constancy does not refer to a system property, but to a relation between system and perturbation. Constancy can thus be designed for by avoiding exposure to disturbance. It requires what have been called 'robust control measures', rather than indestructible system components. In agriculture, as well as in other industries, this has led to production systems with high levels of automation, and to protective environments in which production is stabilised at maximum levels by avoiding disturbances. This strategy manifests itself, for instance, in greenhouse farming, where crops are being grown under highly protective, stable, controlled and manipulable conditions that avoid exposure to some stressors (such as temperature shocks and drought), and significantly reduce the chances of being exposed to other ones (e.g. insect pests and diseases). It is based on strengthening protection at the boundaries of the technological agri-system within which crops are integrated, thereby aiming to shelter subsystems from environmental fluctuations and disturbances with which they previously had to cope.

Resistance

The second notion of stability, resistance to change, denotes the stability that results from a system's tendency to remain unchanged, structurally or functionally, when exposed to perturbations. According to this conceptualisation, one can only speak of the robustness of a system when it is subjected to disturbing influences. It is a definition of robustness that describes a range of environmental conditions within which a system operates without functional or structural degradation and independent of failure-avoiding measurements or the capacity to recover. Theoretically, this means that the structural or functional state of the system is the same *before*, *during* and *after* the disturbance. As Hansson and Helgesson argue, this is only achieved when the recovery time after a disturbance is nil (Hansson and Helgesson, 2003). In other words, the system is inert, or inherently robust.

Inherent robustness can be achieved in various ways, for instance with redundancy or by selecting parameters that are less susceptible to variations (Taguchi, 1995). Discussions of robustness in terms of inherent resistance are particularly relevant in relation to uncertainty in system *functioning,* i.e., when aiming to satisfy predetermined sets of performance requirements, despite exogenous variability (Allen et al., 2006; Willinger and Doyle, 2005), or in relation to *structural* stability, where robustness is commonly associated with risk analysis (Lamont et al., 2006).

Robustness conceptualisations as inherent resistance are common in breeding programmes that aim to reduce major control methods such as fungicides and insecticides (Chandirasekaran et al., 2009). Both the economic and ecological benefits associated with inherent resistance at crop or animal level are main reasons for breeding for robustness.

Resilience

Above we have described the lack of resilience as an aspect of vulnerability. As a notion of stability, resilience relates to the capacity of a system to return to its original position and to not transit easily between alternative steady state points. Particularly engineering resilience, or the elasticity conceptualisation of robustness, is being used in agriculture to describe an animal or crop's capacity to recover from periods of stress and adapt easily to environmental fluctuations (Star et al., 2008; Ten Napel et al., 2006; Ten Napel et al., 2009). Engineering resilience focuses on the behavior of systems near equilibrium states, and systems with a high engineering resilience are generally appreciated for their speed of recovery.

Ecological resilience, or the amplitude conceptualisation of robustness, is, for instance, relevant in transition management and innovation studies, where robustness of the existing regime is usually considered a hindrance to realise desired transitions. Not the speed of recovery, but the capacity to sustain, or the effort needed to overthrow, a particular system configuration is relevant. The application of ecological resilience in agricultural systems is limited.

Robustness states

Robustness is not easily separated from system vulnerability or system stability. Claims about a system's robustness should at least make explicit the system under consideration, the disturbance against which the system is believed to be robust, and the notion of stability intended. This suggests that robustness is a state that exists, rather than a clear-cut system feature, and that has value only in the absence of stability and by the grace of disruptions that could possibly harm the system structurally or functionally. Indeed, to be called robust, a system must not only continue to exist after being disturbed, it also should only derive its robustness from the continuous threat of being disturbed again. So whether or not we call a system robust depends on the structural or functional impact that a disturbance may have on the system.

From high to low impact, we may distinguish the following impacts (figure 3):

1. Permanent loss of structure and function (discontinuation): the system is unable to cope with the disturbance and dies, or discontinues to exist;
2. Permanent change of structure and/or function (adapt): the system is unable to maintain structure and/or function as a direct result of the disturbance and is compelled to structurally change and adapt to its environment to survive in a different form;
3. Temporary change of structure and/or function (recovery): the system is temporarily unable to maintain structure and/or function as a direct result of the disturbance, but is resilient enough to regain balance when the disturbance comes to an end. The steady state the system reaches after recovery may be equal to the steady state before, but could also be an alternative steady state;
4. Preservation of structure and function (resistance): the system is inherently resistant and can maintain both structure and function despite being exposed to disturbance. The system remains in its steady state before, during and after the disturbance. Recovery time is 0;
5. Non-exposure: the relationship between system and disturbance is such that the system is being screened off, and as a consequence not exposed to the disturbance. Regardless of the coping capacity of the system itself, the disturbance has no impact.

The larger the expected impact on the system, the least likely we consider the system to be robust. Undoubtedly, we do not consider systems robust that are inclined to collapse or degrade if exposed to environmental fluctuations. It is clear that robustness includes at least persistence of certain system features. However, it is debatable whether systems can be called robust if such features may persist through

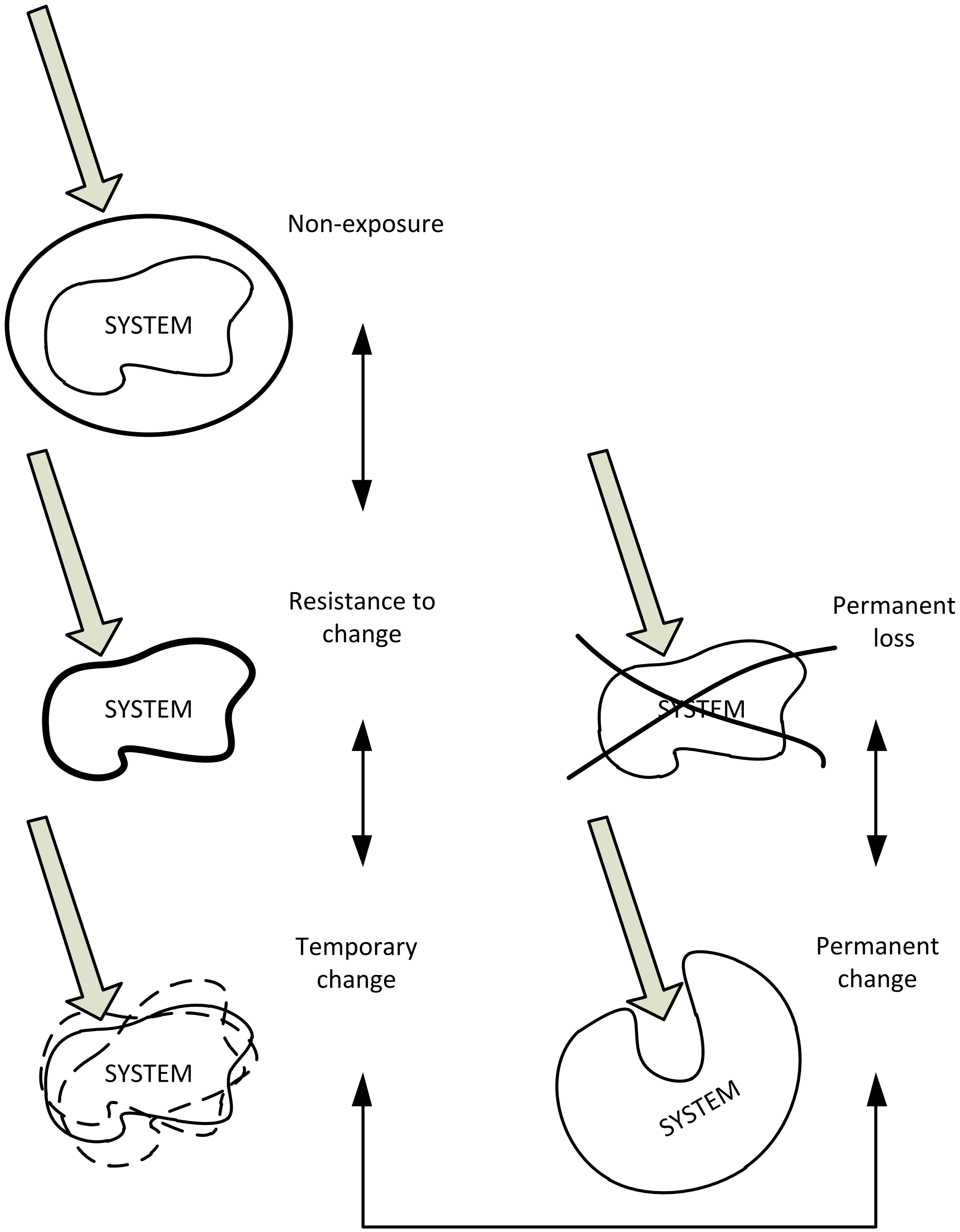

Figure 3. ***Arrangement of impacts of disturbances on systems.*** *While permanent loss and permanent change of structure and/or function are generally considered non-robust, systems that recover from, resist or avoid exposure to disturbances may be called robust*

adaptation, temporary change, inherent resistance or non-exposure. We recognise that to a greater or to a lesser extent, each system is vulnerable to disturbances. Systems may develop different strategies to cope with vulnerability aspects that constitute overall system vulnerability.

Vulnerability, robustness and stability of systems are closely related. We have distinguished three aspects of vulnerability and three images of stability, that constitute notional ends of continuums that range from 'vulnerable' to 'stable'. One such continuum is for instance formed by non-resilience on the vulnerability-end, and resilience on the stability-end, where non-resilience refers to a situation in which a system is never able to recover from any disturbance it encounters, whereas resilience as a stability image refers to a situation where disturbances of unlimited magnitude are absorbed and have absolutely no effect on the system. Other continuums extend from never able to withstand exposure (sensitivity), to inertness or inherent resistance to every exposure (resistance), and from structural inability to avoid exposure to specific disturbances, to constancy and non-exposure. In each continuum, we believe robustness exists between the chaos represented by the aspect of vulnerability on the one hand and a static stability image on the other, thus distinguishing an intermediate sphere in which a system's capacity to cope with both ordinary and occasional disturbances is optimised. We will call these intermediate spheres robustness states. The robustness states that exist on the three continuums differ in the degree by which systems are allowed or inclined to follow changes in their environment. From low to high inclination to follow environmental changes, we may distinguish the following robustness states (figure 4):

1. Avoid exposure: robustness following from precautionary measures or system integration in a larger whole that provides shelter or reduces the likelihood of being exposed to particular disturbances. This relational property of system and disturbance is taken as a measure for system robustness. The presupposed non-robust system is one that fails to avoid exposure to specific disturbances. The ideal, stable situation is one of constancy and non-exposure;
2. Withstand exposure: robustness following from reduced sensitivity to disturbance and increased inherent resistance of systems. Rather than the likelihood of being exposed, the degree to which a system will be affected by a particular disturbance is taken as a measure for its robustness. The presupposed, non-robust vulnerable system is one that will be affected by each and every disturbance, while the ideal system would be inert, or inherently resistant;
3. Recover from disturbance: a state of robustness based on a system's capacity to respond and recover after being disturbed, measuring robustness neither in likelihood of being exposed, nor in the degree by which a system is initially affected by the disturbance, but in the capacity to recover and regain stability in multi-equilibrium stability landscapes instead. The presupposed vulnerability aspect is absolute non-resilience, whereas the resilient stability image supposes systems to immediately regain stability when disturbed.

Discussion

Agricultural systems are illustrative of what we will call a robustness paradox, which refers to a tension created in a system that requires diversity and resilience to cope with unlikely perturbations such as epidemics, while operating in a market

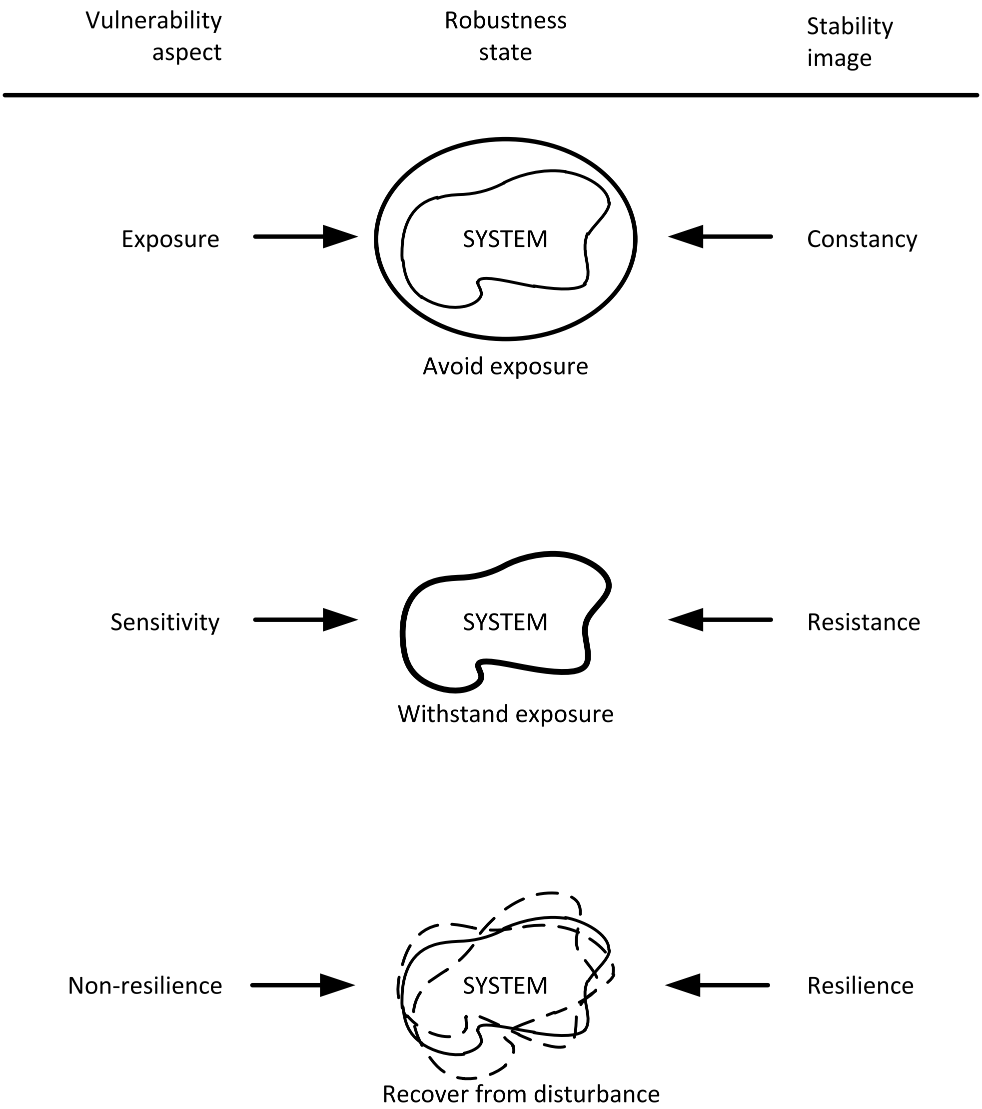

Figure 4. Robustness states. *From low to high inclination to follow environmental changes, robustness states can be based on avoiding exposure, withstanding exposure and recovering after exposure to a particular disturbance.*

that demands uniform and stable output. Indeed, diverse systems that do not comply with the uniformity that society demands may price themselves out of the market, whereas systems that succeed in producing uniformity in size, shape, taste and maturity are usually optimised to produce under 'normal' circumstances, but are consequently more vulnerable to unexpected events. Restraining vulnerability to one disturbance usually enlarges vulnerability to another, an interplay that has been described as a robustness-fragility trade-off and can lead to robust, yet fragile 'highly optimised tolerance' (HOT) systems (Carlson and Doyle, 1999, 2000, 2002; Csete and

Doyle, 2002; Kitano, 2007). HOT is a mechanism for system complexity based on robustness, emphasizing the efficiency and robustness trade-offs that characterise engineering design (Zhou et al., 2005). It was introduced by Carlson and Doyle (1999) as a mechanism for power laws in complex systems. HOT relates to systems that are designed for high performance in an uncertain environment, operating at densities above criticality (Carlson and Doyle, 2000). Carlson and Doyle argue that it is possible to retain maximum yields beyond the critical point in HOT states. HOT is interesting for an analysis of robustness of agricultural production systems, because the model suggests that robustness trade-offs underlie resilience in different systems. This explains why systems that are vulnerable to running into a robustness-complexity spiral may ultimately get bogged down in rigidity traps, i.e. a situation in which a system has irreversibly lost basically all abilities to adapt to changing circumstances. In describing their model, Carlson and Doyle take a classical example of a managed forest, designed to maximise timber yield in the presence of fire risk. In this example, there is a cost or constraint associated with the use of the resource, and an economic gain associated with limiting the sizes of events. By analogy with this example, one might consider a pig husbandry system, designed to maximise pork production in the presence of possible swine flu infections. In both systems, production can be increased and risks reduced by cleverly applying resources, such as firebreaks or disinfectants. The tendency to add resources to increase production and reduce associated risks reinforces itself and this spiral is increasingly difficult to escape. The 'robust, yet fragile' viewpoint claims that systems evolve complexities that make them surprisingly tolerant to uncertainties in environment and systems components, and as a consequence extremely vulnerable to rare and unanticipated perturbations. This viewpoint has been applied to various complex systems with trade-offs related, for instance, to the attack tolerance of the internet (Albert et al., 2000; Doyle et al., 2005), forest fires in organised forestry systems (Moritz et al., 2005) and evolvability in protein structures (Voigt et al., 2005). We believe that modern agricultural systems have evolved to HOT systems, designed for high performance and as a consequence resistant to likely perturbations, yet fragile to the risks of generally absent disturbances, such as epidemic diseases. These trade-offs not only illustrate that robustness and fragility are inextricably bound, but also make clear that a system's robustness state must above all be seen as the result of weighing up pros and cons. It suggests that robustness strategies should be embedded in continual learning and adaptive management (Anderies et al., 2007)

The three robustness states and related robustness strategies that we have formulated can all be found in current agriculture. Resistant plants and resilient animals have indeed been bred systematically, and growth processes are increasingly being controlled in optimised environments. We have seen that each of these states, despite mutual divergence, is actually being related to 'robust agriculture'. We believe this is so because these conceptualisations have a common feature in reacting against a management strategy, unparalleled in success and aversion, namely the eradication of disturbances, such as parasites, with chemicals and antibiotics. No other management strategy has allowed selection for yield above resistance and capacity to recover, and no other development has facilitated uniformity and yield maximisation as much as the development of chemicals and their application in agricultural systems. At the same time, no other agricultural development has raised so much aversion and generated so many calls for change, robustness appeals included. It has become clear that agricultural systems, designed for uniformity and yield maximisation, increasingly rely on additional control measures to protect elements of the system against common disturbances, such as endemic diseases, pathogens, and nutrient deficiencies. Their functional reliability, i.e., stable production, is obtained by using concentrates, fertilizers, chemicals and vaccines, production methods that are increasingly criticised as non-sustainable, but also have consistently neglected the capacity to either resist or recover from disturbances as a breeding objective.

The rationale behind recent calls to make agricultural systems more robust should be seen in the light of both criticisms regarding the sustainability of current agriculture practices and growing concerns about the indispensableness of external control measures as a management strategy. Transitions towards sustainable agriculture start from changing insights into the vulnerability of agricultural production systems and measures applied to arm against them. This is why robustness as a design criterion complies so well with the desire to make agriculture more sustainable. Considering the mutual divergence of the discussed robustness states, it is necessary to take a critical look at robustness strategies that are being applied for this purpose.

In discussing robustness two cardinal questions continue to reappear. Firstly, what feature of a system is robust, and secondly, what kind of disturbance is this feature robust against? (Jen, 2005; Lesne, 2008; Wagner, 2005) In relation to robustness states described in this chapter we suggest adding a third cardinal question, namely, in what way is a system feature robust? Only the latter question gives insight into the actual meaning given to robustness and makes it possible to discuss its morality rather than its outcome. This is particularly relevant in agriculture systems, where living systems are integrated in a world of engineering and control. Especially since these living systems are concurrently product and the means of production and their relative autonomy is a fundamental element of agricultural production, it is important to understand what constitutes their ‘robustness’. Indeed, while robustness on the one hand is promoted as a moral good, on the other hand it raises difficult moral considerations, for instance when it comes to breeding robust animals or modifying crops to create resistance. Should breeding for robustness lead to higher adaptedness, or instead improve the capacity to adapt to changes in environment, i.e., high adaptability? While some argue that the creation of animals that function better in conventional agricultural systems is ethically acceptable, provided that animal integrity is implemented as a breeding goal for robustness (Star et al., 2008), others (Christiansen and Sandøe 2000; Holland, 1995) have strongly rejected the idea of creating more adapted animals, for instance because it essentially “puts respect for the states of a subject above respect for the subject” (Holland, 1995).

Interference with a system’s risk of being exposed to perturbations to reduce vulnerability, is based, as we have argued in this chapter, on the assumption that vulnerability, stability and robustness are properties of the relation between system and perturbation, rather than properties of the system itself. In agricultural systems this relation is unsettled and depends on multiple qualities, such as climate, soil, cropping system and management strategy. However, we do believe that it is this 'external side of vulnerability' – a perceived shortcoming of security – that usually initiates the design of overarching protecting systems in which crops are pampered. Indeed, when vulnerability is externalised – viewed as a property of the relation between system and environment – and controlled accordingly, environment stabilisation will be pursued. This may lead to a situation where the remaining inherent robustness of the subsystem – crop or animal – becomes redundant, and may easily be dismissed as superfluous or obstructing optimal performance. It is increasingly being recognised that the defences offered by controlled, stabilised technological systems have made it possible to 'breed for production', rather than for inherent resistance of vulnerable crops and livestock. This has two obvious consequences. In the first place, redundant robustness of crops and livestock kept in relatively stable environments slowly declines in favour of 'consumer preferences' such as size, taste, or yield per ha through selective breeding. In the second place, these systems increasingly depend on additional control measures, which, in some cases appeared to go hand in hand with problems of efficacy and with negative side-effects such as freak accidents, chronic stress and overburdening of animals, soil degradation, emerging pests, weed and disease problems and have therefore been explicitly criticised for being non-robust (Ten Napel et al., 2006). We therefore believe that calls to increase robustness in agriculture should clearly specify the robustness state intended, and strategies chosen to achieve this state. Recognizing that an important goal of robust system design is a durable match of system output and dynamic stakeholder expectations, robustness states of exposure-avoidance, exposure-resistance, and resilience might not be equally desirable, and moreover, subject to shifting preferences. For instance, dominating demands to produce uniformly and stable suggest that in current agricultural production systems the significance of production outweighs the need to be prepared to respond to the unexpected. At the same time, agricultural systems are characterised by production processes that are undeniably liable to unwanted variations. Preventing exposure to the causes of these variations, such as diseases, pests and extreme weather conditions, would require control of the production environment; a strategy that can be realised in some, but certainly not in all production systems. Further research is needed to work out to what extent, and based on which value judgements, the urge for robustness in agriculture steers agricultural production systems towards resilience and adaptation, towards protection and exposure-avoidance, or towards a course of breeding vigorous cows and resistant apples instead. Of particular interest are the trade-offs involved.

Robustness as an image of sustainability

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Abstract

Sustainability is a catch-all term in need of more tangible, yet qualitatively measureable operationalisations. This chapter discusses the relevance of robustness as an image of sustainability. We argue that robustness has conceptual advantages against sustainability because it is embedded in system thinking and gives direction to operationalisations of sustainable development more than sustainability ever can. We consider conceptualisations of robustness in three TransForum projects which were set up to develop the concept of robustness in agricultural innovation. In these projects, robustness is conceptualised from an engineering perspective in relation to system efficiency and control. We suggest a frame of reference based on two organising principles, and suggest that other conceptualisations of robustness should be taken into account when operationalising sustainable development through robustness.

Introduction

The TransForum program (van Latesteijn and Andeweg, 2011) was initiated in 2004 to stimulate Agro innovation for sustainable development. As the type of innovation aimed for was argued to transcend the normal operational impact of innovations, the program called for new mindsets to "do better things", rather than "doing things better" (van Latesteijn and Andeweg, 2011). The program rejected the prevailing focus on improving efficiency and urged for an agricultural reinvention in which sustainable development would be an innovation target. TransForum used sustainability and sustainable development from a triple bottom-line (3BL) perspective, focussing on the triple P-values people, planet and profit. The 3BL approach is the most accessible and most applied method to evaluate sustainability. Although to some extent the 3BL narrows down the methods of constituting sustainability as an object of science, it also contributes to many different operationalisations of sustainability and lengthy debates about their appropriateness. As a consequence, triple P-sustainability and triple-P sustainable development must be understood as catch-all terms, rather than as clear innovation targets which can contribute to purposeful reinventions of agricultural practises. We therefore believe that more tangible, yet qualitatively measureable, images of sustainability are needed: operationalisations of sustainability that include shared normative values and can shape mindsets to "doing better things".

In this chapter we consider one of these, namely robustness: a concept that has rapidly gained attention as a possible solution for a variety of sustainability problems which characterise modern agriculture. In reaction to experienced increases in vulnerability to unwanted fluctuations, Ten Napel et al. (2006) suggested that agricultural systems should be made more robust. However, we have observed that the term is used loosely in various contexts and that it has been given equally diverse meanings.

Although robustness and sustainability are both intuitively attractive, contested concepts, robustness has several conceptual advantages over sustainability:

- the disturbances against which systems develop robustness are disturbances that can potentially harm the system structurally, or functionally, and should therefore be seen as sustainability problems; robustness thus gives direction to potential solutions to sustainability problems, i.e. a contribution to the operationalisation of sustainable development in practice.
- robustness is embedded in system thinking – a perspective which focuses on interactions of the element being studied with other elements with which it forms a system (Aronson, 1996); a discussion of system robustness is relevant only when, and subsequently requires that, both system feature and potential thread are specified (Jen, 2005; Lesne, 2008). As a consequence, a description of system robustness relates to a strategy to cope with a specific thread and ideally not only specifies *what* is robust to *what*, but ultimately also *how*. From an engineering perspective, the latter is of strategic importance to operationalise sustainability.

Three scientific research projects which were started within the TransForum program more or less conceptualised robustness through the selection of inventions directed at sustainability of specific production systems. These projects were:

1. 'Stacking functionality expressed in apple genes'. The aim of this project was the development of high-quality apple varieties that have a durable resistance to apple scab (*Venturia inaequalis*) by means of cisgenesis;
2. 'A monitoring and control system for conditioning of plants and greenhouses'. The project aimed to quantify physiological effects of climate conditions on plants in energy efficient and energy producing greenhouses, and develop intelligent crop monitoring systems of plant performance;
3. 'Robustness of animal production systems'. The main objective of this project was to develop the concept of robustness of animal production systems at various levels using system and control theory and apply these concepts to cases in the production system (farm), the production chain and at regional level.

In this chapter we present a framework against which we assess the robustness conceptualisation of the above-mentioned projects.
For this purpose, we shortly introduce the three projects, explore the conceptualisation of robustness in each project and use these results to discuss suitable and less suitable conceptualisations in the context of sustainable agriculture. We aim to show which operationalisation of robustness is dominant in the context of sustainable agriculture, and which alternative operationalisations might be worth considering. In other words, which problems and potential benefits are associated with the different conceptualisations? First, we introduce two organising principles to distinguish four potential conceptualisations of robustness. We will use this framework in our analysis of robustness conceptualisation used in the three TransForum projects.

From sustainability to robustness: a new mindset?

Implicitly, robustness has been an issue of concern in various agri-businesses, but as a concept, it has particularly been discussed in animal husbandry, where it is typically narrowed to physiological, behavioural and immunological performance. Conceptualised at the animal level it is mainly used to refer to an animal's ability to maintain homeostasis in increasingly dynamic environments and the capacity to adapt successfully to changing environmental management and health conditions (Kanis et al., 2005; Kanis et al., 2004; Klopčič et al., 2009; LNV, 2007a; Star et al., 2008; Ten Napel et al., 2006). At livestock system level, robustness has emerged as a design criterion for housing systems, signifying much the same as the flexibility to change (Wageningen UR Projectteam Houden van Hennen, 2004b). At the genetic level, phenotypic robustness (Hermisson and Wagner, 2005), also called phenotypic buffering (Fu et al., 2009) or canalisation (Levy and Siegal, 2008; Scharloo, 1991; Waddington, 1953), rather denotes the invariance of phenotypes in the face of both genetic and environmental perturbations. Robustness has also been related to performance under poor production environments (Sall et al., 1998); to production potential in a wide variety of environmental conditions (Knap, 2005); strategic decision-making in the context of unknown futures (Cittadini et al., 2008) and capacities to respond to crop failures (Lien et al., 2007b). Still, the meaning of robustness in different agricultural contexts as well as its justification vis-à-vis current transition processes towards more sustainable and socially acceptable agriculture remains unclear.

In this chapter we argue that these different conceptualisations of robustness are not so much related to different disciplines, but rather to different views of systems. The basic components of such systems – input, throughput, output and environment – have all been related to robustness. This is not surprising, since robustness is embedded in system thinking. From a system perspective, robustness may well be a prerequisite for existence. On the other hand, we do not consider all systems to be equally robust. When attempting to assess system robustness, it is precisely this subjectivity which explains the need to make explicit how specific system features cope with specific threats. These specifications are preceded by contentious visualisations of the system under consideration, its boundaries, and the environment in which it operates. In the next section, we use two organising principles to construct dimensional descriptions which classify different conceptualisations of robustness.

Organising principles

A specification of the features and perturbations of a system gives rise to different views of the stability and behaviour of the system in relation to its environment. We argue that different stability views, different understandings of a system's behaviour and to a lesser extent perceptions of the system environment are organising principles in a theoretical classification of conceptualisations of robustness. We discuss each principle below.

Stability view

System stability can qualitatively refer to the efficiency of execution, or quantitatively to the presence of a certain functionality. Robustness then refers either to the efficiency of function, or to the persistence of functionality (see also (Holling and Gunderson, 2002; Jen, 2005; Kitano, 2007). The first relates stability to system performance in the vicinity of a desired steady state. In this view, robustness refers to the capacity of a system to withstand perturbations and to stabilise a steady state of optimised efficiency. We will refer to this view as the 'efficiency of function' perception of robustness. Efficiency of function perceptions of robustness are common when system functions are related to qualitative or quantitative output levels. Robustness is then measured in terms of sensitivity, resistance or rate of return. In agricultural contexts, efficiency of function perceptions of robustness include for instance water use efficiency aspects of drought tolerance, disease resistance and the ability to recover from stress.

The second way of looking at system stability assumes that systems have multiple steady states; these being mainly found in descriptions of social-ecological systems (Levin and Lubchenco, 2008; Walker et al., 2005). Rather than defining robustness as the ability to keep the system in a steady state of optimised efficiency, robustness as persistence refers to the capacity to maintain a particular state of balance, i.e. to persist in one configuration, rather than another. We will call this view the 'persistence of functionality' conceptualisation of robustness.

Robustness as this persistence of functionality is expressed as a magnitude of disturbance that a system can withstand before it moves to an alternative steady state. Consider for instance food webs, the robustness of which can gradually decline due to biodiversity loss, thereby reducing equilibrium stability and increasing the chances of transitions to alternative steady states (Gilbert, 2009).

System behaviour

Different views of the relation between a system and its environment lead to different views of robustness. In general, this distinguishes two bipolar views of the ability of systems to cope with disturbances. Systems are assumed to be either in essentially stable or essentially unstable states. In a stable system, robustness is likely to refer to an inherent capacity to recover or reorganise. Systems have one or more stable steady states, or equilibria, towards which systems will return after disturbances. We will refer to this system behaviour as 'adaptation'. In an essentially unstable system, robustness relates to external control measures to protect desired states, presuming a necessity of continuous supervision and regulation. We will refer to this way of coping with disturbances as 'control'. Ten Napel *et al.* (2006) make a similar distinction between a traditional 'control model' and a presumed, more robust 'adaptation model'. In their view the difference between the two models lies in the ability of systems to cope with disturbances independently, and the changeability incorporated into the system's design. The 'control model' suggests that the system needs human support to maintain its function. Adaptability, on the other hand, refers to a system's capacity to adapt successfully to changing environments. Under the 'adaptation model', the system steady state is typically viewed as an equilibrium: a sphere at the bottom of a cup or valley. Not only does this suggest that it is hard to disturb the system, it also suggests that the system will easily and naturally return to its stable position at the bottom of the cup. These differences in perception of system behaviour suggest that this behaviour is a second organising principle in a robustness framework.

Perception of relation between a system and its environment

It has been argued that relational views between a system and its environment can be static or dynamic, depending on how the underlying forces which shape disturbances and system reactions are understood.

Especially in ecology, systems are understood as operating in a dynamic relation with their environments (Carpenter and Brock, 2008; Levin and Lubchenco, 2008; Walker et al., 2005; Webb and Levin, 2005). When relations between a system and its environment are static, robustness relates to known and predictable perturbations, while in dynamical relations robustness becomes increasingly connected to unpredictable changes in system variables and environmental dynamics. Although this distinction is highly relevant in analyses of what have become known as complex adaptive systems (Holland, 2006; Holland, 1992; Levin, 1998), it is of lesser importance for an analysis of system robustness in man-made agricultural production systems. We do therefore not include the distinction between static and dynamic system approaches as an organising principle[2].

Based on these principles, we can construct a conceptual framework of robustness, consisting of four quadrants that represent potential conceptualisations of robustness. We use bipolar dimensions of system robustness as organising principles, meaning that system stability is either related to efficiency of function, or to persistence of functionality, and likewise system behaviour is either control or adaptation. We

[2] *As part of the conceptual analysis a framework based on all three organising principles was worked out(see appendix 2). This framework was presented at a workshop of the Dutch-Flemish network for Philosophy of Science and Technology in April 2009, but it does not form a part of the framework used in this thesis.*

believe that different conceptualisations of robustness can be reduced to different combinations of dimensional descriptions, for instance Efficiency – Control (EC) or Efficiency – Adaptation (EA).
The organising principles thus generate a framework consisting of dimensional descriptions that represent what we believe are four different robustness conceptualisations. To underline differences we use synonyms of robustness meanings (robustness as…) to refer to these conceptualisations (see Table 1).
Although embedded in system thinking, the framework is not a system taxonomy, but only meant as an overview of different meanings given to robustness. Note that for its construction we have used organising principles related to different interpretations that have been given to robustness, rather than principles to organise different systems.

Table 1. A framework of robustness in dimensional descriptions

Dimensional description	Robustness as …
1. Efficiency, Control (EC)	Reliability / Insensitivity;
2. Efficiency, Adaptation (EA)	Resilience (Elasticity);
3. Persistence, Control (PC)	Continuity / Applicability;
4. Persistence, Adaptation (PA)	Resilience (Amplitude)

Conceptualisations of robustness

In the next section we will describe each conceptualisation of robustness in more detail.

Efficiency – Control

A combination of a view of stability focusing on efficiency of function and a relation between a system and its environment requiring external control is typical for engineered systems, in which robustness refers to functional reliability of – independent – system components in the presence of *predictable* chances of failure. Robust design typically aims to reduce uncertainty in system responses and to satisfy predetermined sets of performance requirements, despite exogenous variability (Allen et al., 2006; Willinger and Doyle, 2005).
Many strategies to create functional reliability may be distinguished, including the use of redundant components and design for reduced sensitivity.

Application

1. Redundant components. Redundancy is the duplication of critical components, possibly in combination with majority voting systems, with the intention of increasing the reliability of a system. The basic idea behind engineered redundancy is that a failure in one component, does not lead to total system failure. Consider, for example, multiple modular redundancy in Fly-by-Wire (FBW) control systems. FBW control systems generally consist of three or four independent and differently designed modules in order

to prevent common mode failure and a loss of signals when one or even two modules break down. The combination of diversity (different design), modularity (functional independence) and redundancy (duplicates of functionality) significantly reduces the probability of failure under expected levels of environmental variation.

2. Reduce sensitivity. Since many factors that affect a system cannot be controlled in actual applications – ambient temperature, humidity etc. – various studies have suggested the creation of robustness by selecting parameters that are less susceptible to variations (Robinson et al., 2004; Roy, 2001; Taguchi, 1986, 1995; Taguchi et al., 1999). This approach was termed quality engineering (Taguchi, 1986), but is more commonly known as the Taguchi approach. The ultimate goal of the Taguchi approach is a quality design that is immune to the influence of uncontrollable noise factors. It is assumed that this can be achieved by properly choosing the levels of controllable factors once desired quality levels have been achieved. The approach thus aims to achieve optimal conditions for quality consistence. It is based on a philosophy of prevention and a strong belief that robustness problems should be tackled at source and not through additional control measures such as inspection and screening. Taguchi's design method has cost-benefit advantages over modular redundant systems and has led to an increased understanding that choices made in early phases of design have a disproportionately large impact on design outcomes such as costs and quality (Allen et al., 2006; Clausing and Frey, 2005; Jugulum and Frey, 2007).[2]

Benefits and Shortcomings

When trying to create robust products or processes, engineers tend to focus on tightly controlling manufacturing processes to optimise trade-offs between cost and quality. In agriculture, this has led to production systems with high animal concentrations, low labour requirements, high levels of automation, and protective environments in which production is stabilised at maximum levels by keeping disturbances away from crops and animals. Policies that rely on this view not only impose few limitations to control and manipulate crops and livestock, but they also encourage human control and domination to keep balance, thus focusing on reliable controlling measures, rather than on the inherent robustness of the production system. These controlling measures appeared to go hand in hand with problems of efficacy and with negative side-effects such as freak accidents, chronic stress and the overburdening of animals, soil degradation, emerging pests, weed and disease problems, which may all have dramatic consequences. New system designs can reduce sensitivity to variation caused by noise factors, but do not necessarily reduce the intensity of control measures. Moreover, focussing on a particular system's sensitivity to noise may shift attention away for hierarchical interactions that underlie unexpected events. In other words, this approach loses attractiveness when uncertainty increases and the need to maintain adaptive capacity is high.

Efficiency – Adaptation

In contrast to control strategies, adaptation strategies try to reduce the consequences of variation by managing, rather than eliminating, their sources. Ten Napel *et al.*

(2006) argue that agricultural production systems should be designed accordingly; they should be able to return to optimal 'original' positions after a disturbance. According to this view, robustness is measured in terms of elasticity. It concentrates on the stability of systems in the vicinity of steady states of equilibrium and refers to both a resistance to change and to a system's rate of recovery after disturbance. In ecology, it is also known as engineering resilience or the Pimm definition of resilience (Holling, 1996; Holling and Meffe, 1996; Pimm, 1984; Tilman and Downing, 1994).

Application

Examples of robustness as elasticity are found in homeostatic control systems, where it relates to the regaining of efficiency of function by means of feedback loops and regulation systems. In dairy farming, consider the rate of return to positive energy balance after energy balance nadir (lowest energy balance) during early lactation. Pollott and Coffey (2009) argue that a return to positive energy balance, the level of nadir and the rate of return are important features affecting a cow's luteal activity and day of first heat. Selection for high milk production may have reduced the capacity of lactating cows to regain positive energy balances. In plant sciences, an example of robustness as elasticity is found in the relation between temperature and the recovery of photosynthetic efficiency (Sowinski et al., 2005). Maize is for instance considered less robust in temperate climates since the times needed to attain maximal growth speeds after a temperature shock are longer in temperate climates than in tropical climates. Note, however, that robust plants in terms of elasticity are not necessarily less sensitive to the disturbances from which they easily recover (see for instance (Kamoshita et al., 2004).

Benefits and shortcomings

This conceptualisation of robustness is useful when referring to a system's resistance to change and its recovery capacity. It is used at animal and crop level to assess their capacity to function in sub-optimal conditions. In situations where this conceptualisation of robustness is used, it is suggested that environmental conditions cannot be controlled and disturbances cannot be avoided. Hence, the efficiency of the system depends on the inherent capacity of the system under consideration to cope with variations and disturbances encountered. Many animals and crops have developed an inherent capacity to resist change and cope with unexpected events. Selectively making use of these capacities can contribute to robust production systems. However, trade-offs have been discovered between production and robustness features. As energy invested in the maintenance of coping capacities cannot be utilised for production, high yield varieties which satisfactorily cope with sub-optimal conditions and unexpected events are rare.

Persistence – Control

Persistence-conceptualisations take robustness not as the efficiency of function, but as the maintenance of functionality, or the capacity to maintain a particular state of balance. The control model assumes that these states are unstable but manipulative. As a measure for the capacity to remain balance, the control model takes robustness as the ability to remain structurally unchanged. In dynamic environments, this conceptualisation may extend to the range of system effectiveness.

Application

Robust structural design. Some systems are meant to remain unchanged, in the sense of being built for eternity or designed against structural failure. Consider the World Trade Centre, that was designed to withstand the impact of a Boeing 707[3]. In relation to structural design, robustness refers to a system's capacity to withstand extreme circumstances, such as fire or earthquakes and is commonly associated with risk analysis. In contrast to engineering against functional failure, robust structural design does not depend on additional safety measures or passive protection, but on inherent resistance instead (Lamont et al., 2006). Building for eternity is an attempt to realise structural failure avoidance. Systems that are built to remain cannot adapt, intervene or control their existence. In other words: structurally, these systems are static and the only alternative state they can be in is a state of not-being. Note that the function of such systems may nonetheless change dramatically over time, e.g. ancient temples becoming tourist attractions, churches becoming mosques, schools becoming care-centres and factories becoming museums. For these systems, robustness is related to a continuation of existence, or an avoidance of not-being, regardless of the function it fulfils and without necessary interventions.

Flexible modes of operation. Robustness Analysis (RA) aims to preserve potentially fruitful options when future conditions are uncertain, future performance is expected to be influenced by uncontrollable future developments and when future evaluation criteria are uncertain or likely to change (Best et al., 1986; Driouchi et al., 2009; Rosenhead, 1980). Policy changes may for instance initiate transitions of all kinds. In operation research literature, robustness refers to the flexibility that an initial decision of a plan maintains in order to achieve near-optimal states in conditions of uncertainty (Rosenhead et al., 1972). Consider the ability of a particular trading strategy to stay effective in different markets and under varying market conditions, or the potential of a production strategy to stay socially acceptable in different societies and under changing moralities. In these situations, robustness is a supplementary criterion for the choice of an initial decision, and it is intrinsic because it exists as a by-product of selection for a specific strategy, rather than as a target in itself. One could say that robustness here relates to the range of system effectiveness.

Benefits and shortcomings

Robust structural design has value only for the structural elements of agricultural systems. Housing systems for instance should be designed to withstand forces that can be reasonably expected as to avoid structural failures. As an operationalisation of sustainability, improving the structural robustness of agricultural systems has limited value. The second application, referring to system effectiveness and the preservation of flexibility, proceeds from the idea that future conditions are uncertain and likely to change. This application has implicit, but strategic relevance for sustainable development studies. We consider this view as a recommendation to relate robustness to the composition of a stock of options, rather than to an 'all-or-nothing' solution and invest in the flexibility and preservation of these options. As a

[3] *BBC News, March 7th 2002 suggested that the WTC exclusively collapsed because of the fuel on board the hijacked Boeing 767s that were used in the 9-11 attacks.*
See also http://news.bbc.co.uk/2/hi/science/nature/1858491.stm

shortcoming of this approach, we observe that robustness is seen as a supplementary criterion, rather than as a guiding principle in the initial decision. As an image of sustainability, this conceptualisation lacks tangibility and measurability.

Persistence – Adaptation

A more adaptive view conceptualises robustness in terms of resilience, concentrating on the ability of particular sets of organising structures and processes to persist in the vicinity of thresholds (Holling, 1973; Levin and Lubchenco, 2008; Walker et al., 2005). Unlike resilience studies which focus on the resistance to disturbance and the speed of recovery in the vicinity of steady states of equilibrium (section above), this view focuses on conditions far from steady states of equilibrium and the corresponding instabilities that may cause transition towards alternative steady states (Holling et al., 2002). This view is known as 'ecosystem resilience' (Holling, 1996; Holling and Meffe, 1996). Ecosystem resilience is not related to the rate at which a system returns to equilibrium, but rather to the maximum magnitude of disturbance which a system can absorb before its structure changes. Ecosystem resilience measures the amount of space in which a particular configuration can persist, or its susceptibility to being transformed to an alternative configuration by stochastic events. The concept was developed in regard to ecosystems and referred specifically to the preservation of their ability to function in the presence of external pressure (Holling, 1973). The idea of systems alternating between stationary stable states has been worked out in many different fields outside ecology. It is an adaptive view in the sense that policies and management approaches can influence the internal dynamics which systems experience.

Application

This conceptualisation takes robustness as the magnitude of disturbance which a system can absorb before its structure changes and suggests that system robustness is determined by the dynamic interactions of various processes at different periodicities and spatial scales. This idea was worked out in detail by Gunderson and Holling (2002), who introduced the term *panarchy* to 'capture the adaptive and evolutionary nature of adaptive cycles that are nested one within the other across time and space scales'.

The idea of panarchies has mainly been applied to ecological and social-ecological systems (SES), the robustness of which is usually referred to as social-ecological resilience. A social-ecological system is a complex system that incorporates human societies, ecosystems, and their interactions (Cumming, 2011). SES studies recognise that human societies not only depend on natural resources for exploitation, but consequently also modify these resources (Janssen et al., 2007).

Anderies *et al.* (2004) therefore argue that SES are robust if they successfully prevent '*the ecological system upon which the social component relies [moving] into a new domain of attraction that cannot support a human population, or that will induce a transition that causes long-term human suffering'*. In other words, a robust SES is sustainable because it stays on track, or continues to succeed in finding sufficient resources to exploit for its maintenance. Robustness then relates to the preservation of resilience and persistence in the history of life, rather than to the resilience of the system against a specific perturbation per se.

Benefits and shortcomings
This conceptualisation combines some of the views discussed above, but adds a feature characteristic for social systems, namely the capacity to anticipate and plan for the future, which makes it relevant from a perspective of sustainable development. Although the term robustness is in use for this idea, it is more commonly referred to as ecosystem resilience. This conceptualisation also challenges the dominant 3BL approach of sustainability, since it rejects the ideals of stability based on static assumptions such as maximum sustainable yield and carrying capacity that are typically related to 3BL sustainability. Instead, the sustainability approach of ecological resilience thinking is based on continuous change at various system levels, suggesting that sustainability cannot be considered as preserving a status quo, but is only achieved through adoption and evolution, whether or not through radical reorganisation. This approach is in keeping with the science of complexity which aims to explain non-linearity and unpredictability in complex system dynamics. We observe that the increasing interest in complexity studies within the agricultural sciences undermines the 3BL sustainability paradigm.

TransForum Project 1: Stacking functionality expressed in apple genes

Objective and background
The aim of this project was the development of high-quality apple varieties that have a durable resistance to apple scab (*Venturia inaequalis*). The dominant idea behind this project was that durable resistance to apple scab allows a strong reduction in fungicide usage in apple growing. This idea will perhaps contribute to a sustainable development of apple production in north-western Europe and makes it possible to position apple production in or near urban areas, where city dwellers can enjoy the beauty of flowering and fruiting orchards.
To achieve durable resistance, the project aimed to stack two resistance genes isolated from resistant apple plants that have an insufficient fruit quality, and introduce them into elite high-quality varieties by means of cisgenesis, genetic modification with species-specific genes only. This procedure is much faster than conventional breeding. The initiators argued that conventional breeding could lead to the same results, but that the goals to reduce chemical input the agricultural sector has jointly formulated with the Dutch government do not allow four or five decades of conventional breeding.
For more information on this project, and an overview of publications, see: http://www.transforum.nl/projecten/wetenschappelijke-projecten/item/47-stapeling-van-genen-voor-duurzame-resistentie-tegen-appelschurft

Sustainability approach
The sustainability approach is mainly social-economical. Two sustainability problems are highlighted in the project.

1. Economic viability. Due to import from other parts of the world, apple cultivation in the Netherlands and north-western Europe is generally not economically viable.

2. Social-ecological conditions. The present high-quality cultivars are susceptible to apple scab, and therefore require approximately 15 chemical sprays per year, however the aim is to reduce the chemical input. It is suggested that high-quality cultivars with durable resistance to apple scab are urgently needed in order for the fruit growers to survive. Hence, economic sustainability is considered within social-ecologically limiting conditions. The desired integration of fruit growing and living areas the initiators have in mind would indicate that these limiting conditions are met.

Conceptualisation of robustness and contribution to sustainable farming

To achieve the above sustainability goals, the project aimed to develop a more durable resistance strategy at plant level, i.e. robust apple varieties. It is suggested that such robustness requires at least two functionally expressed resistance genes, stacked in a variety. This is called gene pyramiding, or gene stacking. The project uses genetic modification to stack two apple scab resistance genes in susceptible elite cultivars with superior fruit quality to provide these varieties with durable resistance to scab. Stacking genes through genetic modification to create durable resistance is an innovative approach which can be applied to all other crops, without the necessity of time-consuming breeding programs.

Polygene resistant varieties are expected to maintain their resistance longer than monogenic resistant varieties, since the pyramiding of resistance genes creates redundancy. This strategy shows remarkable similarities with the use of modular redundancy as applied in Fly-By-Wire Control Systems in aeronautical engineering, for instance. Where the use of different groups of computers, based on different hardware and equipped with different software has considerably reduced the risk of aircraft loss due to flight control failure, the pyramiding of resistance genes intentionally combines parallel and independent resistance genes to increase overall resistance, including a back-up system in case one of the resistance genes is overcome. In the dimensional description that we suggest, this project conceptualised robustness at the plant level as a combination of efficiency and control. On a social level, the project anticipated social-ecological and social-economic developments such as dynamic market shares, taste preferences and the social acceptance of chemical input versus the use of genetic modification.

TransForum Project 2: SynErgy: A monitoring and control system for conditioning of plants and greenhouses

Objective and background

Stimulated by high energy prices, new greenhouses are being developed which will only need a small fraction of the energy they need today or will even be net producers of energy. These energy-poor and energy-producing greenhouses have a completely different type of climate than conventional greenhouses. So far, the

SynErgy project has identified a number of barriers that obstruct the development of energy-producing greenhouses. A major bottleneck for this invention is how to monitor and control the crop in these greenhouses. It is suggested that a new method of growing plants, called conditioned growth, is needed to successfully reduce energy use by the greenhouse industry, while further optimising the production of vegetables, cut flowers and pot plants. The project continues to aim to quantify physiological effects on plants of new climate conditions such as high air humidity under summer conditions, and develop intelligent crop monitoring systems of plant performance.
For more information on this project, and an overview of publications, see: http://www.transforum.nl/projecten/wetenschappelijke-projecten/item/55-synergie-gewas-van-de-toekomst-in-kas-van-de-toekomst

Sustainability approach
This scientific project has contributed to the invention of an energy-producing greenhouse in combination with a very high and controllable production. It is argued that this has ensured the competitiveness of the greenhouse horticultural sector for the future. Although energy reduction has ecological benefits, the sustainability approach of this project has mainly been economic. High energy prices, rather than ecological limitations, impose energy reduction on the horticultural sector. Physiological limitations of crops and necessary crop monitoring systems are the main barriers which obstruct the development of energy-producing greenhouses.

Conceptualisation of robustness and contribution to sustainable farming
This project relates to a specific form of robustness at the level of a cropping system and individual plants. It has thus far aimed to create a cropping system which optimises production under the very specific growth conditions of energy-producing greenhouses by continuous monitoring and adapting. This optimisation consists of an iterative process of technological innovation and crop physiology. Although not explicitly expressed, the project has taken the inherent robustness range (plant requirements) of the plants as a starting point for the design of new greenhouses. The results of this study aim to give insight into the quantitative effects of new climate conditions on crop performance and should not only make clear which critical plant processes must be monitored, but also give direction to the development of novel optimisation procedures and adaptations of greenhouse design. The project has thus contributed to both a redefinition of desired quality levels within the new greenhouses, and the optimisation of controllable levels therein to promote consistent high-quality production and reduce the influence of uncontrollable noise factors. To make conditioned growth possible, it has been argued that the plants should be 'vandal-proof' to be able to cope with expected deviations from optimal growth conditions. Concentrating on the stability of crop production in near-optimal conditions, robustness is conceptualised at the plant level in terms of resistance to change or engineering resilience. At cropping system level, it is used as a parameter to design reliable monitoring and control systems. Here, robustness relates to reliability. In the dimensional description that we suggest, this project conceptualises robustness in terms of efficiency and control.

TransForum Project 3: Robust animal production

Objective and background

The main objective of this project was to develop the concept of robustness of animal production systems at various levels using system and control theory and apply these concepts to cases in the production system (farm), the production chain and at regional level. The starting point for the project was a working paper by Ten Napel et al. (2006) discussing two approaches on achieving stability in agricultural production systems. The prevailing approach, which is called the 'Control Model', is to protect crops and livestock from disturbances as much as possible, to regain balance with monitoring and intervention and to look for add-on solutions only. The alternative model, called the 'Adaptation Model', is based on reducing the consequences of disturbances, rather than preventing. Ten Napel et al argued that this means utilising and supporting the intrinsic robustness of crops and livestock, i.e. their capacity to deal with disturbances by adaptation. For more information on this project, and an overview of publications, see: http://www.transforum.nl/projecten/wetenschappelijke-projecten/item/54-robuustheid-bij-dierlijke-productiesystemen

Sustainability approach

In the context of robustness, this project defined a sustainable animal production system as an animal production system which is able to maintain its functionality and/or its form in a set time interval, whereby system components need not be maintained. To assess sustainability, the 3BL approach was used. The project defined robustness as a means to achieve the stability of specific sustainability aspects, either in space or in a certain time scale. Robustness deals, amongst other things, with stability of production systems, or more precisely, stability in time and space of measurable indicators defined by means of a sustainability analysis.

Conceptualisation of robustness and contribution to sustainable farming

For the relation between robustness, stability and sustainability, robustness is seen to connect sustainability to system stability, i.e. to contribute to the preservation of a desired, sustainable steady state. While sustainability is described as maintaining functionality, robustness is explicitly related to achieving stability of production-related sustainability aspects in time and space. Especially since the project clearly proposed that "Robustness deals with the stability of measurable indicators that are defined by means of a sustainability analysis", it becomes clear that the system-stability view behind this project was ultimately based on efficiency of function. The project relied on control theory to achieve consistent, optimised production in animal production systems, but rejected the traditional role of engineering as aiming to control variation. Instead, it built on the 'adaptation model' (Ten Napel et al., 2006) to reduce the consequences of uncontrollable fluctuations and discover novel ways to create order in animal production systems.

This project focused on robustness at the level of herd, production chain and landscape, and not at the animal level, although it sought to utilise robustness at the

animal level for robustness at higher levels. One of the main goals of the project was to make sustainability of production systems more operational by developing the concept of robustness, from a system-theory perspective. The project was positioned as an interdisciplinary project between two major disciplines, i.e. measurement and control theory, and animal production systems. Following the vision that the robustness of systems is basically a control problem (how are output or internal state variables kept within pre-set limits?), the project assumed that control theory can be applied and used to make animal production systems more robust, i.e. less sensitive to unwanted fluctuations. Robustness was thus here explicitly seen as a designable system feature. By integrating social and environmental considerations into the system design, it aimed at reducing sensitivity to unwanted variations which can be expected under normal conditions. All in all, the sustainability approach and operationalisation of robustness therein has a strong focus on people and profit.
In the dimensional description that we suggest, this project conceptualised robustness as a combination of efficiency and control; a condition in which the production process is insensitive to variation in individual factors.

Discussion

Our analysis of the three TransForum projects which operationalised robustness suggests that in all the projects robustness was or has been narrowly used to refer to the efficiency of the function of systems and in relation to control. In this section, we return to the suggested frame of reference and discuss the relevance of conceptualisations used, as well as alternative conceptualisations of robustness in agriculture.
In the TransForum projects, as well as in other agricultural contexts, engineering conceptualisations of robustness such as reliability or insensitivity (3.1) appear dominant, not only with regard to control and monitoring systems in advanced greenhouses, but also with regard to livestock and crop systems, where robustness is generally considered at animal or crop level. It is relevant from an engineering and efficiency perspective, in which solutions are being sought for relatively well-defined sustainability problems in relatively well-defined systems. It is an approach that relies on the predictability of fluctuations and the corresponding chances of failure.

The second conceptualisation, a combination of efficiency and adaptation is attractive, but trade-offs between adaptive capacity and efficiency have been found. This conceptualisation seems useful when relatively low productivity is acceptable or the costs of efficiency-maintaining control measures are too high. However, designing for adaptation ultimately leads to increased control at the operational management level. Whenever the adaptive capacity of systems becomes a target of design, it becomes planned, and purposefully placed under care of the farmer. Planned adaptation is essentially different from associate adaptive capacity which contributes to system robustness independently of the farmer's planning, just as planned diversity such as the variety of crops and animals is essentially different from associate biodiversity. Planned adaptation and diversity have become part of the operational management of the system, and thus make adaptive capacity or diversity an element of control. While associate adaptation has a structural value, planned adaptation has a functional value, since it has relevance only in relation to the (long-term) efficiency of the system and obtains its value as a rational choice (Vandermeer, 2011). This is also our main critique of Ten Napel *et al.*'s adaptation model (2006). The adaptation model suggests that adaptive capacity can be increased with control theory, i.e. controlled adaptation. Rather than reducing the intensity of control on the system, the adaptation model adds adaptive capacity to the existing control model.

The Persistence – Control conceptualisation of robustness was developed in structural engineering as well as strategic decision support. The TransForum projects discussed do not suggest that this conceptualisation has direct relevance in agricultural contexts. However, the relevance of this conceptualisation is merely implicit. Consider the idea behind TransForum Project 2 in which the desire to sustain apple production in Western Europe requires strategic decisions to design production methods which are effective despite unknown political decisions. The effectiveness of the suggested solution ultimately depends on the exemption of cisgenesis from the existing regulations on genetic modification. Recognising that current production methods may have reached the limits of applicability, the suggested alternative lacks flexibility in its modes of operation, since it seeks a solution to the side-effects of existing production methods, rather than strategically preserving potentially fruitful options. In other words, the cisgenic apple has no near-optimal state: it is an 'all-or-nothing' solution. If one takes into account that cisgenesis is, at this moment, not even permitted by European regulations, one must conclude that the applicability conceptualisation of robustness is extremely relevant for this project. As an operationalisation of sustainability, this robustness conceptualisation is relevant because it stresses the importance of considering the flexibility of a decision to achieve near-optimal states when future circumstances depend on developments outside one's own control.

The fourth robustness conceptualisation, namely the ecological resilience view, is largely ignored in agricultural innovation projects. This conceptualisation has developed in complexity theory, and is particularly relevant in relation to so-called complex adaptive systems. Similar to the applicability conceptualisation of robustness, this view has implicit relevance, but particularly at high abstraction levels. That is due to the fact that it is assumed that agricultural systems operate in complex adaptive systems: social-ecological systems in which agriculture is a disturber, rather than a vulnerable. System robustness thus extends the level of the agricultural sub-system, and increasingly relates to the impact of resource modification agriculture has on the absorbing capacity of the ecological system in which it is practiced. This view stresses that the social and economic components of sustainability rely on the ecological system and it is therefore at odds with the 3BL sustainability approach that was endorsed in the TransForum Project. Operationalisation of this view of robustness in agricultural innovation projects would require a reconsideration of the epistemic methods that constitute sustainability as an object of science. We believe that the added value of this view is the insight that agricultural practices can lead to collapsing ecosystems and a reduction in exploitable resources. The examples are many that whereas 3BL is a noble endeavour, ecological resilience is an inevitability. Our ability to measure and understand the non-linear dynamics underlying ecological resilience is limited, but slowly increasing. Future assessments of agricultural sustainability cannot side-step this operationalisation of robustness.

Conclusion

We suspect that TransForum's intial choice to endorse the 3BL approach to stimulate sustainable development explains why robustness has been conceptualised in terms of efficiency and control. We observe that the 3BL approach is scientifically disputed since it enhances the quantitative measurement of sustainability aspects and subsumes environmental and social concerns therein, and it is particularly criticised for its inability to include normative values in the metrics it uses (Gibson, 2011).

Recently, KPMG International (KPMG, 2012, available at: http://www.kpmg.com/Global/en/IssuesAndInsights/ArticlesPublications/Documents/building-business-value.pdf) urged businesses around the world to apply systems thinking in their sustainability strategies and develop resilience, flexibility and adaptive capacity to prepare for the unexpected, rather than focusing on measurable risks and probabilities. This call connects with some of the robustness conceptualisations – not yet applied in agricultural contexts – which we found in our analysis, most notably those related to persistence of functionality.

We believe robustness has the potential to function as an image of sustainability in agriculture. As yet, the concept has been narrowly used to refer to improved efficiency and increased controllability of engineered systems, thereby largely ignoring that robustness is embedded and has particularly evolved in complex adaptive system thinking. Considering the growing interest in complex (adaptive) systems and alternative system approaches (Darnhofer et al., 2010a; Darnhofer et al., 2010b) within the agricultural sciences, it is time to reconsider the meaning of robustness vis-a-vis sustainable agriculture.

Can we design for a break through spiralling complexity?

Submitted for publication

Abstract

Livestock Production Systems (LPS) are susceptible to a process of spiralling complexity when suppressing unwanted vulnerabilities or taking advantage of opportunities for increased performance. This process explains growing fragility to unexpected events. This chapter analyses the effectiveness of the Reflexive Interactive Design Approach (RIO) to break through spiralling complexity. The Houden van Hennen (HvH) project is taken as a case. Stakeholder demands based on needs of farmer, laying hen and citizen that were collected in a Programme Of Demands (POD) in this project are classified in terms of desired robustness strategies and their distribution over the social, biological and technological subdomain of the system. The results of the HvH project indicate that 30% of all demands relate to coping with potential perturbations, of which 86% aims at avoiding perturbations and mainly directed at management level. The POD does not express a need for adaptive management and shows a perception of system vulnerability mainly at the animal level. The use of their natural behaviour and adaptive capacities to cope with disturbances seems motivated by structural system optimisation and is purposefully placed under care of the farmer. Rather than to a radical shift in egg production that was anticipated, the POD hardly challenges the existing regime. RIO has not led to a radically different way of producing eggs and did not break through spiralling complexity.

Introduction

Agricultural innovations rely on the adaptive capacities of agricultural systems, while often initiated by perturbations or perceived vulnerabilities of existing practices. Modern livestock production systems (LPS) have successfully incorporated new knowledge and technologies to keep up with stakeholder expectations, e.g. concerning food safety or costs of production. This rationalisation process, that has only accelerated during the last decades, has unremittingly added complexity to LPS and has contributed to a state of Highly Optimised Tolerance (HOT) (Carlson and Doyle, 1999, 2000), susceptible to what (Willinger and Doyle, 2005) described as complexity/robustness spiralling, a spiral of increased complexity to suppress unwanted vulnerabilities or take advantage of opportunities for increased performance. The drawback of optimised tolerance is hyper fragility to unexpected events, making the HOT state characteristic for 'robust, yet fragile' systems (Csete and Doyle, 2002). Reasons for increased fragilities of livestock production systems are twofold. Firstly, the context within which LPS have to be managed changes rapidly and in unexpected directions (Darnhofer et al., 2010b) suggesting that LPS that lack adaptive capacity will increasingly be confronted with the relativeness of their licence to produce. This is not typical for LPS, but the effect of increased demands for sustainability in the social, ecological and economic domain that not only sharpen stakeholder expectations but also accentuate contrasts and highlight hardly compatible sustainability goals. Secondly, the impact of unexpected, infrequently occurring events such as the incursion of Classical Swine Fever (CSF) into the Netherlands (Meuwissen et al., 1999; Pluimers et al., 1999) tends to increase with spiralling complexity. The hypersensitivity that is expected to emerge along the complexity/robustness spiral calls for a radically new modernisation approach, that breaks through the self-enhancing process of complexity/robustness spiralling that increasingly confronts us with the side-effects of responding to stakeholder demands for improved performance with additional complexities or short term solutions. This is not an easy task and to be successful, such an approach should be warned not to follow the direction of increasing tolerance to anticipated perturbations and already known vulnerabilities. On the other extreme, it should not disregard qualitative distinctions between system functions at farm level in its aim to increase self-organising capacities, resilience and adaptive capacities of systems. The challenge of designing robust agricultural systems is to find a middle course, i.e. integration of the two mechanisms; optimising the production potential of desired outputs not regardless of, but deliberately integrating the resilience and adaptive cycles of all co-evolving subsystems of the agricultural system under consideration. It is argued that Reflexive Interactive Design (RIO) offers such an approach. RIO (Bos, 2008, 2010; Bos et al., 2009; Groot Koerkamp and Bos, 2008) is a deliberative design of strategies for reflexive modernisation. It aims, in other words, to break with existing patterns of thinking and doing to realise system innovations. It is a strategy 'under development' that builds on diverse methodical and theoretical contributions from various fields, among which social theory, innovation studies and philosophy of technology. RIO takes a constructivist approach to technology development and integrates diverse system views and stability images. RIO is based on three steps, namely 1. System and actor analysis, including reflection on needs, desires and presuppositions of main actors and analysis of dominant structures, that can hinder or contribute to desired developments, definition of key challenges and future vision development, 2. Structured design, a methodical design approach based on systematic reflection on the presuppositions, goals, functions and their mutual ordering in order to achieve a technological synthesis of needs of different stakeholders, and 3. Anticipating niche and structural change, a strategic application of results to facilitate structural changes, that break with practices that are set in habits.

We want to analyse the effectiveness of RIO as an attempt to break out of spiralling complexity. Integrating diverse system views and stability views, we expect that RIO can integrate the two mechanisms underlying different directions of innovation to construct a future vision of agricultural system that are neither 'robust, yet fragile', nor neutral towards system functionality.

Method and case selection

We selected the Houden van Hennen (HvH) project (Wageningen UR Projectteam Houden van Hennen, 2004a, c) as a case for our analysis. Firstly, because it explicitly made the articulation of the concept of robustness a main challenge of the project (Wageningen UR Projectteam Houden van Hennen, 2004c). Secondly, the project aimed to deliver concepts that would initiate transitions towards sustainable and socially responsible laying-hen husbandry systems. The RIO approach was chosen to give direction to this course of action. The project thus combines the conceptualisation of robustness and agricultural transition processes towards sustainability, at a moment where analyses of LPS are characterised by presumed hypersensitivity and the need for adaptive management. Because LPS are particularly criticised for their incapacity to adequately cope with shocks and perturbations, we expected a significant pressure to reform animal productions systems accordingly. HvH distinguished three vulnerable features of laying-hen husbandry systems: production, animal welfare and, as a precondition, animal health. A program of demands (POD) based on the needs of poultry farmer, laying hen and citizen (Wageningen UR Projectteam Houden van Hennen, 2004a) was developed to guarantee that these vulnerable features were sufficiently taken into account in the design phase.
Moreover, we expected that stakeholders opt for a radically different way of coping with anticipated perturbations, judging by the critical evaluations of developments of modern technologies and 'control-approaches' in technology driven agriculture, and especially because the HvH project asked participants to envision their ideal way of keeping hens. We expected that in the reflexive design process the so called 'control approach' (Ten Napel et al., 2006), characterised by avoiding and eliminating perturbations and fluctuations, would be rejected in favour of more adaptive and resilience based approaches.

Methodology

We based our assessment of robustness strategies on the POD. It is the most complete wish list of stakeholders in husbandry systems for laying hens in the Netherlands. We specifically considered demands related to potential perturbations and formulated preferences of how to cope with these. We assumed that the POD included demands that are related to the most highly ranked attributes of the different aspects of sustainability. Moreover we expected that perturbation related demands formulate a coping strategy, i.e. when confronted with perturbation "p", we want the system "s" to apply robustness strategy "r", where "r" is avoid, resist or recover (De Goede et al., 2013a). Analysing p, s and r in the POD we answered the following questions:
1. Which perturbations are anticipated?
2. At which system levels are perturbations anticipated?
3. Which robustness strategies are demanded?

We categorised all demands in the POD (n=280) in the following categories:
1. Demand primarily related to optimisation of efficiency;
2. Demand primarily related to coping with perturbations, namely:
    a. Avoiding exposure to perturbation;
    b. Resisting exposure to perturbation;
    c. Recovering after exposure to perturbation;
3. Demand related to something else.

A second step in our analysis of results of the HvH project concerned the distribution of perturbation related demands over the social, technological and biological subdomains of the agrisystem. For this purpose we further classify demands found under 2a, 2b and 2c as directed at the social level, the technical system, or the laying hen herself.

Robustness conceptualisations

One of the main challenges of the HvH project was to articulate the concept of robustness. Conceptualisations of robustness relate to sustainability problems of specified systems and either describe a relational property of system and environment together, or an independent system feature. We refer to the process in which the concept robustness is crystallised and corresponding management strategies are developed as the conceptualisation process (figure 5), which consists of three steps. The first step is the construction of images, typically metaphorical representations of the current state of LPS. Images are value-laden, and facilitate communication about complex and often controversial subjects where opposing value orientations meet in public debate (Beers and Veldkamp, 2011). In innovation processes, and affected by attributes from the social, economic and ecological sustainability aspects, images of existing LPS (pre-innovation) commonly have negative associations, while images of the future (post-innovation) depict desirable, more sustainable futures. Note that both robustness and naturalness are part of images of the future, rather than of the present.

The second step relates the value laden representation of the current system to its vulnerabilities and sustainability problems. The problem definition must explicitly make clear which system features create system vulnerability, and which sustainability aspects are involved. This explication requires a specification of the hierarchical level of the considered system and its boundaries. These two questions, which one may refer to as the "of what?" and "to what?" questions describe a non-robust system, such as a pig (system level) vulnerable to temperature stress when exposed to high temperatures (perturbation). Its stable counterpart, a pig that is resistant to temperature stress when exposed to high temperatures, is a post-innovation image that includes a desired stability image. This image can be relational when it concerns the exposure to a specific perturbation, or refer to a reinterpretation or strengthening of weak or non-existing system resistance or resilience.
The third step concerns the construction of a robustness strategy as a means to move towards the desired stability image in coping with recognised vulnerabilities. In the pig example, a relational stability image may lead to protective measures to reduce exposure to high temperatures, while a non-relational stability image focusses on coping capacity of the pig and for instance results in inclusion of temperature shock resistance as a breeding goal; not to avoid, but to minimise the impact of temperature shocks and increase the overall recovering capacity instead. In our conceptualisation framework we assume that the meaning given to robustness and related robustness strategy in innovation processes ultimately depends on the depicted non-vulnerable post-innovation state of the system, rather than the other way around.

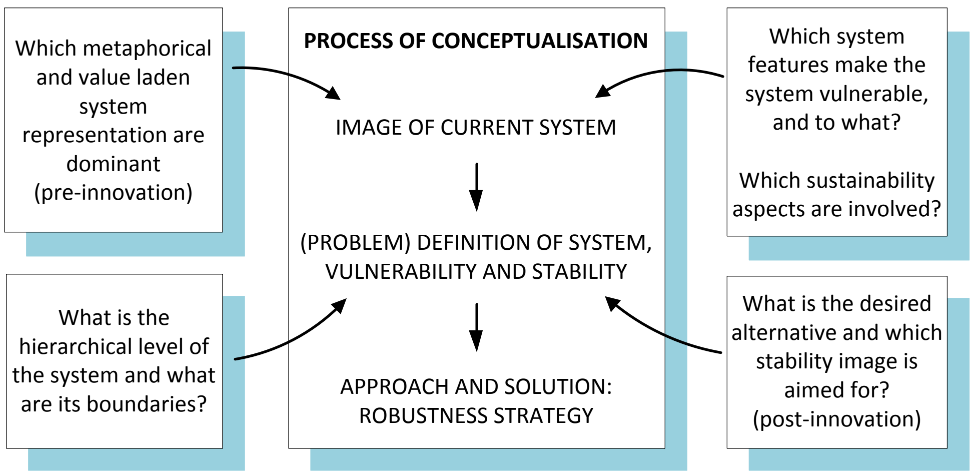


Figure 5. Schematic representation of the process of conceptualisation of robustness in three steps: *the construction of a pre-innovation image of the system; a problem definition, including specification of the hierarchical level of the system, its boundaries, its vulnerable system features, perturbations in relation to a desired stability image (post-innovation) and; the construction of a robustness strategy as a means to move towards the desired stability image in coping with recognised vulnerabilities.*

Analysis of results of the Houden van Hennen project

In the design process, robustness was related to the need of reducing vulnerability of both the animals and the system as a whole, aiming to enhance the system's adaptational range and allowing for internal perturbations and external influences within the adaptational range (Groot Koerkamp and Bos, 2008). In line with this the concept of naturalness was operationalised in terms of ethological needs of animals and used as a requirement to promote self-organisation at animal level. Although the articulation of robustness exceeded the robustness of the animal, the HvH project worked on robustness mainly from the leading perspective that the laying hen is vulnerable and has the ability to manage for herself. Rather than making use of technology or management interventions, HvH aimed to exploit the coping capacity of the laying hen to create a more robust system (Wageningen UR Projectteam Houden van Hennen, 2004c). One of the main challenges of the project was therefore to create the preconditions to gradually and partially leave the system functioning to the laying hens ability to cope for themselves.

Figure 6 shows the conceptualisation process with descriptions of system image, vulnerable features and sustainability aspects, hierarchical system level of the project and the aimed for stability image, as far as explicitly mentioned in the HvH project. A dominant image of the present that was central to the HvH project, and to innovations for sustainability in animal husbandry in general, is one of extreme vulnerability to non-anticipated perturbations. This image represents a far from idealised system where robustness and naturalness have been traded off against short term profitability and suggests that husbandry systems are hypersensitive and not able to adapt to even the smallest fluctuations, which creates sustainability problems in the social and economic sustainability aspect, i.e. health and welfare at animal level, and profitability at farm level are explicitly mentioned as vulnerabilities. The urge for robustness is thus positioned in existing concerns about social and economic sustainability. As a consequence robustness becomes a solution, or a means to achieve sustainability. With regard to this sustainability and desired stability of the system, the HvH project formulated specific challenges, such as "enhancing the adaptational range" and "allowing for internal and external influences within the adaptational range", directly linking system stability to resilience and adaptation: a line of reasoning obviously inspired by Complex Adaptive System approaches, that are successfully used to describe system dynamics at social-ecological or social-political levels. Its applicability to lower system levels is unclear. In the next paragraph we will analyse how the desired stability images were specified at the defined system levels and try to reformulate robustness strategies from the Programme of Demands (POD).

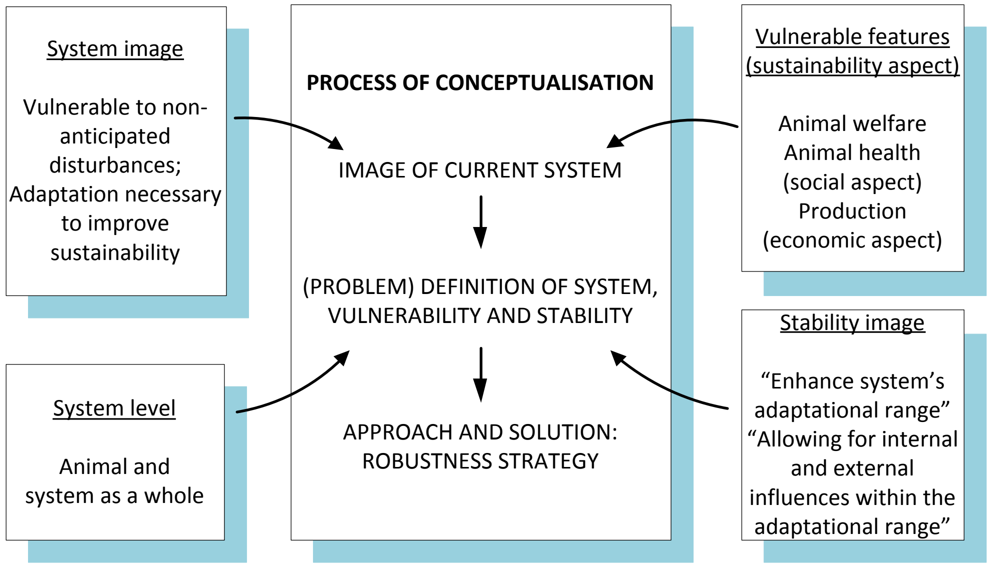


Figure 6. Robustness conceptualisation in the Houden van hennen project

Translating the programme of demands to 'robustness strategies'

The programme of demands (POD) lists 280 demands, to be taken into account in the design of a husbandry system for laying hens. The demands are based on needs of the poultry farmer (111), the laying hen (73), Citizen (31) and consumer (36). For three different types of citizens, namely cosmopolitans (9), Post-materialists (9) and Traditional citizenry (11) additional specific needs of the laying hen are listed. In our analysis of the programme of demands we distinguished between demands to optimise efficiency, demands to cope with perturbations, and other demands (table 2). For a comprehensive classification of demands of the Houden van Hennen Project, see appendix 3.

We have classified demands as 'optimising efficiency' when expressing a need to optimise or sustain processes from a production perspective. Consider demands to optimise temperature, light intensity and oxygen concentration, that are relevant from a production perspective or as a precondition to sustain necessary physiological processes. Although such demands may be in the interest of laying hens and citizens, optimisation is typically demanded by farmers (e.g. housing climate) and consumers (e.g. egg quality). We have classified 54 demands as relating to optimisation of efficiency of the system.

Demands were classified as 'coping with perturbations' demands when expressing a desired coping strategy against potential perturbations, for instance in relation to the resistance of the construction during calamities. In total 81 demands relate to coping with perturbations, expressing desired strategies of stakeholders to protect systems against the consequences of anticipated and unanticipated perturbations. We distinguished avoiding, resisting and recovering strategies. The majority (86%)

of the coping with perturbations demands (70) refers to perturbation-avoiding. Examples include avoiding feather pecking, stress, aberrant sleeping behaviour and exposure to germs of diseases at the animal level, preventing unsafe working conditions for the poultry farmer and employees, and avoiding the presence of residuals or contaminations in the final product.

Demands concerning resistance to perturbations (7) relate to the natural resistance of the laying hen (4), to the structural robustness of the housing system (2), or to the firmness of the final product (1).

Recovery as a strategy to cope with perturbations is hardly reflected as desired strategy in the programme of demands, even though resilience seemed one of the goals of the HvH Project. Still, citizens demands typically include freedom of the laying hen and possibility to self-organise her activities. Although not explicitly related to recovering from perturbations, these demands express the desire that laying hens make their own choices in finding solutions for perturbations they encounter. Consider a citizens demand that laying hens are offered places to seek shelter against rain. This requires a system that allows laying-hens to cope with rainfall in flexible ways, i.e. a choice whether or not to shelter and where to do so. It is this controlled self-organisation inside the system that adds new complexity to the system. The system needs to be designed and optimised to allow environmental influences, and provide the laying hen alternative options to cope with them. Roughly half of the demands (145) relates to other needs than optimising efficiency or coping with perturbations. Besides technical requirements and limiting conditions, these demands relate to operational management, marketing and aesthetics, to name a few. Examples include 'providing family with necessaries of life', 'natural elements in the husbandry system', and 'friendly appearance of the housing system'. Our interest here is particularly focussed on the demands related to coping with perturbations. We have therefore not further specified to which system features the 'other' demands relate.

Table 2. Classification of demands of laying hen, farmer, citizen and consumer. *The 280 demands of the programme of demands are classified as related to optimisation of efficiency (54), coping with perturbations (81) or other (145). Perturbation related demands are specified on desired robustness strategy. Table 2 shows that most perturbation related demands express a demand to avoid perturbations, rather than integrating coping strategies in the system design.*

Demands (Programme of Demands)		**Coping with perturbations**			
	Optimisation of efficiency	Avoid	Resist	Recover	Other
Laying Hen (73)	10	24	1	0	38
Farmer (111)	27	29	1	2	52
Citizen (31)	2	1	2	2	24
Consumer (36)	15	11	1	0	9
Specific needs according to:					
Cosmopolitans (9)	0	0	1	0	8
Post-Materialists (9)	0	2	0	0	7
Traditional citizenry (11)	0	3	1	0	7

Robustness preferences in the HvH Project

Almost 30% of the demands relates to coping with potential perturbations. A majority of 86% aims at perturbation-avoidance, rather than integrating coping strategies in the system design. In particular concerns about social attributes of sustainability, namely animal welfare and animal health, are related to prevention. Moreover 60% of the demands aiming at perturbation-avoidance is directed at the management, whether or not in combination with technical requirements. Less than 9% of perturbation-avoiding demands, and roughly 11% of all perturbation related demands is directed at the laying hen herself (table 3).

Table 3. Distribution of disturbance related demands over the social (management), technical and biological (animal) domains. *Demands can be directed at more than one domain. Table 3 shows that only 11% of the perturbation related demands is directed at the laying hen. Most demands require avoiding measures at management and/or technical domain.*

	Management	Technology	Animal
avoid (70)	43	38	6
resist (7)	4	3	3
recover (4)	4	0	0

These results suggest that, despite objectives of the project to reduce unidirectional control approaches, strategies to cope with perturbations are still predominantly found in the social-technical sphere and possibilities to use natural behaviour to increase coping capacities, are limited. Natural behaviour is frequently demanded, but as a welfare issue rather than as a solution to cope with potential perturbations. Interestingly, Bos et al. (2003) already outlined and discussed a novel design approach for livestock housing based on recursive control that considered the natural behaviour of animals as an integral part of the functioning of livestock systems. The Recursive Control Approach (RCA) was introduced as an alternative to the so-called ‘unidirectional control approach’, which suffered from spiralling complexity caused by robustness trade-offs, and structurally neglected the potential of animals to act as a participant and co-constructers of ‘their’ production systems. Two features that are essential to make recursive control possible, namely adaptive responses at animal level, and (genetic) variability of animals, are also mentioned in the POD in relation to the social sustainability aspect. Natural resistance is mentioned as a prerequisite for animal health and listed as an – operational management – demand. The POD does not express a need for adaptive management or make reference to the husbandry system as an adaptive system. Key features of adaptive systems, such as resilience, adaptation, or self-organisation are absent in the programme of demands. While conventional systems are being criticised for being vulnerable to perturbations, the programme of demands hardly formulates alternative strategies to cope with these perturbations and reduce system vulnerability.

The vulnerability-perception of the system is concentrated at the animal level.

Demands to limit exposure to germs of diseases, optimising living environment to influence physiological processes, shield from predators, and promoting natural resistance and adaptive capacity of animals specifically focus on the animal as vulnerable subsystem. Also at higher system levels, the demands seem to concentrate on perceived vulnerabilities of the animal sub system, rather than on the vulnerability of the sector or the farm against social or ecological perturbations. Remarkably, the programme of demands does not contain any demands in relation to the social-ecological system. Table 4 lists perturbations, robustness strategies and related sustainability attributes for system features explicitly mentioned in the programme of demands at different system levels. Table 4 illustrates that demands are primarily related to lower system levels, the animal level in particular. Higher systems level, such as the social-ecological level are absent in the programme of demands.

Table 4 Vulnerable system features, relevant perturbations and robustness strategies mentioned in the programme of demands at different system levels and their related sustainability aspects. *Features marked with an * were explicitly mentioned as robustness goals of the project HvH.*

System level	Vulnerable features	Perturbation	Robustness strategies	Sustainability aspects
Hen	Animal health* (precondition for production)	Pathogens	Avoid: limit exposure to germs of diseases; optimise living environment to influence physiological processes. Resist: promote natural resistance Recover: exploit adaptive capacity of animal in system design	Economic Social
	Animal welfare*	Predators	Avoid: shield animals from predators;	
	Productivity*	Climate	Resist: stimulate natural resistance	
Pair	Animal welfare*		Avoid: prevent reasons to develop unnatural behaviour	
Housing System	Ability to maintain structure	Calamities	Resist: don't collapse	Social
Housing system (Vulnerability related to, and considered at animal level.)	Ability to provide the preconditions to allow laying hens their natural behaviour; Social acceptance; Image	Changing societal demands / laws and regulations relating to required preconditions (welfare, hygiene)	Adaptation to societal demands. The housing system is designed to create the preconditions to gradually and partially leave the system functioning to the laying hens ability to cope for themselves.	Social Economic
Sector	Image	Licence to produce	Adaptation / social robustness: include societal demands in system design; increase public support	Social

Discussion

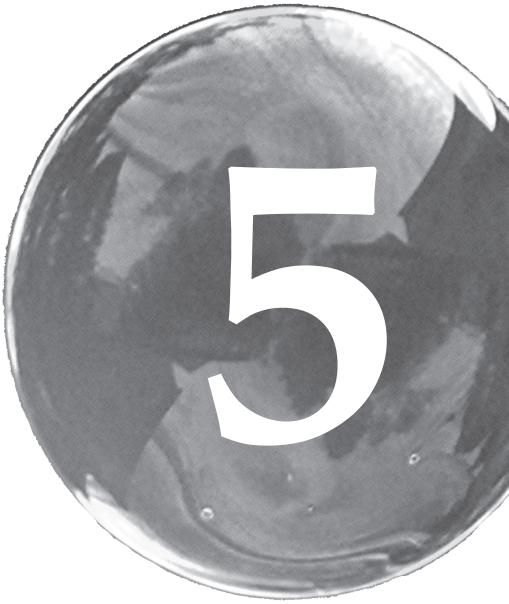
It is often argued that the frequency and impact of recent shocks and perturbations in LPS were decisive factors in the urge for transition and structural reform of LPS. The intended outcome of reflexive design is a course of action on the way modernisation should proceed (Grin and Van de Graaf, 1996). The POD may not yet describe the best way forward, but at least gives direction to this course of action. We expected that the stakeholders involved in the reflexive design approach would opt for a radically different way of coping with anticipated perturbations, based on adaptation and resilience, rather than avoidance and elimination. The results of our analysis of the POD do however not confirm these expectations. For the different groups of actors, the percentage of demands directly related to potential perturbations varied from 21% for citizens to 34% for the laying hen, but of these demands a relatively large percentage (86%) was directed at avoiding, rather than creating resistance or resilience. Particularly because the POD was developed with maximum input from actors within and outside the dominant social-technical regime, this suggests that the need for a radically different course of action, at least with regard to robustness strategies against anticipated perturbations, is smaller than one would have you believe. The POD does not press designers to shift attention towards long-term adaptability rather than short-term efficiency. The POD does contain precautionary measures to limit surprises, but gives no direction to the course of action needed to cope with unavoidable fluctuations and extreme events. In addition, the POD does not incite designers to reduce connectedness. Rigid connectedness is commonly believed to reduce resilience of the system and increase vulnerability to unexpected events. This is precisely why resilience studies of social-ecological systems typically stress the relevance of flexibility and self-organised connectedness at multiple system levels (Gunderson and Holling, 2002) and enhancing adaptive capacity is increasingly seen as a necessary step to achieve sustainable farming systems (Darnhofer et al., 2010a; Darnhofer et al., 2010b).

We have argued that complex systems, designed to produce efficiently are at risk of getting involved in a complexity/robustness spiral that could lead to robust, yet fragile systems. In the complexity spiral, agricultural subsystems, including animals and plants, are gradually instrumentalised and subjected to technical rationalisation. Increasingly, the environment of these rationalised systems becomes antagonised, as the systems becomes more and more vulnerable to environmental fluctuations. Managing these requires a robustness strategy aimed at avoidance. The attractiveness of complex adaptive system approaches is the suggestion that rather than antagonising and attempting to control the environment of the system, it is beneficial to integrate the capacity of a system to adapt to its environment in the system design. Note however that such planned adaptation in technical systems is essentially different than the associate adaptive capacity of social-ecological systems. When integrated in a system design adaptive capacity becomes planned, and purposefully placed under care of the farmer.

Consider also the difference between biodiversity, contributing to system resilience independent of farmers planning, and planned diversity such as variety of crops and animals that has become part of the operational management of the system. When functional optimisation goes at the cost of the foundations of associate robustness, their restoration is only possible when integrated as design criteria and management points of interest. Designers can not comply with the desire to return to old breeds, with natural resistance that roamed freely on small, surveyable farmyards, or to a situation where food safety was not yet an issue. Loss of genetic variation, new rules and regulations, as well as recent outbreaks of avian influenza are just a few reasons why a simple return to otherwise less efficient and more labour intensive systems is unrealistic. The associate robustness of earlier times can however be mimicked in the design of new systems. Recently, Ten Napel et al (2011) for instance suggested to integrate the three foundations of ecological resilience, namely diversity, redundancy and modularity (Webb and Levin, 2005) as sources of robustness in new design processes. The difference is that contrary to associate robustness features, sources of designed robustness have relevance only in relation to the efficiency of the system and obtain their value as a rational choice (Vandermeer, 2011). Mimicking sources of associate robustness in new designs should therefore be considered as a next step in complexity/robustness spirals.

Conclusion

Does RIO break through spiralling complexity? We argued that RIO was adopted in a design process to create sustainable, robust agricultural systems that was initiated in a time where trust and believe in further optimisation and higher efficiency was at rock bottom and the need for radical change was positioned in a complex adaptive system approach of LPS. Although the HvH project took into account specific changing social demands in the design process through which societal demands are included in the measurement of system efficiency, the POD ultimately resembles a demand to highly optimise the housing system for laying hens. Rather than to a radical shift in egg production that we anticipated, the POD justifies incremental, but important changes that nevertheless hardly challenge the existing regime. It shows that by means of natural behaviour, that is eventually completely human controlled, animal health and animal welfare must be shaped and designed according to stakeholders expectations. At the same time, the POD reveals that this definition of natural behaviour is highly selective. An undoubtedly unnaturally high system output of 300 egg per chicken per year is for instance taken for granted, illustrating the perverseness of claiming that the natural behaviour of animals could be objective points of departure in the design of animal husbandry systems. With regard to strategies to cope with anticipated and non-anticipated perturbations the HvH project suggested that laying hen husbandry systems should designed to protect the laying hen against anticipated perturbations. Whether reflexively designed systems, such as the Roundel, are flexible and diverse enough to adapt to the dynamic context in which they need to be managed and able to withstand further complexity/robustness spiralling to suppress yet unborn fragilities cannot be judged at this moment. In the trial period of the system design, the chosen design approach appeared highly adaptive, as dynamic societal demands could relatively easily be integrated in the system design. By explicitly including heterogeneous sets of values in early stages of the design process one has contributed to the social acceptance of the Roundel system. Even though the final design may not significantly differ from systems previously criticised for lacking robustness, and put extra challenges on the poultry farm, the integration of diverse societal demands has made the Roundel almost resistant to criticism.



Reducing damaging behaviour in robust livestock systems

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Abstract

This chapter focuses on how farmers can reduce damaging behaviour in livestock systems by using robustness strategies. We suggest to focus not only on breeding and improvement of early life, but also on supporting adaptation to the environment by offering a suitable housing environment. First, we describe the theoretical background to robustness. Three different robustness strategies are then related to one external and two internal aspects of system vulnerability, namely, exposure, resistance and resilience. Subsequently, we investigate the extent to which robustness can contribute to the reduction of damaging behaviour.

Introduction

One of the ways that the livestock sector gets its 'license to produce' from society is by ensuring optimal animal welfare (Wijffels et al., 2001). In today's livestock farming, animals are dependent on their caregivers for shelter, security, food, drink, health and welfare. It is not just about the survival of the animals, but above all about the quality of their lives. In 1965, Brambell expressed this in terms of five freedoms for animals: freedom from thirst, hunger and malnutrition; freedom from physical and thermal discomfort; freedom from pain, injury and disease; freedom from fear and distress; and freedom to engage in their natural (species specific) behaviour (Brambell, 1965). In freedoms 1–4 the focus is on the absence of negative symptoms of welfare, while in the fifth freedom the focus is on positive welfare (Bracke and Hopster, 2006), for example, rooting in pigs, grazing in cattle, and scratching and dust-bathing in poultry (Wijffels et al., 2001). These principles are still central in animal welfare science today. Thus, the vulnerability of animals and their dependence on human caretakers have become important issues in livestock farming.

In the past decades European and North American farms have become more 'industrial' in character (Short, 2000). Following this trend, Dutch livestock farmers have kept more and more animals in increasingly intensive systems, driven by economic incentives. As a consequence, more negative social interactions can occur between animals that have an enormous impact on animal welfare (Star et al., 2008). In chickens and pigs, behavioural problems like cannibalism and tail-biting occur, which can spread through the group like an epidemic. Beak trimming in laying hens and tail docking in pigs are still widely used to manage these problems. Such interventions offer no lasting solution and will eventually be prohibited in the European Union. Because of the trend to create larger groups and the desire to ban beak trimming (Wageningen UR Projectteam Houden van Hennen, 2004a) and tail docking, the risks of damaging behaviour will greatly increase.

As a reaction to these developments, it is not only societal organisations such as Wakker Dier and the Dutch Society for the Protection of Animals that have developed campaigns about the treatment of individual animals in intensive farming in general, and in favour of the reduction of damaging behaviour in particular (Bracke, 2010). Farmers' organisations also are willing to take measures to improve the welfare of their animals and, in cooperation with knowledge institutes, are looking for an alternative approach, focusing on robustness, that will yield the best possible welfare (Goessens, 2013). Robustness refers to the relative vulnerability of a system/animal in relation to a specific disturbance. New housing systems, such as the Roundel system for laying hens, are being designed in such a manner that they enable animals to co-organise their own welfare, for example by offering hiding places and choice in climate (Groot Koerkamp and Bos, 2008). Through breeding and rearing practices animals can be bred that are more resistant to environmental fluctuations or that are able to recover easily from relatively small disturbances. Does the challenge to reduce damaging behaviour and to improve animal welfare require livestock farmers to switch to robustness strategies?

This chapter focuses on the question of whether robust livestock farming systems can be developed that may reduce damaging behaviour. First, we briefly describe the theoretical background to robustness. Three different robustness strategies are then related to one external and two internal aspects of system vulnerability, namely, exposure, resistance and resilience. Secondly, we investigate the extent to which these robustness strategies can contribute to the reduction of damaging behaviour. We argue that solutions to these unwanted side-effects have to be found by considering them primarily as features of the animal under consideration, rather than as relational properties of the animal and the physical- and social environment together.

Robust animal production

What is robustness and what does it have to offer? In several fields of expertise, including biology (Kitano, 2004, 2007; Wagner, 2005), technology and system engineering (Clausing and Frey, 2005; Frey et al., 2007; Taguchi et al., 1999) and production economics (Vlajic et al., 2012) robustness plays a role. However, the term is loosely used in various contexts, making it difficult to give an unambiguous meaning (De Goede et al., 2013a). For example, robustness may refer to functional reliability in the case of known and predictable distortions (Clausing, 2004) or the capacity to cope with the unexpected (Doyle et al., 2005; McManus and Hastings, 2006). Robustness has been related to the range of circumstances in which a particular system structure can maintain itself, as well as to the capacities of a system to maintain a particular functional efficiency within specified conditions. Particularly in the automotive and electronics industries, major successes with 'robust designing' have been achieved, aiming at a state where technology, product and process are minimally sensitive to variation caused by faults (Taguchi et al., 1999).

Robustness is not new to agricultural development. In the 1940s, robust crops were developed with the aim of achieving uniform growth to maximise production under varying weather and soil conditions (Robinson et al., 2004). Nowadays, robustness is rather related to genetic diversity, and in livestock farming to animal health and welfare. These are, next to food safety, the main features of the social sustainability aspect (Van Calker et al., 2005). Robustness is increasingly seen as a solution to a variety of (sustainability) issues, such as production under suboptimal conditions (Sall et al., 1998), maintaining production potential in varying conditions (Knap, 2005), strategic decision making in uncertain times (Cittadini et al., 2008) and the ability to recover after growth retardation or other disturbance (Lien et al., 2007a). A scientific focus on robustness would furthermore allow us to breed animals that fit in a range of housing systems, in order to improve animal health and welfare, without compromising animal integrity (Star et al., 2008). Ten Napel, Bianchi and Bestman (Ten Napel et al., 2006) claim that vulnerability to adverse environmental change has proved to be a drawback of technology-driven intensive production. They have suggested that livestock farming systems have to become more 'robust', whereby we need to understand robustness as the ability of a system to return to its original position after a disturbance. In this way robustness refers to the relative vulnerability of a system or animal in relation to a disturbance. In this chapter we follow the suggestion that robustness is a flip side of vulnerability. We relate robustness to the relative vulnerability of a system in relation to a disturbance. We distinguish three aspects of vulnerability: the exposure of a system to perturbations; the resistance of a system to a disturbance; and the resilience of a system to recover after a disturbance. In the case of the exposure of a system to perturbations, the vulnerability of a system is measured as the relationship between a system and its environment. Resistance and resilience are system properties that belong to a system regardless of the environment in which it is located. Exposure is therefore seen as a relational characteristic, or the 'external side' of vulnerability. To treat vulnerability, it is important to understand whether it is experienced as a relational characteristic or as a system feature. We will use the same distinction to distinguish strategies aimed at enhancing relational characteristics and strategies aimed at enhancing system features.

Table 5. Robustness states between extremes of vulnerability and ideal images of invulnerability

Extremly vulnerable	*Robustness state*	*Ideal of invulnerability*	*Strategy*
S is never exempt from exposure to D (relational)	S is exempt from exposure to D in specially designed and controlled environments	S is always exempt from exposure to D (relational)	Avoid
S never has enough resistance to resist any exposure to D without damage	S has sufficient resistance to exposure to D within a 'normal range' to withstand without loss of structure and / or functionality	S always has enough resistance to resist unlimited exposure to D without damage	Resist
S has never been sufficiently resilient to recover from the damage caused by exposure to D	S can restore within the 'normal bandwidth' inflicted temporarily loss of structure and / or functionality by exposure to D	S always has sufficient resilience to recover from the damage caused by exposure to D	Recover

In Table 5 (column 1) three extremes are shown, in which system (S) in relation to disturbance (D) may occur. The opposites of these extremes of vulnerability are ideal images of invulnerability (column 3).

We understand robustness strategies as management strategies designed to strengthen a specific robustness state, a state of relative invulnerability of a system in relation to exposure to a disturbance. In Table 1, these strategies are referred to as: avoid, resist and recover, where avoid relates to relational characteristics of the system, while resist and recover relate to coping capacities of the system regardless of their environment. These robustness strategies are visible in numerous and very different systems. Think of the efforts to control and eradicate the prevalence of bovine tuberculosis in cattle herds, that ultimately appears to lead to increased preventive

control measure in the systems environment, e.g. badger removal (Donnelly et al., 2003; Griffin et al., 2005). This is an example of an avoidance strategy, where the focus is on the relational characteristics of the system and the robustness of the preventive control system. An example of a resistance strategy is the attempt to increase the vertical structural robustness of buildings against for instance earthquakes, where the focus is on achieving a desired coping capacity of the system even when the disturbance never occurs. Following the Dutch Occupational Health and Safety Act (ARBO), animal housing systems should be designed with a structural robustness of at least 30 minutes (see for example Wageningen UR Projectteam Houden van Hennen, 2004a) As an example of a recover strategy, consider the determination of fishing quotas on the basis of demonstrated resilience of fish populations. To sum up: a description of system robustness includes at least a specification of the system (animal, housing system, fish stock), the disturbance against which robustness is achieved (bovine tbc, natural disasters, predation) and a strategy, by which robustness is achieved (avoid, resist and recover).
Robustness in livestock farming is often limited to physiological, behavioural and immunological qualities (Conington et al.; Knap, 2005; Mormède et al., 2011; Rodenburg and Turner, 2012; Star et al., 2008). In this case, robustness is associated with individual animals that are able to cope with disturbances and to reduce the negative effects of continued selection for production. From policy documents, in which robustness is defined as a goal, a clear relationship with animal welfare and animal health can be discerned (LNV, 2007a, b; Van der Weijden and Schrijver, 2004). What we call robustness is therefore primarily conceptualised at the individual animal level, where it refers to the inherent capacity of self-regulation in environments, and to the capacity to adapt to changing management and fluctuations in hygienic conditions (Kanis et al., 2005; Kanis et al., 2004; Klopčič et al., 2009; LNV, 2007a). In livestock farming, robustness is thus primarily conceived as a property of the individual animal, rather than as a relational property of the animal and its physical and social environment. The latter would require control of the physical and social environment in which the animals are kept. Robustness strategies rather focus on strengthening the capacity of the individual animal to deal with disturbances.

Robustness strategies to reduce damaging behaviour

In recent years, the damaging behaviour of production animals has been one of the major concerns in animal welfare debates (Star et al., 2008). Pigs biting one another's tails and chickens pecking one another's feathers are the best known examples of animal welfare issues that have emerged in these debate. These issues can be considered as characteristics of the current production system or as features of the animal subsystem, leading to different robustness approaches. From the perspective of robustness, different management measures are conceivable to reduce damaging behaviour. For example, the trimming of beaks in chickens and tail docking in pigs is an attempt to control the relational characteristics of the animal and its housing system together, a robustness strategy aimed at avoiding exposure rather than strengthening a capacity to cope. However, these measures are seen in both the public and the scientific debate as inhumane(Gentle, 2011; Sutherland and Tucker, 2011). Moreover, the potential benefits of banning – other than enhanced animal welfare – of these measures, for example with respect to labour conditions and attractiveness of employment in animal production, are as yet underexposed. We conclude that controlling the relational characteristics of the animal and the physical and social environment together is a problematic robustness conception to reduce damaging behaviour in livestock systems. Are robustness strategies based on the robustness conception of the individual animal a better alternative? We discuss three examples of alternative robustness strategies to reduce damaging behaviour: early-life conditions, rearing conditions and breeding.

Early-life conditions play an important role in the behavioural development of many farm animals. Influences have already begun before the animal is born or hatches from the egg. In pigs, a stressful treatment of sows during gestation leads to changes in behaviour, physiology and pain sensitivity among their piglets (Jarvis et al., 2006). Similar results were found in chickens: when stressed, hens change the hormone composition of their eggs and chicks become more fearful, less competitive and smaller (Janczak et al., 2007). Reducing stress in the parents can thus positively influence the behaviour of the offspring. The environment in which animals grow up also plays a crucial role in the development of behaviour [32].

In current livestock farming, we barely take the influence of rearing conditions on the development of damaging behaviour into account and focus on 'trouble-shooting' later in the production cycle, for instance by dimming the light in case of problems with feather pecking during the laying period (Drake et al., 2010; Mohammed et al., 2010; Shinmura et al., 2006). Chicks are reared without a mother and usually also with a limited amount of, or even without, litter, while we know that both factors enhance the risk of feather pecking. Farrowing pens for pigs are usually too small for optimal development of social behaviour and for the opportunity to forage together with the mother (Lammers and Schouten, 1985). Piglets of a sow that is loose-housed during lactation, instead of being confined in a farrowing crate, exhibit less damaging behaviour after weaning and show more play behaviour (Oostindjer et al., 2011a). Furthermore, more freedom of movement for the sow has a positive effect on the development of the piglets' foraging behaviour (Oostindjer et al., 2011b). To avoid problems caused by damaging behaviour, we must keep the animals in an environment that meets their needs, both during early and later life. This also applies to parents and grandparents, because stress in these animals influences the behavioural development of their offspring (Goerlich et al., 2012).

The incidence of damaging behaviour is not determined by the rearing conditions only, but is also partly heritable. Breeding for high productivity has, however, also contributed to the emergence of health and welfare problems in farm animals, including tail biting (Breuer et al., 2005; Rauw et al., 1998). Results in the past have been achieved mainly by genetic selection on the performance of individual animals, whereas it is now becoming increasingly clear that the production, health and welfare of pigs and chickens are strongly influenced by interactions with other animals in their group. Selection on individual performance (as related to production properties) is therefore unsuitable to solve problems caused by interactions between animals, and can even lead to an increase in competition and damaging behaviour. This has become evident from a selection experiment aimed at increasing body weight in quail. Two methods were compared in this experiment: one focusing on individual growth and one focusing on group growth. After 25 generations of selection, it was found that the method focusing on group growth was indeed successful in meeting the aim of increased growth. However, in the individually selected birds selection for increased growth resulted in an average weight loss and a sharp increase in mortality from aggression and cannibalism (24% mortality compared to 6% in the starting population) (Muir, 2005). This extreme example illustrates that classical breeding in animals living in groups is not necessarily optimal for the whole group, and may even lead to deterioration of the productivity and welfare of the group. Does this mean that we should use breeding directly aimed at behavioural properties to reduce damaging behaviour? In practice this is difficult, because it requires extensive measurements of behaviour, which are time consuming and costly. Breeding directly aimed at behavioural properties is therefore rare in practice. New breeding methods have been developed that take the effects that animals have on one another into account. These methods enable the mapping of social genetic effects, that is to say, the genetic influence of animals on the properties of other animals in their group (Muir, 2005). Taking into account these social genetic effects in breeding may lead to the selection of different animals, that are not necessarily the fastest growing or highest producing individuals, but that have a positive effect on the performance of the group as a whole. This is a major advance, because these methods do not require the registration of animal behaviour on a large scale. So, as opposed to breeding focused on behaviour, this method is applied in practice with a realistic deployment of resources. The first results suggest that these social effects can be substantial. For example, fattening pigs appear to have a heritable effect on the growth and feed intake of their pen mates (Bergsma et al., 2008). Similar effects have been found for mortality from cannibalism in laying hens, where the heritability for survival during the laying period rises by more than 50% because of these social genetic effects (Ellen et al., 2008). These results clearly show that social genetic effects are important in breeding programs. Recently, a selection experiment started with laying hens that were not beak trimmed, aimed at reducing mortality by feather pecking and cannibalism, and using the social genetic effects on survival of pen mates. This selection method immediately yielded a significant improvement in survival during the laying period, from 70 to 80% in the first generation, and also caused behavioural and physiological changes. In the second and third generations, the effect on survival was less clear, possibly due to low selection intensity. This is currently being investigated further. In the second generation it was revealed that the hens from the selection line were less fearful and sensitive to stress than hens from the control line and also showed less cannibalism (Bolhuis et al., 2009). In addition, changes were found in the serotonergic system (Bolhuis et al., 2009), which plays an important role in dealing with fear and stress, and with pecking motivation. These results show that selection that takes social genetic effects into account is a useful method to reduce undesirable behaviours within groups and to reduce mortality in group-housed animals (Rodenburg et al., 2010).

Conclusion

The breeding of more social animals provides new opportunities for simultaneous improvement of the productivity and the welfare of group-housed animals. It also assumes that breeding criteria should be adjusted, but the solutions to these trade-offs are not unequivocal. This applies in particular to the question of whether breeding criteria ought to be sought in adjustment to specific circumstances (specialisation), or just the ability to adapt to changing circumstances (a more general approach). Kanis et al. (Kanis et al., 2004) argue that animal welfare is related to the maintenance requirement in a specific environment and conclude on that basis that animal welfare should be improved by selection for low maintenance needs. On moral grounds, Star et al. (Star et al., 2008) have recently advocated implementing robustness as a breeding goal for both animal health and animal welfare reasons. Both of these reasons are linked to the ability of animals to function optimally in a range of production systems and the changing conditions within these systems. However, the ability to adapt to changing conditions is not only genetically determined. For instance, early-life experiences can also increase an animal's capacity to adapt in later in life and make a positive contribution to the strengthening of robustness (Walstra et al., 2010). The adaptability of animals is also partly determined by the organisation of the environment in which they are reared and therefore can be supported by optimising the social and physical environment of the farming system. In practice, this means, for example, the provision of materials for nest building/ insulation and creating cooling options.

The robustness approach aimed at the animal level does not use the avoidance strategy, but tries to bring about changes and challenges in a social environment. Thus, in the coming years, the social breeding strategy in pigs will be further developed by research on the behaviour, welfare and productivity of pigs that differ in their social genetic effects on the growth of pen mates. The behaviour of these pigs will be studied in both standard and enriched housing. We expect this selection method in pigs to improve – in addition to growth at group level – the social functioning and welfare of the group.

6

General discussion

One of the main goals of this thesis was to describe the relevance of robustness for agricultural systems. This has particularly been a challenge because both 'agricultural system' and the concept of robustness have been given diverse meanings. When I started with this PhD research, it was generally being suggested that more attention for robustness could be beneficial for the development of agricultural systems, especially in relation to their sustainability. Although neither successful engineering approaches of robust design and robust engineering, nor the concept of biological robustness or ecological approaches stressing the importance of resilience and adaptation had escaped the notice of life-scientist at Wageningen University, the applicability of these approaches in agribusinesses and their potential contribution to sustainable agriculture had not yet been researched. The general assumption that robustness and its diverse approaches in different fields of science had potential relevance vis-à-vis sustainable agriculture, has shaped the structure of this thesis to three main research questions:

1. What is robustness and how is it approached in different fields of science? How do these approaches relate to sustainability?
2. Which conceptualisation(s) are being worked out in agriculture? Which conceptualisation(s) are dominant and which have potential?
3. What is the relevance of robust agriculture vis-à-vis sustainable agriculture?

In this chapter I return to these three questions. I shall first describe the main approaches to robustness and ideas that underlie robustness conceptualisations in different fields of science. I will discuss strengths and weaknesses of these approaches in relation to their application in agriculture and sustainability. Then, I shall relate the robustness conceptualisations that were found in the Transforum projects aimed at robust and sustainable agricultural production systems to robustness approaches found in other fields of science. I shall finish my discussion with an evaluation of the relevance of robustness and robust agriculture in relation to sustainability and sustainable agriculture.

Robustness approaches in different fields of science and their relation to sustainability

Robustness is a contested concept and this is only underlined by the diversity of definitions that I encountered during this research (see appendix 1). The question what robustness is, cannot be separated from the scientific tradition within which the question is asked and ones approach to the system. The robustness strategies that I described in this thesis are derived from engineering, biology and ecology. I do not suggest that these approaches are unique for engineers, biologists, or ecologists or have relevance only in relation to the technical, biological, or ecological subsystems of agricultural systems. Rather, they represent different ideas and assumptions that underlie specific conceptualisations of robustness that can nevertheless be found in various contexts. In this section I shortly describe the different approaches and how they achieve robustness. The conceptual impetus to the following description of these approaches was given in chapter 2 and partly builds on robustness conceptualisations that were presented in chapter 3.

Engineering approaches – optimise and maintain efficiency of function

I have argued that engineering approaches typically relate robustness to functional reliability of – independent – system components in the presence of *predictable* chances of failure. Engineering approaches start from the idea that robustness can be designed, and are therefore particularly relevant for technological systems. Common strategies to improve engineered robustness of independent system components include designed overcapacity (margins), redundancy and the selection of less vulnerable technologies or system components.

In agriculture, the engineering approach to robustness provides an attractive and powerful strategy to cope with potential threads, but also a robustness strategy with side-notes. Firstly because the strategy is clearly biased towards known and expected disturbances. One cannot design protection against unknown or not expected disturbances. As the internet shows, sooner or later previously unknown or unexpected events can bring to light weaknesses of originally robust structures (see for example Forrest et al., 2005). Willinger and Doyle (2005) describe how the typical engineering approach to dealing with internal and external changes, i.e. responding to demands for improved performance or more robustness with increasingly complex designs, has a tendency to create further and more disastrous sensitivities. Especially when original structures are maintained and improved, a likely consequence of this approach is a complexity / robustness spiral that results in states of high tolerance, and extreme fragility to the unknown or in relation to system aspects that were previously not given any priority. In the agricultural context, such fragilities appear to emerge mainly in the social sphere, for instance when additional complexities to create robustness are socially contested. Consider the commotions caused by the development of genetically modified disease resistant crops to cope with restrictions in fungicide use.

Secondly, the engineering approach requires a clear distinction between the system and its environment. A reductionist definition of system boundaries is inherent to engineering, but it is precisely the emphasis on a system in need of protection against environmental dynamics that threaten optimal system functioning that leads to a focus on *avoiding*, rather than coping with, environmental fluctuations. In this thesis I have argued that a robustness strategy that is based on avoiding exposure to expected disturbances eventually antagonises the system's environment. As a consequence, engineering approaches tend to expand measures of control not only within system boundaries, but generally also including system environments. Thus, engineering approaches tend to consider robustness as a relational property of system and its environment together, and, rather than seeking strategies to cope with disturbances, link it to a strategy of avoiding failures. A very strong argument in favour of this strategy is its potential to increase system efficiency. Indeed, protection against common disturbances removes barriers to optimisation and specialisation of subsystems. In other words, systems that function in stable environments can afford to trade-off adaptive capacity against productivity. In horticulture for instance, greenhouses provide shelter and controllable production environments in which robustness at plant level can be traded off against functional efficiency. In an hierarchical system (e.g. plant, crop, greenhouse) this implies that associate robustness that is present in plant and crop can be concentrated in the outer layer of the system, i.e. the greenhouse, more specifically as a control mechanism. If successful, the outer layer protects all lower system levels against the most common, known and expected disturbances, with that undo the advantages of system redundancy on which the associate robustness of the lesser controlled system was based. Thus, successfully avoiding exposure to known and expected disturbances creates room to remove redundant coping strategies at lower system levels and set free the energy spend on it, in favour of extra growth efficiency. The theoretical endpoint of this strategy is a situation in which all inherent resistance, resilience and adaptive capacity is surplus to requirements. Many developments in agriculture have contributed to this approach, most notably the introduction of antibiotics.

From a sustainability perspective, the engineering approach has value especially in the economic domain. It is an anthropocentric, and clearly result oriented approach that has relevance only when robustness criteria can be quantified. The incorporation of qualitative value judgements is much harder in robust engineering approaches. In agricultural contexts, as well as in other partly, but not completely, engineered systems, the engineering approach may be criticised for its attempt to standardise a system that is subject to dynamic and largely unpredictable changes.

Biological approaches – increase fitness and resistance

Biological approaches to robustness refer to an inherent resistance or low sensitivity to perturbations at system level, that is generally considered as a result of adaptation or natural selection. Being resistant to perturbations is closely related to the adaptedness to specific environment, or an organisms fitness. It is therefore not surprising that robustness, understood as resistance against the most common fluctuations, is omnipresent among living systems. Indeed, evolution selects on traits that enhance robustness against such perturbations.

Adaptation to prevailing circumstances can occur at different levels with different causes (see e.g. Gould and Lewontin 1979), that can be worked out in specific robustness strategies at farm level:

Non-heritable plasticity that determines how organisms develop during ontogeny. In livestock production farming, it has been suggested that early life experiences, including rearing conditions during gestation or hatch periods are important factors in the development of behavioural qualities, such as stress, fear, and aggression. In chapter 5 I described that robustness strategies taking early life conditions into account can help to reduce damaging behaviour (de Goede et al., 2013b).

Heritable non-Darwinian adaptation imposed by learning. Taking the influence of rearing conditions on the development of social behaviour into account is relative new, but it has already been shown that the development of social behaviour of chicks and piglets is enhanced when rearing conditions allow gathering and opportunity to forage together. This is not a genetic adaptation, but rather unintentional and unconscious transmission of traumatic experience, the relevance of which has long been underestimated. Because the possibility of transgenerational trauma transmission increases when rearing conditions obstruct non-Darwinian adaptation by learning, I suggest that robustness strategies for livestock production systems should include facilitation of adaptation through learning. A practical example is

weaning at higher ages in pig production units to increase the social learning of pigs. Darwinian adaptation based on genetic variation. Most calls to integrate robustness as a breeding goal refer to adaptive capacities based on genetic variation. Genotypic selection on performance characteristics can be used to improve relevant robustness traits, such as disease resistance, tolerance to temperature shocks, but also behavioural characteristics. Several trade-offs between productivity and robustness have been related to genetic variation. Consider positive correlations between milk production and sensitivity to mastitis, pigs growth rates and aggressive behaviour. Fragility and performance setback are common trade-offs in robust living systems and robustness against specific perturbations is usually accompanied by fragility elsewhere (Chabot, 1977, Gross, 1982) (Kitano, 2004, 2007). Trade-offs between robustness and resource use have also been described.
The biological approach, more than the engineering approach, follows environmental fluctuations and considers robustness against them a system feature, rather than a relational feature of system and environment together. From a sustainability perspective, the biological approach to robustness is especially relevant in the social domain. That is because biological robustness refers to a system's wellbeing, or adaptedness, to its environment. Indeed, biological robustness is eventually measured by the extent within which a system is comfortable in its environment. Because of this, the biological robustness approach is accessible to ideological considerations, such as breeding back social traits to improve animal welfare. Biological robustness can therefore not just be measured quantitatively, but is rather based on value judgements.

Ecology approaches – recovery and structural persistence

In ecology, robustness has been related to and equated with aspects of resilience (De Goede et al., 2012b). Although both the elasticity and amplitude conceptualisation of robustness were developed in the domain of ecology, from a sustainability perspective they have relevance in the other domains as well. Especially the amplitude conceptualisation has been applied in sustainability studies of diverse social-ecological and social-economic systems. In relation to agriculture, the amplitude conceptualisation is particularly relevant to study the dynamics of complex adaptive systems in which agricultural practices, just as other land uses, are considered as modifiers of structure or even disturbing interventions, rather than as a vulnerable. In line with this, the amplitude conceptualisation is found in studies of so called regime shifts, that can radically change ecosystem services, including biodiversity, soil quality, water cycling and other services that provide us the possibility to produce food. Understanding how structural persistence is achieved is particularly relevant because it helps to develop mechanisms to stop the progressive loss of resilience that is considered a main cause of ecosystem degradation and collapses (Anderies et al., 2006; Folke, 2006). Because of this, the amplitude conceptualisation of robustness thinking is deep rooted in the principles of organic agriculture. Organic farmers take the structure of the ecosystem as a starting point, its preservation as a leitmotif, and are willing to make concessions to their operational efficiency to sustain ecological structures. Still, ecosystem resilience, the amplitude conceptualisation of robustness can hardly be measured or used in a quantitative manner. Its application outside ecology, especially in relation to engineered systems is debated. Main drivers behind this approach are protection and structural conservation, which clearly distinguishes the approach from the engineering approaches that are driven by development, modernisation and innovation instead. Nevertheless, (Ten Napel et al., 2011) have suggested to utilise determinants of ecological resilience to design industrial livestock production systems for robustness, namely genetic diversity of livestock, modular design of housing systems, and designed overcapacity of production lines. For engineered systems, the elasticity conceptualisation of robustness holds a greater attraction because it is easier related to functional optimisation. The disturbances it refers to are relatively small and can be overcome through either resistance or capacity to regain the balance. In its narrowest and most quantifiable form, i.e. a system's speed of return to the original position after well-known events with by and large repeated patterns, engineering resilience is implemented as a selection criterion in animal or crop breeding programmes, see for examples Klopčič et al. (2009). As a functional derivative of the structural system state, the elasticity conceptualisation is relevant to monitor and evaluate a systems ability to return to sustainable values. This ecology approach aims to clarify which system features contribute to a system's capacity to resist and recover from functional deviations in the neighbourhood of optimised steady states. Main drivers behind this approach are system improvements to reduce the impact of exposure to environmental variations and disturbances, and increase the capacity to recover from the damage caused by exposure to disturbances. Concentrating on the internal side of vulnerability, this robustness approach gives priority to creating sufficient resilience to restore temporarily loss of structure and / or functionality inflicted by exposure to perturbations.

Conceptualisations of robustness approaches in agricultural systems

In this section I return to my analysis of robustness conceptualisations in the three Transforum case studies (De Goede et al., 2012b) and discuss the potential of the robustness approaches in agriculture.

To answer the question how robustness was conceptualised in the TransForum scientific projects, I looked at the research proposals and deliverables of the projects.

Stacking functionally expressed apple genes for durable resistance to apple scab

In the project proposal, one reference to robustness was made: "*This project uses an innovative approach of stacking genes and cisgenesis enabling durable resistance management of apple scab and therewith to a reduction of the fungicide use in fruit cultivation. This contributes to a sustainable agriculture with more robust varieties.*" However, the project was documented with a project evaluation[4] and a PhD thesis (Joshi, 2010), in which robustness is mentioned 0 times. An analysis of the use of robustness-related terms in the papers and thesis show that resistance is frequently used, as opposed to other

4. *http://www.transforum.nl/projecten/wetenschappelijke-projecten/item/47-stapeling-van-genen-voor-duurzame-resistentie-tegen-appelschurft*

robustness-related terms such as resilience, stability or constancy that do not appear in the texts. In the PhD thesis, resistance is the third most frequently used noun, after gene and apple. It is used in combination with the nouns gene and scab, specifying both the abstraction level of the researched system and its disturbance, and the desired coping strategy.

SynErgy: Monitoring and control system for conditioning of plants and greenhouse

The research proposal stated that this project relates to a specific form of robustness at the level of cropping system and individual plants, but does not explicitly define how robustness is understood. The final report of the TransForum scientific project "SynErgy: Monitoring and control system for conditioning of plants and greenhouse" (Dieleman et al., 2010) does not mention, define, or make any reference to the concept of robustness. On being asked, it was declared that the technical innovation adds robustness to the production environment, allowing the grower to better control the climate in the greenhouse. In optimised climates, existing robustness features at plant level become redundant and can be traded off against higher production. At system level, this highly optimised efficiency goes at the cost of reduced flexibility to change business.

Robustness of animal production systems: concept and application.

In the research proposal, a broad definition of robustness was used: *minimal variation of target features following disturbance*. The methodology of Robust Design is mentioned as "a promising methodology to utilise robust components and design the production process for minimal variation". For crops and livestock this methodology would involve "utilising and supporting their intrinsic ability to deal with disturbances by adaptation. Related to controlled livestock systems, it is argued that a controlled system is robustly stable if it remains stable if the system is slightly changed, and has a robust performance when its performance stays more or less the same if the system is changed a little. The final report of the TransForum scientific project "Robustness of animal production systems" conceptualised robustness as the ability of a system to maintain sustainability in the presence of disturbances (ten Napel and Groot Koerkamp, 2010). To improve robustness of sustainability of the production system, the project suggests a design strategy that includes aspects of ecological resilience, namely diversity, redundancy and modularity, selectively applied to different system levels and integrated (ten Napel and Groot Koerkamp, 2010; Ten Napel et al., 2011). This project was not carried on as expected, but eventually wrapped up in slimmed form.

Despite the facts that two TransForum projects have not explicitly conceptualised robustness and the third project was only carried on in slimmed form, the general approaches to robustness can be deducted from the research proposals, project deliverables, and personal interviews that I had with researchers from the projects in question. I have not aimed to develop alternative conceptualisations of robustness for the concerned sectors independently, but rather assessed the approaches against the conceptual framework that has been described in this thesis.

Robustness approaches in the Transforum case studies

The engineering approach to robustness concentrates on the external side of vulnerability, and focuses on protecting systems against exposure to potential threads. Protection typically goes hand in hand with increased control of a system's environment. Developments in horticultural systems, e.g. Transforum case "SynErgy: monitoring and control system for conditioning of plants and greenhouses", are a good example of this. Far-reaching possibilities to condition production environments within horticulture production systems contribute to a separation of the technological production system from its ecological environment. The so-called 'closed greenhouse' in which growing circumstances are being conditioned forms a controlled zone between the crop and its original environment that protects the crop against environmental fluctuations with which it previously had to cope. This controlled zone reveals redundant tolerance mechanisms at crop level, that need re-evaluation in relation to breeders' interest. Nevertheless, where the engineering approach builds on presumed animosity between system and environment, the main driver behind biological approaches is increasing fitness, or applicability, of systems as things are. Practical applications of biological robustness have mainly concentrated on genetic heritability of robustness traits and integrated in breeding programs. Because such programmes in general purposefully aim to improve system functioning in the presence of predictable disturbances, the biological approach is easily interrelated with engineered robustness at technical system levels, and in some cases, such as genetic modification of biological systems the distinction with the engineering approach may even become faint. This is for instance the case in TransForum case "Stacking functionally expressed apple genes for durable resistance to apple scab". The project took a technical approach by stacking isolated resistance genes from non-commercial apple varieties and introducing them into high quality varieties by means of genetic modification. The resistance that is created with designed redundancy should reduce the need for fungicide application. This strategy shows remarkable similarities with the use of multiple modular redundancy as applied in for instance Fly-By-Wire Control Systems (see chapter 3).

As opposed to the greenhouse case, where increased control of the production environment makes robustness traits at crop level superfluous, pyramiding of resistance genes builds redundancy at crop level to strengthen inherent resistance at crop level. The ultimate goal is to make fungicides as an external control measure superfluous and to make it possible to grow fruits near residential areas. From a current situation of eradicating sources of disturbance, i.e. robustness as a relational property aimed at controlling the production environment with added complexity, this strategy explicitly considers robustness as a system feature at crop level. The urge for robustness at crop level can only be explained by the side effects of control mechanisms that compensate for the vulnerability of existing commercial apple species. Lack of acceptance undermines the social sustainability of this production method. However, where the application of fungicides in orchards turned out to be a socially contested complexity to avoid contagion, the use of GM is a socially contested manner to create resistance at plant level within the context of European bans on the production of GM crops. Both strategies are scientific-technical trouble shooting that suffer from a lack of social support, but illustrate that calls for robustness are often

not only related to reducing costs or impact of existing control measures, but also highly context-sensitive.
The high context-sensitivity of robustness needs is particularly clear in animal husbandry, where robustness is narrowly related to animal welfare. TransForum case "Robust animal production" is an example of a project that dealt with narrowly defined robustness goals. The project recognised that the current designs of livestock systems are heavily based on tolerance design, and frustrate the intrinsic ability of animals to cope with perturbations (Ten Napel et al., 2011). Rephrased in the robustness approaches as described above, the project reacts against the side effects of predominant engineering approaches, and aims to utilise resilience at animal level to create robust, sustainable LPS. To remove barriers of current designs to utilise intrinsic robustness of animals, the project seeks alliance with industrial design methods to design LPS in which animals perceive perturbations no longer as shocks, but as noise within the normal bandwidth only, and that support adaptive responses of animals. The design approach at the technical level of the system must therefore be understood as a continuation of the engineering approach, though integrating the adaptive responses of animals as a design criterion. As I have argued in this thesis, this adds complexity to the system design and its management, and cannot break through complexity/robustness spirals (see chapter 4). Adaptedness of animals in newly designed LPS is needed to support an overall engineering approach at the technical level of agricultural systems.

The engineering approach to robustness is the dominant conceptualisation currently worked out in agriculture. At least, the engineering approach is the only approach that is clearly visible in each of the three TransForum projects. The amplitude conceptualisation within the ecology approach is not applied in the TransForum cases. This is relevant because it illustrates that robustness in agriculture is not associated with preservation of system structures and persistence of functionalities, but rather with functional efficiency.
Moreover, the cases illustrate that robustness as a system property increasingly derives its relevance from the instrumentalisation of biological systems within otherwise largely technology driven agricultural systems. Evolutionary optimised tolerance to events that a system encounters in its environment is no longer seen as a by-product of evolution, but as a functionality instead. Clearly, such tolerance has evolutionary relevance and it has been argued that evolution can turn what was a random by-product into something that adds functionality (Gould and Lewontin, 1979). However, the functionality of inherent tolerance of the biological system is no longer measured in terms of competitive advantages in the light of evolution, but in terms of instrumental contribution to the functioning of engineered systems instead. This undermines conceptualisations of robustness as a system property. The examples illustrate that undermining of the biological approach to robustness can take place in two ways. Either robust engineering reduces inherent robustness at crop or animal level to a redundant system feature superfluous to requirements, or the side effects of complexity-robustness spiralling lead to a revaluation of 'inherent' robustness features, and a transformation of associate robustness into designable system features. As soon as robustness is no longer associate but planned, it has

relevance only in relation to efficiency of the system and obtains its value as a rational choice (Vandermeer, 2011). The emphasis on optimisation allows a continuing instrumentalisation of the biological sub-systems involved and stimulates economic rationalisation of these systems. The simultaneously increasing focus on risk prevention (compare Beck, 1992) gives rise to changing understandings of system vulnerability. Indeed, the more complexity is needed to protect a system against unexpected changes, the more its vulnerability will be experienced as a relational property of system and environment together. In overemphasizing the relevance of one of its functions, achieving the HOT state thus not only requires to separate system functions that were previously united, but maintaining it increasingly invites us to locate the source of emerging vulnerabilities in the relational sphere, rather than as a system property. Eventually, uncommon fluctuations and environmental dynamics become a thread to the sustainability of the system. This is precisely why resilience thinkers claim that it is necessary to move away from analytical assumptions of equilibrium thinking and manage for resilience to uncommon fluctuations. That is, taking into account the long-term adaptive cycles of each subsystem and their interaction in space and time, understanding the dynamic nature of structures as a panarchy, a cross scale nested set of adaptive cycles (Gunderson and Holling, 2002), and recognizing that complex systems consist of constantly changing and co-evolving subsystems, part of the complexity of which results from the fact that they evolve at different speeds. By that perception the question whether or not a farm is robust, resilient or able to adapt at a specific moment in time is close to trivial. What does matter is the direction of its long term transformation (Darnhofer et al., 2010a).

Preferences: can we rank robustness approaches in agriculture?

If we agree that robustness should not be seen as a clear cut system property, but instead as a multi-interpretable flip-side of vulnerability, one may wonder whether all flip-sides of vulnerability are equally desirable. In other words, can we rank the robustness approaches and related strategies on the basis of their applicability in agricultural production systems? To answer this question, it is important to keep in mind that robustness refers to an approximation of the most desirable intermediate between a vulnerability aspect and its opposite notion of stability (see chapter 2). Ranking of the most appropriate robustness approach or strategy therefore cannot be done without first assessing the vulnerability aspect and the desired stability within the production process.

To sum up, two main robustness directions, namely persistence of functionality and efficiency of function are distinguished. The efficiency of function directions is divisible into three robustness approaches with different orientations, corresponding robustness strategies and specific measures (see table 6). I have suggested that the main difference between the robustness strategies is the degree by which systems are allowed or inclined to follow environmental changes and showed that the mechanisms that underlie complexity behind the different robustness strategies radically differ In chapter 4 I have described Highly Optimised Tolerance (HOT) as an example of structured, organised and optimised systems with low associate resilience, but very high planned and purposefully designed robustness, aimed at maintaining a state of high productivity and failure avoidance. The mechanism underlying this tolerance

providing complexity is conservation and functional efficiency. The efficiency of function direction puts function first and accepts structural adjustments to achieve this. Consider a change to a new greenhouse to increase energy-efficiency.
On the contrary, the mechanism underlying resilience providing complexity is change. Its sustainability is measured by the capacity of the system to absorb environmental changes without structural damage. The persistence of functionality direction puts structure first and accepts functional adjustments to achieve this. Consider multifunctional agriculture as an example that adds new functions as a means to preserve existing structures. Systems with resilience providing complexity are often referred to as complex adaptive systems (CAS). They obtain their robustness and complexity through self-organisation leading to maximised adaptive capacity and (ecological) resilience. HOT and CAS thus represent two extremes in the schematic visualisation of robustness strategies, where CAS are generally considered self-organising, i.e. unmanaged, systems with high associate resilience, and HOT systems on the other hand are structured, organised and optimised systems with low associate resilience, but very high planned and purposefully designed robustness aimed at maintaining a state of high productivity and failure avoidance. It has been argued that self-organising CAS can evolve to a state of Highly Optimised Tolerance through so called complexity robustness spiralling. This evolution can only succeed when adaptive capacity is traded off against additional tolerance, i.e. when mechanisms underlying the complexity of the system are replaced. Such trade-offs are often the result of human structuring and optimisation.
I believe that agriculture, optimised and structured food production, is an example of a human activity that has significantly altered the mechanisms underlying the complexity of our social ecological systems. This is the result of complexity-robustness spiralling that started with the independent emergence of agricultural activities within a number of self-organising Neolitical social ecological systems, as an adaptive response to either cultural (demographic) or ecological dynamics. Thus broadly speaking, agriculture is a persistent social complexity that has emerged and still adds robustness to modern social ecological systems. As an adaptive response, agriculture affected the resilience of the social ecological system it entered, and as societies increasingly took up arable farming and stockbreeding, the functional efficiency became more important as a mechanism underlying the complexity of these social ecological systems. In other words, from an adaptive response, agriculture developed to a system shaping functionality. As a response it provided resilience to social ecological systems that existed, as a functionality it is evaluated in terms of efficiency. Indeed, modern agricultural systems are human managed systems, the purpose of which is to create structure, organisation and regulation of food production. Self-organisation is still a driving force of agricultural system dynamics, but it is increasingly embedded in, and restricted by rules and restrictions of the social ecological system it belongs to. The inherent necessity of structured functioning and related tendency to optimise efficiency in agricultural systems is at odds with unmanaged natural systems in which not functional efficiency, but structural persistence is maximised. Hence, purposeful management moves systems away from a conceptualisation of robustness related to associate resilience, and contributes to a merely efficiency related conceptualisation of designable

Table 6. Robustness directions divided in approaches and their corresponding properties, orientations and strategies. *For each robustness approach is listed to what kind of disturbances it provides robustness, how robustness is measured and what the theoretical end point of this approach is*

Robustness direction	**Approach derived from**	**Robustness property**	**Orientation (robustness state)**	**Robustness strategy**	**Disturbance**	**Measure**	**Theoretical End point**
Efficiency of function	Engineering	Relational	State of avoiding exposure	Avoiding	Strictly Anticipated	Period of non-exposure	System is always exempt from exposure to disturbances (relational).
	Biology	System	State of inherent resistance	Resistance	Mainly anticipated	Preservation of structure and function	System always has enough resistance to resist unlimited exposure to disturbances without damage.
	Ecology (elasticity conceptualisation)	System	State of response and recovery after perturbation	Resilience	Both anticipated and unexpected	Recovery rate	Recovery time to original position is infinitesimal.
Persistence of functionality	Ecology (amplitude conceptualisation)	Relational	State of structural persistence	Ecological Resilience	Mainly unexpected	Persistence far from equilibrium	The amplitude of the structural configuration within which the system is functional is infinite.

robustness instead. Moreover, a conceptualisation of robustness as a designable aspect of managed systems contributes to an ontological separation of system and environment. This separation is hardly relevant when describing persistence of functionality, but gains relevance when systems are evaluated in terms of efficiency of function, because it makes us see robustness increasingly as a relational property. The idea of designable robustness contributes to a positioning of the agricultural production environment as a potential threat to achieving optimal performances. This is because we assess functional robustness always in relation to environmental influences, such as performance under suboptimal conditions. The functional relevance of pure systemic robustness, such as resistance at crop level, can only be explained in relation to such environmental dynamics. Self-organising adaptation of the agricultural system takes place in the light of efficiency of function and in relation to environmental dynamics. The system gains complexity, not to adapt to the unexpected, but rather to recover from, resist or avoid exposure to anticipated variation. Thus agricultural systems are pulled along in spiralling complexity leading to states of highly optimised tolerance. Along this spiral, the inclination to allow environmental influences on the functioning of the system decreases, suggesting that approaches related to the functional efficiency of the system, i.e. the elasticity conceptualisation of the ecology approach, the biological and the engineering approach are ranked accordingly. The robustness approaches found in the TransForum cases support this observation and show that robustness is mainly seen as a relational property and related to avoidance.

How then should we rank robustness strategies? The complexity/robustness spiralling points a direction of robustness spiralling against anticipated perturbations. As activities – for instance agriculture – evolve from adaptive responses to system shaping functionalities, the relevance of their robustness evolves from persistence of functionality to efficiency of function. The complexity robustness spiral starts with measuring an adaptive response as functionality in itself. In terms of the robustness strategies I described, it is a narrowing down of the ecology approach that occurs when an adaptive response, the robustness of which is determined by its structural persistence, is also measured as functionality in itself in terms of efficiency. This leads to shifting assessment criteria. In our society, studying the amplitude of the social ecological system in which agricultural practices are functional is less common than studies to improve the efficiency of our agricultural practices;

When the relevance of functional efficiency increases, or the acceptability of environmental fluctuations influencing the functioning of the system decreases, robustness is rather related with inherent resistance than with capacity to recover. On a system level, this will lead to extra resistance to anticipated disturbances.

Once robustness is related to functional efficiency against anticipated disturbances, it can no longer be considered strictly as a system feature, but becomes a relational property of the system and its environment together. Functional efficiency is always assessed in relation to environmental influences, i.e. performance under suboptimal conditions. At this stage, additional control measures are added to improve the relation between system and environment. Focussing on anticipated disturbances, the system gains complexity to avoid failures, create fault tolerance and realise longer periods of non-exposure.

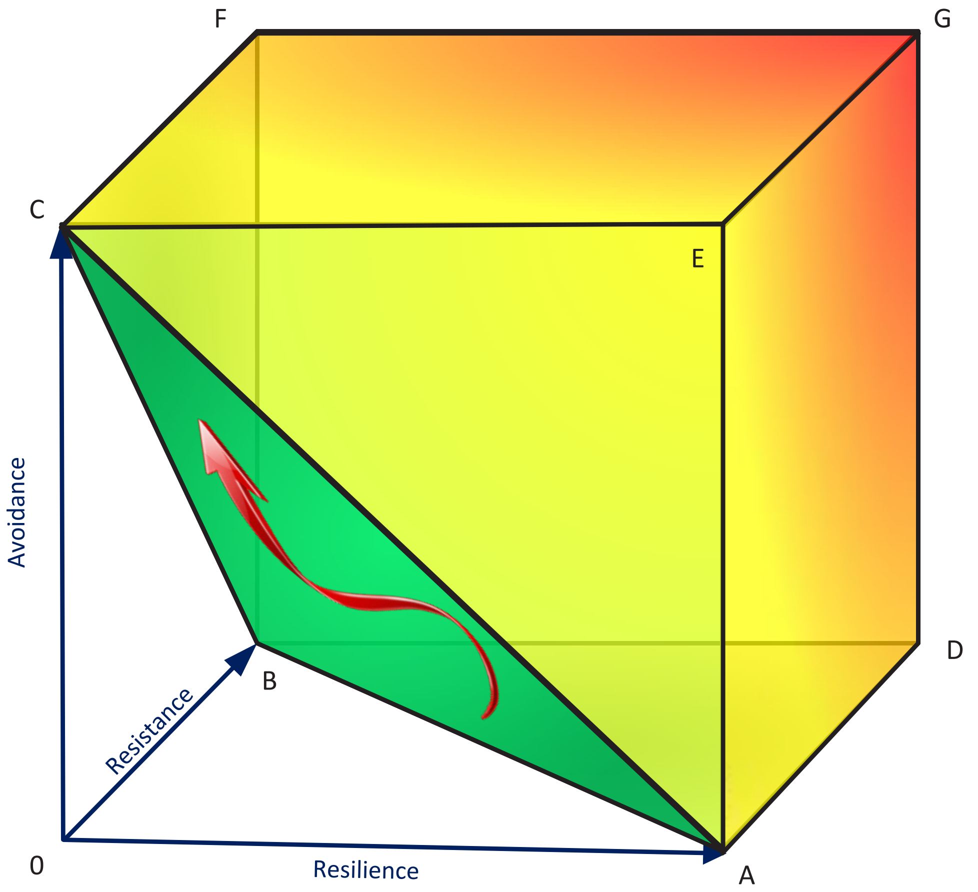


Figure 7. ***Schematic visualisation of robustness strategies directed at efficiency of function,*** *where A, B, and C represent the theoretical end points of robustness strategies Resilience, Resistance and Avoidance respectively. The spiral points the direction of robustness spiralling against anticipated disturbances.*

Figure 7 reflects the space of robustness strategies directed at efficiency of function in the presence of disturbances where A, B, and C represent the theoretical endpoints of robustness strategies Resilience, Resistance and Avoidance respectively. A is a theoretical situation where the system is able to recover from exposure to disturbances in any form and size, but has no inherent resistance and no possibility to avoid being exposed. Theoretically, all inherent resistance and additional environmental control to avoid exposure are redundant;

B refers to an ideal situation where the system achieves sufficient resistance to withstand exposure to disturbances in any form and size, but has no capacity to recover and no possibility to avoid being exposed. Theoretically, all inherent resilience and additional environmental control to avoid exposure are redundant.

C is a situation where the production environment is completely controlled and the system is always exempt from exposure to disturbances, but has no inherent resistance and no capacity to recover. Both inherent resistance and inherent resilience are redundant.

0 is a situation where the system cannot avoid any exposure to disturbances, has no inherent resistance to withstand any exposure to disturbances and no resilience to recover from exposure to disturbances. Space 0ABC is not robust, while any point on the side ABC represents a theoretical minimum robustness level where combinations of resilience, resistance and avoidance provide a system with just sufficient capacity to avoid or cope with exposure to disturbances, although not necessarily in its most desired form. At any point above side ABC two or three robustness strategies overlap and create a robustness surplus. Theoretically, a maximum robustness surplus would be achieved in point G. However, as shown in this thesis, robustness trade-offs take place and, as perturbations become more anticipated, bring about a spiralling from primarily adaptive to merely tolerant systems, i.e. an evolution from A towards C. Systems do not incline to create robustness surpluses and preserve multiple strategies to cope with anticipated perturbations. Rather, they exchange one robustness strategy for another. As a consequence, system robustness will not only evolve in the neighbourhood of side ABC, it will evolve towards point C. In other words, in case of a robustness surplus systems tend to dispose coping capacity rather than the power to avoid disturbances, and capacity to recover from the damage caused by exposure to disturbances rather than the inherent resistance to such exposure.

Potential of robustness approaches in agriculture: plea for a holistic approach

Each of the above mentioned approaches are conceptualisations of robustness that are appropriate in specific fields of science and in relation to specific systems and situations. However, if we try to position agricultural systems one has to acknowledge that, even though the engineering approach appears to dominate conceptualisation of robustness in agriculture, agricultural systems do not have an obvious relation to either of the robustness approaches. Or, to put it differently: agricultural systems are multi-robust. The reason for this is that agricultural systems are unique amalgamations of diverse complex systems with radically different underlying robustness mechanisms. Indeed, agricultural systems are technological systems the robustness of which is designed and measured as a relational property. The technological system however surrounds an indisputable biological core of the agricultural system, namely its crops and animals that produce themselves because of their own biology. Their robustness is mainly associate and the result of long term natural selection, although more recently a purpose of selective breeding practices. In addition, the agricultural system interacts with its environment and is part of a social ecological system that can only persist in its current ecological equilibrium and thus requires maintenance of its current steady state for its long term sustainability. System dynamics at the technical, biological and social-ecological level of agricultural systems cannot be seen in isolation, but should be considered in connection. Hence, a holistic approach is needed to understand robust agriculture. In the next section I refer to homoiothermism as an example of holistic robustness.

Holistic approach to agricultural robustness: homoiothermism as an example

Homoiothermic animals are animals that keep a relatively constant body temperature despite fluctuations in temperature of their environment and variations in their degree of muscular activity. As Hill (1961) already observed, it requires remarkably good control over related processes, e.g. oxygen consumption, to achieve such a delicate balance between heat production and heat dissipation. When confronted with low environmental temperatures, homoiotherms maintain their body temperature by adapting their rate of heat production, while in warm environments heat loss through evaporation increases. The temperature range within which homoiotherms have a constant metabolic rate is narrow and has been termed thermal neutral zone (Eckert and Randall, 1983), or comfort zone, because in this zone body temperature regulation requires no changes in metabolic effort. Below the lower limit of the comfort zone, a homoiotherm enters a zone of metabolic regulation, in which thermoregulation requires increased metabolic activity. In this zone of metabolic regulation metabolic activity rises in proportion with environmental temperature falls. Environmental temperatures above the upper limit of the thermal neutral zone lead to hyperthermia – a state of abnormally high body temperature – , unless active heat dissipating mechanisms, such as evaporation, are brought into play (Eckert and Randall, 1983). In other words, at temperatures above the upper limit of the comfort zone, a homoiotherm enters a zone of active heat dissipation. Metabolic processes in homoiotherms are up to 10 times faster than in poikilotherms and can only take place at high temperatures. Homoiothermic systems are being kept at a temperature that is close to lethal. Small changes can be very dangerous. Yet, some fluctuation / flexibility is tolerated. All in all, homoiothermic systems use thermoregulation as a buffer to avoid functional dependency on environmental temperatures, are capable of maintaining a constant body temperature under fluctuating environmental conditions and muscular activity within the thermal neutral zone, adapt functional efficiency of the system to environmental temperatures outside the thermal neutral zone, and are capable to recover from thermal shocks that lead to sub-optimal body temperatures by triggering heat producing or heat dissipating mechanisms until it returns to its steady state within the thermal neutral zone. The robustness of homoiothermism cannot be attributed to either of the strategies, but lies in the combination of multiple connections and feedback loops that result in a state of relative constancy. For instance: homoiotherms use thermoregulation as a buffer to avoid functional dependency on environmental temperatures. Stronger, the homoiotherm's interior is exempt from exposure to temperature variation; within the thermal neutral zone, homoiotherms remain body temperature constancy and resist fluctuation in environmental temperature without changes in metabolic activity; at temperatures below or above the thermal neutral zone, the functional efficiency of the system decreases and the system is triggered to use heat producing or heat dissipating mechanisms to cope with environmental circumstances until it returns to its steady state within the thermal neutral zone.

The homoiothermic body has several ways to influence the production and dissipation of heat, such as constriction or dilatation of the blood vessels, or shivering. Some of these strategies, such as the capacity to transpire more constantly when exposed to heat, and increased blood supply to extremities when continuously exposed to cold is the result of acclimatisation. Increased blood supply as a result of continuous exposure to cold has for instance been observed in Eskimo societies as well as fish tracers that have to hold ice-cooled fish with their hands (Daanen, 2004). Although this acclimatisation seems favourable to prevent cold-based injuries, the disadvantage of it is that extremities such as fingers and toes dissipate much more heat than the thermic core of the body and therefore comes at the cost of increased risk of hypothermia. This trade-off shows that homoiothermism is also an example of robust, yet fragile system. When confronted with extreme and long-lasting cold, a homoioterm system will always sacrifice structure for function, i.e. in order to prevent general hypothermia, the supply of warm blood to tail ends of the body will be reduced even if this leads to cold based injuries, i.e. being caught by the frost. Unfortunately, such injuries continue to occur every now and then, for instance during sporting events in winter time, such as the 11-city skating marathon in Friesland, where toes and fingers happen to be amputated.

Comparable to homoiothermic systems, modern agricultural production systems are characterised by a relatively high productivity, and a relatively small range within which that productivity is actually sustainably reached. But where metabolic rates are constant within a one-dimensional thermal neutral zone, every sustainability domain puts specific requirements on production methods and forms a dynamic, critical border of the neutral zone within which agriculture is sustained. That means that while the homoiotherm can return to static balance, i.e. a range of temperatures with fixed upper and lower critical values within which metabolic constancy is certain, agricultural systems are confronted with dynamic critical values, making their sustainability a moving target. The idea that the tri-dimensional sustainability zone is a more or less fixed and static zone in which sustainable agriculture is possible and in which adaptations are hardly needed is a false impression of things. The borders of sustainability, i.e. the critical values of the tri-dimensional sustainability zone in which the agricultural production system operates, are not only variable, but are, as a consequence of complexity/robustness spiralling, also tightened. This is the result of long term selection on efficiency and maximisation of production within the bandwidth of expected variation, for which ecosystem resilience (amplitude conceptualisation of robustness) and adaptability against unexpected events has been sacrificed. Non-specific associate robustness has gradually been replaced by selective, but purposefully chosen robustness traits. Irrevocably, this process of functional optimisation has reduced the bandwidth within which that productivity is sustainably reached. To put it differently, the neutral zone shrinks, and as a consequence, the likeliness of border-conflicts, comparable to cold-wars in homoiotherms, continues to increase. This only enhances complexity/robustness spiralling and stimulates sacrificing remaining adaptive capacities against additional control measures to avoid functional disintegration.

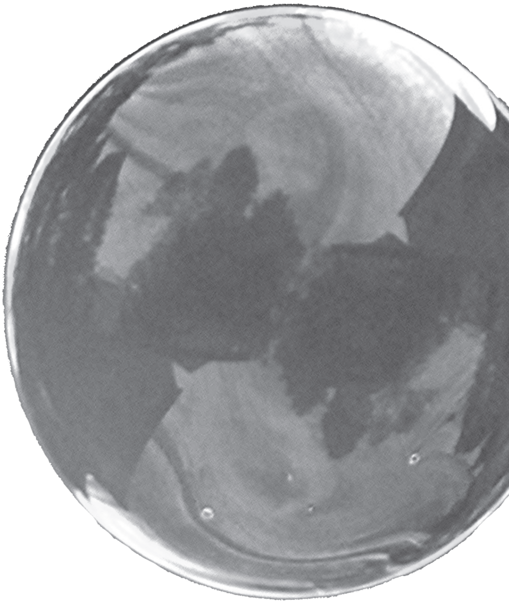
Relevance of robust agriculture vis-à-vis sustainability: robustness as a guiding principle

Along with the rapid increase in awareness of the importance of sustainability, as well as the increased availability of various information sources, the number of sustainability terms and their definitions continue to increase (Glavič and Lukman, 2007). New terms emerge, but often without giving critical attention to the definitions and their semantic meanings. As a consequence, sustainability terms are often ambiguous and not appropriate to serve as guiding principles for innovations towards sustainability. I have argued that robustness too is an ambiguous, contested concept. However, as opposed to sustainability, robustness can be captured in a few strategies as described in this thesis. This makes robustness a far more tangible concept than sustainability. In addition, whereas multi-word sustainability terms, such as 'sustainable development', 'sustainable design' and 'sustainable growth' have something paradoxical if not exposed as true oxymora, robustness has since long been associated with engineering and design. It may therefore be expected that, as a guiding principle, robustness can facilitate the discussion about deploying purposeful design to achieve specific sustainability goals more than sustainability ever can. Due to its contested nature, robustness can profit from a fundamentally positive attitude of various stakeholders while at the same time applying to specific systems and sustainability attributes. On the contrary sustainability irrevocably refers to multiple attributes and principles simultaneously and consequently allows multiple and conflicting interpretations already at the start of the debate. For instance, a message that GM could help to develop purposefully designed organisms to achieve specific sustainability goals may be experience a lot of controversy when presented as a sustainable development, or a design for sustainability. That is, because we also associate technologies such as GM with engineering, technology and matters that recall images of threat, rather than solutions to sustainability. Indeed, solutions that aim to combine social, ecological and economic dimensions of sustainability have to cope with existing images and related tensions between the three sustainability domains. Because sustainability is only achieved when the three domains focalise, fundamental differences of visualisation in the three domains could paralyse sustainable developments. That is precisely why I believe robustness could function as a guiding principle to achieve sustainability. Its association with engineering clearly indicates that robustness is something that requires human design. Unlike sustainability, robustness instinctively justifies human interference to protect systems against potential disturbances. This implies that focusing on robust design, rather than designing for sustainability, allows one to avoid touchy subjects that could strengthen potential tensions between ecological principles, social responsibilities and technological innovations. It also implies that robustness is not a neutral concept when used as a guiding principle towards sustainable development, or as an image of sustainability. Robustness requires design and as an image of sustainability implicitly takes human interference as a precondition, not as a talking point. Such justified meddling is not at all new to agricultural development, although it seems that the meaning of robustness has changed over time, and always in relation to themes in the social (sustainability) domain. Consider that shortly after World War II, when food security was the key issue for European societies, robust crops were being developed with the aim of achieving uniform growth to maximise production(Robinson et al., 2004). Nowadays robustness is still related to the main features of the social sustainability aspect such as genetic diversity, food security, animal health and animal welfare. This suggests that robustness is indeed more naturally associated to the social sustainability aspect. This natural association with the social sustainability aspect only emphasises the relevance of the biological robustness approach. While the engineering approach to robustness is criticised for being indifferent to non-functional assessments of agricultural production systems and boosting complexity spiralling, and the ecology approach suffers from assumed functional disorientation as a main drawback, the biological approach offers consumers the possibility to steer the evolution of agricultural systems, both structurally and functionally. The engineering approach or the ecology approach alone are incomplete and combinations of the two may lead to indifferent functional disorientation rather than holistic robustness if not pursued via an integrated approach in which the biological approach is equally considered. As with sustainability, robustness requires a holistic integrated approach that pursues a balance of all dimensions of robust agriculture. That is, not starting from the biological approach, but also not instrumentalising biological robustness to achieve other robustness goals. The instrumentalisation of biological robustness is however encouraged by the rapid development of biological sciences and their amalgamation with technical applications. Different disciplines of biology and related biotechnologies have developed rapidly since the 19th century when industrialisation of agricultural production got off the ground. Biotechnology relates to technologies that use biological organisms for the development of new products, food and medicines. Some biotechnologies are established practices that have been in use for centuries. Consider selective breeding, but also the use of yeast and lactic bacteria to produce bread respectively cheese. Modern biotechnologies increasingly use knowledge produced in new disciplines of biology, such as molecular biology, molecular genomics, synthetic biology and genomics to name a few. What these modern applications of biological knowledge have in common is their purposeful use of knowledge of theories of heredity and genetic material to develop specific utilisations of biological processes. In other words, modern biotechnologies add functionality to biological processes and contribute to a functional optimisation of biological systems and their newly assigned functions. While the replacement of the biological metaphor of *nature as organism* by the *nature as machine* metaphor in the 17th century opened the way to study the functioning of natural systems as if they were engineered for particular purposes, modern biotechnologies move one step further and consider the functionality of biological systems open for improvement. It is precisely the evaluation of biological features in terms of functionality – *nature as utility* – that undermines the biological approach to robustness. Using genetic screening can support breeders to include robustness traits in breeding programs but it transforms biological robustness from a by-product of natural selection into a designable system feature and a goal of rational optimisation of production systems using biological components.

Still I argue that the biological approach to robustness offers stakeholders of agricultural systems an entrance to develop the ideological dimension of robustness, because it requires a concretisation of the purpose and the environment to which we want our production animals and crops to be adapted. The biological system determines which functions can be achieved within the given structure, even when it is ultimately human constructed. The biological approach combines functional orientation with receptiveness to normative values. The biological approach plays a key role in breaking through the Technology-Ecology (or Function-Structure) stalemate that has diametrically opposed industrial and organic agriculture. To be successful, both paradigms need biological robustness, i.e. as an ideologically justified strategy to coping with system vulnerability.

Acknowledgements

I owe thanks to Buzz Holling who suggested homoiothermism as a metaphor for robust agriculture.



Concluding remarks

Undefined and contested, the term robustness emerged as a buzzword when it came to operationalizing the eroded objective of sustainability. In agriculture however, the term already seems to be on its way down. Where the expiration date of the term sustainability is continuingly put to the test, the buzz continues about resilience rather than robustness. While the differences and similarities between the two concepts are still debated, there are reasons to assume that the potential of robustness as an image of sustainability are overlooked. I have argued in this thesis that both engineering resilience and ecological resilience are potential, but uncommon conceptualisations of robustness in agriculture. I have, in other words, supported the idea that robustness and resilience are mutually related, without suggesting that one is a limiting case of the other.
This thesis identified several reasons why it is worth the while to reassess the relevance of robustness vis-à-vis sustainability.
Firstly, whereas resilience has developed and is primarily associated with ecosystems, i.e. the ecological sustainability domain, robustness is naturally associated with the social sustainability domain and non-natural, managed systems. Robustness easily relates to design, engineering, and management. A call to increase a systems robustness is an implicit plea to improve its design, or manage differently. Conversely, a request for increased efficiency to improve sustainability, or legal obligations to strictly monitor for food safety reasons, is more likely satisfied with robust design than with resilience thinking.
Secondly, systems cannot increase their resilience in the same way robustness can be designed. While resilience is easier related to unexpected events robustness primarily relates to anticipated perturbations against which additional complexities are relatively easily added. Robustness protects a system to small fluctuations and noise, while resilience is tested against unexpected shocks. When related to a systems capacity to cope with anticipated and relatively well known perturbations, robustness holds greater attraction than resilience. Most perturbations in agriculture, as well as in other human designed and controlled systems, are anticipated.
Thirdly, because agricultural systems continue to develop in the direction of states of Highly OptimisedTolerance, it is important to distinguish between their robustness and their resilience. Resilience is needed in relation to the ecological carrying capacity and the preservation of Social Ecological Systems that rest on structures built by agriculture. Robustness on the contrary is primarily needed to protect optimised functionality against anticipated perturbations and is unrelated to the ecological dimension of sustainability. The trade-offs between optimised tolerance and adaptive capacity illustrate that robustness and the role it plays in spiralling complexity of agricultural systems cannot be considered in isolation, but should always be related to the resilience of these agricultural systems and the SES in which they function.

The results of this conceptual study of robustness relate to, and add knowledge to, several fields of science. First of all, the study has made more clear that robustness relates to complex systems and should theoretically be considered in relation to upcoming interest in complexity theory and the evaluation of agricultural systems as complex adaptive systems.

The study has also made clear that robust designs are inspired by examples from nature. This suggests that robustness thinking has practical relevance in relation to biomimicry – the use of scientific understanding of biological systems to exploit ideas from nature in order to construct technologies (Passino, 2005).

Complex adaptive system thinking

The insight that agricultural systems are in constant co-evolution with their environment has increased the relevance of adaptability as target of research in agricultural science. This results in more attention for the dynamics of farming systems and their contexts. Especially the possibilities of complex adaptive system (CAS) theory to explain agricultural dynamics are being explored (Darnhofer et al., 2010b). The CAS approach is useful to study those kind of systems that have, what John Holland (1992) called an 'evolving structure', referring to their capacity to change and reorganise their component parts to adapt themselves to the problems posed by their surroundings. Systems, in other words, that constitute a 'moving target', because both internal and external dynamics lead to substantial structural system changes that are difficult to understand and control. CAS approaches strongly defy reductionist thinking, and take a hierarchically nested system view to explain how system structures arise from the interaction of basic elements at lower system levels. The application of CAS theory extends diverse and large problems from ecology to information technology and from biology to economics. In agricultural sciences, the CAS approach offers a concept to analyse a production system's adaptability to keep up with complex social-technical and social-ecological developments. Because adaptive capacities have long been neglected or contained and manipulated, the design of a system that deliberately builds on and exploits existing self-organizing, adaptive capacities, requires a radically new system approach. As Darnhofer et al. (2010b) argue: *"enhancing adaptability goes against the recommendations derived from an engineering approach to farm management"*. First of all, because there is a strong believe in trade-offs between efficiency and adaptability. From an engineering point of view, adaptability has a high price because strategies to enhance adaptability require resources. Additionally, taking adaptive capacity as a starting point for system design is an unexplored approach that not only requires an understanding of the ability of diverse system elements to be adaptive, but ideally more than a vague understanding of the kinds of changes that will challenge the adaptive capacity of these system elements, and the system as a whole. This knowledge is still lacking and although different manners and specific approaches on different system levels are being developed to strengthen the adaptive capacity of production systems, their implementation and integration seems a major challenge to enhance adaptability of the system as a whole. Robustness is central to this tension between the adaptive capacity of complex systems on the one hand, and their ability to resist change on the other. On the social level, agricultural innovations, and the interactions between involved actors are increasingly being analysed, explained and steered in terms of CAS (see for example Darnhofer et al., 2010b; Klerkx et al., 2010). New system design approaches, although not explicitly referring to CAS theory, make use of insights from complexity theory, for instance by seeking legitimacy and public support by allowing different groups of stakeholders to participate in design processes. For

example, the Recursive Control Approach (RCA) that was applied in the Houden van Hennen project suggests that through cleverly designing, i.e. making use of the potential of technological synthesis of needs of different stakeholders, seeming contradictions between for instance animal welfare and economic efficiency can be softened or even designed away. (Bos et al., 2003). As Bos et al. (2003) argue, 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"*. The idea that farm animals should be seen as agents that through their behaviour with each other, other agents and their environment construct patterns of interaction and systemic structures is central to the CAS perspective. The RCA is unique in explicitly granting animals a participating and co-constructing role in the LPS, and this perspective therefore suggests to be one of the most far-reaching implementations of adaptive system thinking in livestock science (see De Goede et al., 2012a), even though its conceptual basis lies within philosophy of technology, most notably Andrew Feenberg's instrumentalisation theory (Feenberg, 1999; Feenberg, 2010) and Gilbert Simondon's notion of concretisation (Simondon, 1989). One essential feature to make recursive control possible is the natural adaptive response of the animal in LPS (Bos et al., 2003). However, as shown in chapter 4, a need for these adaptive capacities is hardly reflected in the programme of demands that was developed as a first step in this design process. This observation is relevant for future projects that aim to enhance system robustness, because it illustrates that even though calls for robustness are frequently initiated by an experienced lack of adaptive capacity to new and unexpected developments, solutions are generally found in increased adaptedness to existing stakeholder demands.
I have related the complexity/robustness spiral that had previously been described in relation to HOT, to different conceptualisations of robustness and formulated an explanation for evolving robustness conceptualisations along the complexity/robustness spiral. This connects to the growing interest in the functioning of complex adaptive systems and the challenges to restore the resilience of SES and break through unwanted spiralling complexity. A particularly relevant point of interest is the apparent connection between rigidness and malleability at different hierarchical levels that contributes to overall robustness of complex systems. Considering the trade-offs that take place between different robustness strategies, robustness ultimately is a matter of balancing rigidness at some, and malleability at other levels of the agricultural chain; between tolerant yet fragile, and resilient yet functional disoriented systems overall. As the relevance of uniformity, efficiency and quantity of the output of agricultural production systems continues to increase, research is needed how to efficiently achieve desired output levels in production environments that are themselves threatened by overexploitation and decreasing resilience. This challenge is best understood from a systems perspective and evaluated in terms of complexity/robustness spiralling.

Design robustness with biomimicry

Innovations for robustness are often inspired by examples from nature on how to cope with perturbations. Already, many robust designs are recognizable applications of scientific understandings of coping strategies found in nature. As a by-product of evolution, biological systems have gained associate robustness that can continue to inspire engineers to design robust agricultural systems, rather than aiming to avoid exposure to potential stressors. (Bio) mimesis is the mimicking of natural solutions or a strategy of reinserting man made systems in natural systems in such a way that the artificial system becomes optimally embedded. The optimisation of the embeddedness of livestock production systems in the social-ecological system is a form of biomimesis. By taking the natural behaviour of animals as a starting point in the design process of livestock production systems, engineers are confronted with a need to design the surrounding production system correspondingly. As such, the technological system surrounding the animals is redesigned and reinserted in the social-ecological system with two-way mimesis. Firstly, in its functioning as a housing system, it mimics the natural environment in which the animals being kept can show their natural behaviour. Secondly, by reducing environmental impacts and answering social concerns it optimises its embeddedness in the social-ecological system surrounding it. Additionally, the re-implementation of animals in agricultural systems can itself be called biomimesis if we understand the recent interest in neglected capacities of production animals as mimicking of natural animal behaviour by production animals to optimise the potential of these animals to shape and structure the production system naturally. This is however precisely what the recursive control approach aims to do. This tendency to re-evaluate natural solutions in terms of functionality and redesign them accordingly to create more robustness was also found in other projects. As the TransForum case "Stacking functionally expressed apple genes for durable resistance to apple scab" illustrates, ideas from nature are not only used to construct robust technologies, but also to compare biological systems among each other in terms of their functionality on the genetic level. Their natural solutions are thus not only a source of inspiration for technological design, but have meanwhile become an object open for improvement. It potentially submits the biological core of agricultural systems to a process in which coping strategies from closely related organisms are, whether with the use of technology or not, mimicked in organisms that benefit from this coping strategy from a human perspective. This is not new, but a critical reflection on the appropriateness of this mimicry-loop is continuously needed to determine to what extend animals and crops themselves can be functionally improved under the cloak of robustness breeding and to what extent robust design is at all a term applicable to living systems.

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Summary

The general aim of the research described in this thesis is to contribute to a better understanding of the conceptualisation of robustness in agricultural science as well as its relevance to sustainability. Robustness rapidly gained attention as a potential solution for a variety of problems that characterise modern agriculture. The Dutch innovation programme "TransForum" considered robustness an important societal value that needed to be developed in relation to innovations for sustainable development of the Dutch agri-sector. However, its meaning to agriculture is unclear, the term is loosely being used in various contexts and has been given equally diverse meanings in different fields of science.

This project takes a conceptual approach to analyse what robustness is and how it is approached in different fields of science, and addresses the question how these approaches relate to sustainability. The empirical part of the research concentrates on conceptualisations of robustness in practice. Cases are used to study which conceptualisation(s) are being worked out in agriculture. The relevance of robust agriculture vis-à-vis sustainable agriculture is discussed.

In chapter 2 it is argued that robustness should not be seen as a clear-cut system feature, but rather as a multi-interpretable flip-side of a specific vulnerability aspect or as a description of a particular notion of system stability. Robustness claims have meaning only when the vulnerability of the system is made explicit. Vulnerability is considered to be constituted by one or more vulnerability aspects: exposure, sensitivity and non-resilience. Sensitivity and non-resilience refer to system properties that are revealed when a system is exposed to perturbations, while exposure refers to the degree, duration and extent to which a system is subjected to such perturbations. As a flip side of vulnerability, robustness can be considered accordingly: as a system property describing a capacity to cope with potential perturbations, or as a relational property of system and environment together, referring to a capacity to avoid exposure and keep perturbations at a distance. Whether or not we call a system robust depends on the structural or functional impact that a perturbation may have on the system. From high to low impact, the following results of perturbations are distinguished (chapter 2):

1. Permanent loss of structure and function;
2. Permanent change of structure and/or function (adaptation);
3. Temporary loss of structure and/or function;
4. Preservation of structure and function (resistance);
5. Non-exposure

It is concluded that robustness should be seen as an intermediate sphere between a vulnerability aspect and its opposite notion of stability. The term "robustness state" is introduced to refer to such intermediate spheres. From low to high inclination to follow environmental changes, three robustness states are distinguished: (1) a state of avoiding exposure, (2) a state of inherent resistance, and (3) a state of response

and recovery after being perturbed. Determined efforts to approach or enhance any robustness state are referred to as robustness strategies.
Chapter 3 discusses the relevance of robustness as an image of sustainability. It is argued that robustness has conceptual advantages against sustainability because it is embedded in system thinking and gives direction to operationalisations of sustainable development more than sustainability ever can. This chapter presents a framework against which the robustness conceptualisations of three TransForum projects which were set up to develop the concept of robustness in agricultural innovation are assessed. These projects were:

1. 'Stacking functionality expressed in apple genes'. The aim of this project was the development of high-quality apple varieties that have a durable resistance to apple scab (Venturia inaequalis) by means of cisgenesis;
2. 'A monitoring and control system for conditioning of plants and greenhouses'. The project aimed to quantify physiological effects of climate conditions on plants in energy efficient and energy producing greenhouses, and develop intelligent crop monitoring systems of plant performance;
3. 'Robustness of animal production systems'. The main objective of this project was to develop the concept of robustness of animal production systems at various levels using system and control theory and apply these concepts to cases in the production system (farm), the production chain and at regional level.

It is observed that in these projects, robustness was conceptualised from an engineering perspective in relation to system efficiency and control. Considering the benefits of other conceptualisations it is suggested that these should be taken into account when operationalising sustainable development through robustness. The growing interest in complex (adaptive) systems and alternative system approaches within the agricultural sciences requires a wider scope of robustness thinking.

The dominant engineering approach to robustness in agriculture has unremittingly added complexity to agricultural systems and has steered agricultural production systems towards states of Highly Optimised Tolerance (HOT), susceptible to spiralling complexity to suppress unwanted vulnerabilities and take advantage of opportunities for increased performance. The drawback of optimised tolerance is fragility to unexpected events, and the result of spiralling complexity is a robust, yet fragile system, i.e. high tolerance to anticipated disturbances, combined with extreme fragility to unexpected events. Chapter 4 discusses the potential of Reflexive Interactive Design (RIO) to break through the self-enhancing process of complexity/robustness spiralling, i.e. optimising the production potential of desired outputs, while deliberately integrating resilience and adaptive cycles of co-evolving sub-systems in the production system. Taking the Houden van Hennen (HVH) project as a case, in this chapter the needs of farmer, laying hen and citizen, as compiled by the project team, are categorised in terms of the robustness strategies that are introduced in chapter 2, and their distribution over the social, biological and technological subdomain of the system. The results show that of all needs to cope with potential disturbances, 86% relates to avoiding exposure. Strategies to cope with disturbances were predominantly found in the social-technical sphere, while the vulnerability perception of the laying hen husbandry system in the HvH project concentrated at the animal level. The use of their natural behaviour and adaptive capacities to cope with disturbances seems motivated by system optimisation and purposefully placed under care of the farmer. These results illustrate that designing for robustness in livestock production systems does not break through complexity/robustness spiralling. In other words, livestock production systems tend to develop robustness against well-known stressors. Even though calls for robustness are frequently initiated by an experienced lack of adaptive capacity to new and unexpected developments, solutions are generally found in increased adaptedness to existing stakeholder demands.

An example of a new system vulnerability that arises along the complexity/robustness spiral in husbandry systems is the risk of damaging behaviour that appears to increase with trends to create larger groups and the desire to ban beak trimming and tail docking. In chapter 5 it is argued that the incidence of damaging behaviour is not determined by rearing conditions only, and that selection on individual traits cannot solve problems caused by interactions between animals. Robustness as a breeding goal should therefore relate to performance of the group as whole, rather than to individual performance. The capacity of animals to cope with various perturbations and fluctuations can be influenced at many different levels. Early life experiences and organisation of the environment in which animals are reared, can support their capacity to adapt in later life and contribute to the overall robustness of system.

The general discussion (chapter 6) combines the conceptual analyses and empirical data to consider the relevance of robustness vis-à-vis agricultural sustainability. It is argued that three main approaches to robustness are particularly relevant for agriculture: 1. engineering approaches, focusing on optimisation and maintenance of efficiency of function; 2. biological approaches, focussing on fitness and resistance; and 3. ecology approaches, focusing on recovery and structural persistence. From a sustainability perspective, the engineering approach has value especially in the economic domain, and relevance only when robustness criteria can be quantified. The biological approach has value from a social sustainability perspective. It is accessible to ideological considerations and value judgements. The ecology approach, most notably the amplitude conceptualisation to robustness has value in sustainability studies of social-ecological and social-economic systems and is particularly relevant to study the dynamics of complex adaptive systems. A plea is made for a holistic approach to robustness in agriculture, referring to homoiothermism as an example of holistic robustness. It is argued that robustness is a far more tangible concept than sustainability and that it could function as an image of sustainability. Due to its contested nature, robustness can profit from a fundamentally positive attitude of various stakeholders while simultaneously applying to specific systems and sustainability attributes.

Samenvatting

Met het onderzoek dat in dit proefschrift wordt beschreven beoog ik een bijdrage te leveren aan een beter begrip van de conceptualisering van robuustheid in de landbouwwetenschappen, alsmede de relevantie van dit concept voor duurzaamheid. Robuustheid heeft snel aandacht gekregen als mogelijke oplossing voor uiteenlopende, karakteristieke duurzaamheidsproblemen van de moderne landbouw. Het Nederlandse innovatieprogramma "TransForum", waarbinnen dit onderzoek werd uitgevoerd, bestempelde robuustheid als een belangrijke maatschappelijke waarde, die verder ontwikkeld zou moeten worden in relatie tot innovaties voor duurzame ontwikkeling van de Nederlandse landbouwsector. Echter, de betekenis van het concept robuustheid binnen de landbouwwetenschap is niet eenduidig. In andere wetenschappen wordt de term eveneens losjes gebruikt in verschillende contexten en heeft robuustheid inmiddels uiteenlopende betekenissen gekregen.

Dit project analyseert met een conceptuele benadering hoe robuustheid wordt begrepen en hoe het wordt benaderd binnen verschillende wetenschappen, en stelt daarbij de vraag hoe die benaderingen samenhangen met duurzaamheid. Het empirische deel van het onderzoek richt zich op conceptualisaties van robuustheid in de praktijk. Aan de hand van casussen wordt beschreven welke conceptualisaties worden uitgewerkt in de landbouw. De relevantie van robuuste landbouw ten opzichte van duurzame landbouw wordt bediscussieerd.

In hoofdstuk 2 wordt beargumenteerd dat robuustheid niet zozeer als een uitgesproken systeem eigenschap moet worden gezien, maar eerder als een multi-interpretabele keerzijde van een specifiek kwetsbaarheidsaspect of als een beschrijving van een bepaalde veronderstelling van systeemstabiliteit. Robuustheidsbeweringen hebben slechts betekenis als de kwetsbaarheid van het systeem duidelijk is. Kwetsbaarheid wordt verondersteld te worden gevormd door één of meer kwetsbaarheidsaspecten: blootstelling, gevoeligheid, en gebrek aan herstellingsvermogen. Gevoeligheid en gebrek aan herstellingsvermogen zijn systeemeigenschappen die zich openbaren als een systeem wordt blootgesteld aan een storing, terwijl blootstelling betrekking heeft op de duur, de grootte en de mate waarin een systeem storingen moet ondergaan. Als keerzijde van kwetsbaarheid kan robuustheid op dezelfde wijze worden beschouwd: als systeemeigenschap die de capaciteit beschrijft om met eventuele storingen om te kunnen gaan, of als een relationele eigenschap van systeem en omgeving samen, refererend aan de capaciteit blootstelling te vermijden en verstoringen op afstand te houden. In hoeverre we een systeem robuust vinden hangt vooral af van de structurele of functionele impact die een storing op het systeem zou kunnen hebben. Van hoge naar lage impact worden de volgende storingsresultaten onderscheiden (hoofdstuk 2):

1. Blijvend verlies van structuur en functie;
2. Blijvende verandering van structuur en/of functie (adaptatie);
3. Tijdelijk verlies van structuur en/of functie (herstel);
4. Behoud van structuur en functie (resistentie);
5. Geen blootstelling (vermijden)

Gesteld wordt dat robuustheid bestaat in een sfeer die is gelegen tussen een kwetsbaarheidsaspect en de daar tegenovergestelde veronderstelling van stabiliteit. De term ‘robuustheidstoestand’ wordt geïntroduceerd om zulke tussengelegen sferen aan te duiden. Van lage naar hoge geneigdheid om omgevingsveranderingen te volgen, worden drie robuustheidstoestanden onderscheiden: (1) een toestand van vermijden van blootstelling, (2) een toestand van inherente resistentie, en (3) een toestand van respons en herstel na verstoring. Doelbewuste pogingen om robuustheidstoestanden te benaderen of te versterken worden aangeduid als robuustheidstrategieën.

Hoofdstuk 3 beschrijft de relevantie van robuustheid als een beeld van duurzaamheid. Gesteld wordt dat robuustheid conceptuele voordelen heeft ten opzicht van duurzaamheid, omdat het is verankerd in systeemdenken en meer richting kan geven aan duurzame ontwikkeling dan duurzaamheid zelf ooit zou kunnen. In dit hoofdstuk wordt een kader gepresenteerd op basis waarvan conceptualisaties van robuustheid in drie TransForum projecten, opgezet om het concept robuustheid verder te ontwikkelen, worden beoordeeld. Deze projecten zijn:

1. ‘Stapeling van genen voor duurzame resistentie tegen appelschurft’. De doelstelling van dit project was het ontwikkelen van hoogwaardige appel variëteiten met duurzame resistentie tegen appelschurft (*Venturia inaequalis*) door middel van cisgenese;
2. ‘SynErgie: Gewas van de toekomst in de kas van de toekomst’. Dit project beoogde de fysiologische effecten van klimaatcondities op planten in energie zuinige en energie producerende kassen te kwantificeren, en intelligente gewasmonitoringsystemen voor groeiprestaties te ontwikkelen;
3. ‘Robuustheid bij dierlijke productiesystemen’. Het hoofddoel van dit project was de uitwerking van het concept robuustheid in dierlijke productie systemen op verschillende niveaus met behulp van systeemtheorie en meet- en regeltechniek, en het toepassen van deze concepten op bedrijfsniveau, op het niveau van de productieketen en op regionaal niveau.

Geconstateerd wordt dat het beeld van robuustheid in deze projecten wordt gevormd vanuit een technisch perspectief en in relatie tot systeem efficiëntie en meet- en regeltechniek. Gesuggereerd wordt dat bij de uitwerking van duurzame ontwikkeling door middel van robuustheid méér rekening gehouden moet worden met alternatieve ideeën van robuustheid en hun toegevoegde waarde. De groeiende interesse in complexe (adaptieve) systemen en alternatieve systeembenaderingen binnen de landbouwwetenschappen vraagt om een breder gezichtsveld binnen het robuustheid denken.

De dominante technische benadering van robuustheid binnen de landbouw heeft onverminderd complexiteit toegevoegd aan landbouwsystemen en heeft deze gestuurd in de richting van toestanden van Hooglijk geOptimaliseerde Tolerantie (HOT), vatbaar voor een opwaartse spiraal van complexiteit om ongewenste storingen te kunnen onderdrukken en in te kunnen springen op mogelijkheden voor verdere resultaatverbetering. De schaduwzijde van geoptimaliseerde tolerantie is kwetsbaarheid bij onverwachte storingen, en het resultaat van een opwaartse complexiteitspiraal is een robuust, doch kwetsbaar systeem: een systeem dat uitzonderlijk hoge tolerantie tegen verwachte storingen combineert met een extreme kwetsbaarheid bij onverwachte gebeurtenissen.

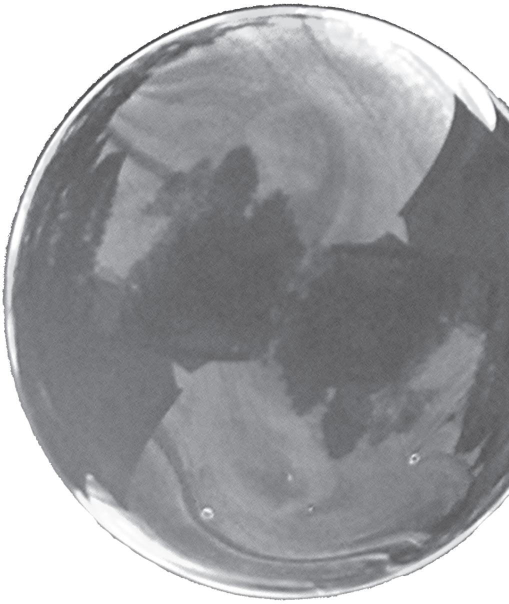
Hoofdstuk 4 beschrijft de potentie van Reflexief Interactief Ontwerp (RIO) om de zichzelf versterkende spiraal van complexiteit/robuustheid te doorbreken, ofwel het productiepotentieel te optimaliseren door bewust veerkracht en adaptatierondes van mee-evoluerende subsystemen te integreren in het totale productiesysteem. In dit hoofdstuk wordt het Houden van Hennen (HvH) project als casus gebruikt om de behoeften van boer, leghen en burger, zoals die door het projectteam zijn verzameld, te categoriseren volgens de robuustheidstrategieën die in hoofdstuk 2 zijn geïntroduceerd, waarbij tevens wordt bepaald of deze behoefte betrekking heeft op het sociale, biologische, dan wel technologische sub domein van het houderijsysteem. De resultaten laten zien dat van alle behoeften die gerelateerd zijn aan het kunnen omgaan met eventuele stroringen, 86% betrekking heeft op het vermijden van blootstelling. Strategieën voor het kunnen omgaan met storingen worden vooral benoemd in het sociaal-technische sub domein, terwijl de kwetsbaarheid van het houderijsysteem in het HvH project vooral wordt ervaren op dierniveau. Het gebruik van het natuurlijk gedrag van de hennen en hun aanpassingsvermogen om met storingen om te kunnen gaan lijkt gemotiveerd door optimalisatie van het systeem en wordt doelbewust onder de zorg van de boer geplaatst. Deze resultaten laten zien dat ontwerpen voor robuustheid in dierhouderijsystemen niet door de zichzelf versterkende spiraal van complexiteit/robuustheid breekt. Met andere woorden, veehouderijsystemen neigen ernaar robuustheid te ontwikkelen tegen algemeen bekende storende factoren. Hoewel de oproep voor meer robuustheid vaak wordt ingegeven door een gevoel dat systemen over onvoldoende vermogen beschikken zich aan te passen aan nieuwe en onverwachte ontwikkelingen, worden oplossingen over het algemeen gevonden in het versterken van de aangepastheid aan bestaande eisen van belanghebbenden.

Een voorbeeld van een nieuwe systeemkwetsbaarheid die zich openbaart naarmate de complexiteit van dierhouderijsystemen toeneemt is het gevaar van beschadigend gedrag, dat lijkt toe te nemen met trends om dieren in grotere groepen te houden en de wens snavelknippen en couperen uit te bannen. In hoofdstuk 5 wordt beargumenteerd dat het optreden van beschadigend gedrag niet alleen wordt bepaald door de fokcondities, en dat selectie op individuele eigenschappen geen oplossing biedt voor de problemen die optreden bij dierinteracties. Als fokdoel zou robuustheid daarom niet zozeer betrekking moeten hebben om individuele prestaties, maar meer op prestaties van de groep als geheel. Het vermogen van dieren om met storingen om te gaan kan op verschillende niveaus worden beïnvloed. Ervaringen op jonge leeftijd en organisatie van de omgeving waarin dieren worden gehouden kunnen bijdragen aan versterking van het aanpassingsvermogen op latere leeftijd en de totale robuustheid van het systeem verhogen.
Hoofdstuk 6 combineert de conceptuele analyses en empirische data in een algemene

discussie van de relevantie van robuustheid ten opzichte van duurzame landbouw. Gesteld wordt dat in het bijzonder drie hoofdbenaderingen van robuustheid relevant zijn voor de landbouw: 1. Technische benaderingen, die zich richten op optimalisatie en behoud van functionele efficiëntie; 2. Biologische benaderingen, die zich richten op conditie en weerstandsvermogen; en; 3. Ecologische benaderingen, die zich richten op herstellend vermogen en behoud van structuur.

Uit het oogpunt van duurzaamheid hebben de technische benaderingen vooral waarde in het economische domein, en relevantie wanneer robuustheid criteria kwantificeerbaar zijn. De biologische benaderingen zijn waardevol vanuit een sociaal duurzaamheidsperspectief. Ze zijn toegankelijk voor ideologische overwegingen en waardeoordelen. De ecologische benaderingen, met name de amplitude conceptualisering van robuustheid, zijn waardevol in duurzaamheidsstudies van sociaal-economische systemen en zijn vooral van belang bij de bestudering van dynamieken van complex adaptieve systemen.

Hoofdstuk 6 is ook een pleidooi voor een holistisch benadering van robuustheid binnen de landbouw. Daarbij wordt gerefereerd aan homoiothermisme, ofwel warmbloedigheid, als voorbeeld van holistische robuustheid. Beargumenteerd wordt dat robuustheid een veel tastbaarder begrip is dan duurzaamheid en dat het kan functioneren als beeld van duurzaamheid. Vanwege de wezenlijk betwistbare betekenis van het begrip kan robuustheid rekenen op een fundamenteel positieve benadering van verschillende belanghebbenden, terwijl het gelijktijdig van toepassing kan zijn op heel specifieke systemen en duurzaamheidkenmerken.



Appendices

Appendix 1. Robustness definitions in Engineering, Biology and Social-Ecological applications

Engineering applications

Author(s)	Definition of robustness	Field of interest
Allen et al. (2006)	A product or process that can be exposed to variations without suffering unacceptable performance degradation.	engineering, optimisation
Allen et al. (2006), Taguchi (1986), Taguchi and Clausing (1990)	A method to improve the quality of products and processes by reducing their sensitivity to variations, thereby reducing the effects of variability without removing its sources.	engineering, optimisation
Asbjornslett and Rausand (1999)	A system's ability to resist an accidental event and return to do its intended mission and retain the same stable situation as it had before the accidental event	systems engineering
Carlson and Doyle (2002) Csete and Doyle (2002)	The maintenance of some desired system characteristics despite fluctuations in the behaviour of its component parts or its environment.	Biotechnology
Clausing and Frey (2005)	The ability of a system to avoid failure under the full range of conditions that may be experienced in the field	engineering, robust design
Forrest et al. in Jen (2005), definition by Jen	Protection against what may be inherently unforeseeable	software engineering
Hansson & Helgesson (2003)	The tendency of a system to remain unchanged, or nearly unchanged when exposed to a disturbance	strain resistance, structural stability, resistance
Hansson and Helgesson (2003)	A limiting case of resilience	stability, resilience
Jen (2005)	The reliability of function in the presence of failures with estimable probabilities and supports	systems engineering
Jugulum and Frey (2007)	A set of engineering methods for attaining high-quality function despite variations due to manufacturing, the environment, detorioration and consumer use patterns	engineering
McManus and Hastings (2006)	Ability of the system to do its basic job in unexpectedly adverse environments	systems engineering
Mens et al. (2011)	The ability to remain functioning under a wide range of disturbance magnitudes	flood risk management

Taguchi et al.(1999)	a state where technology, product and process are minimally sensitive to variation caused by faults	Robust design, systems engineering
Ten Napel et al. (2006)	Ability to switch between underlying processes to maintain the balance (narrow sense)	animal husbandry
Ten Napel et al. (2006)	Minimal variation in a target feature following a disturbance, regardless of whether it is due to switching between underlying processes, insensitivity or quickly regaining the balance (broad sense).	animal husbandry
Ten Napel and Groot Koerkamp (2010)	The ability to maintain sustainability in the presence of disturbances	animal husbandry
Van der Weijden and Schrijver (2004)	Resistance to environmental changes, most notably to infection risk.	Animal husbandry
Walker et al. (2005)	Make a function or process that needs to be controlled robust to uncertainty in model parameters.	Control
Willinger, W & J. Doyle (2005)	Resilient to designed-for uncertainties in the environment or individual components	software engineering

Biology applications

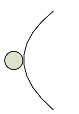
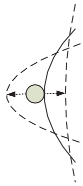
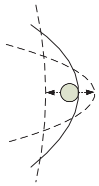
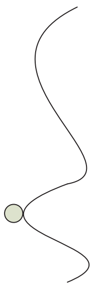
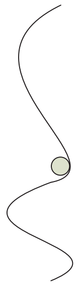
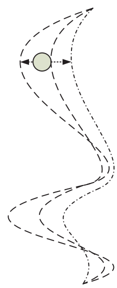
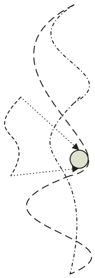
Author	Definition of robustness	Field of interest
Berry et al. (2009)	The ability of the animal to remain close to nutritional homeostasis, i.e to minimise the extent and duration of negative energy balance	animal breeding, dairy farming
Darnhofer et al. (2010b)	Yield stability across a wide range of temperature, nutrient and water conditions	agronomy
De Visser et al. (2003)	Any kind of buffering against nonheritable perturbations (= environmental robustness); the constancy of phenotyopes in the face of heritable perturbations (= genetic robustness)	genetics
De Vries and Cole (2009)	Less variation in production when the environment changes. It usually follows that a robust cow performs less well in an optimal environment, but better under challenging conditions such as heat stress	animal breeding, dairy farming
Felix and Wagner (2006)	The persistence of an organismal trait under perturbations	evolutionary biology
Hermisson and Wagner (2005)	A state of reduced impact from a given source of variation (such as mutations or environmental change) on the trait	genetics
Jen (2005)	The ability of certain metalbolic and regulatory processes to perform correctly within a large range of parameters.	cell biology
Jen (2005)	The ability of developmental processes to stay on track in the presence of perturbations such as environmental insult or developmental noise or knockout mutations.	developmental biology
Kanis et al. (2005)	A trait related to animal welfare and animal health that gives pigs the capability to adapt succesfully to changing environmental management and health conditions, thereby better tolerating those conditions	Animal welfare, health
Kitano (2004)	A fundamental feature of evolvable complex systems	genetics
Kitano (2004)	The maintenance of specific functionalities of the system against perturbations, and it often requires the system to change its mode of operation in a flexible way.	genetics

Kitano (2007)	A general concept according to which a system is robust as long as it maintains functionality, even if it transits through a new steady state or if instability actually helps the system to cope with perturbations	systems biology
Knap (2005)	Combin[ation of] high production potential with resilience to external stressors, allowing for unproblematic expression of high production potential in a wide variety of environmental conditions	animal breeding
LNV (2007a)	A collection of features that keep an animal physically and mentally healthy. A robust animal can better adjust or offer resistance to changes in its environment or diseases.	Animal welfare, health
LNV (2007b)	Increased protection against typical animal health problems and higher efficacy of vaccination	Animal welfare, health
Star et al. (2008)	An animal under a normal physical condition that has the potential to keep functioning and take short periods to recover under varying environmental conditions.	animal breeding
Stelling et al. (2004)	The ability to maintain performance in the face of perturbations and uncertainty	cell biology
Ten Napel et al. (2009)	The ability to maintain homeostasis in commonly accepted and sustainable dairy herds of the future	animal breeding, dairy farming
Ten Napel et al. (2011)	Resistance (= passive robustness); flexibility (= active robustness)	animal husbandry

Social-Ecological applications

Author	Definition of robustness	Field of interest
Anderies et al. (2004)	A SES is robust if it prevents the ecological systems upon which it relies from moving into a new domain of attraction that cannot support a human population, or that will induce a transition that causes long-term suffering.	social-ecological system management
Gallopin (2006)	The capacity to maintain structure	social-ecological system management
Gunderson & Holling (2001), definition by Jen (2005)	Similar to ecological resilience, namely the capacity of a system to undergo disturbance and still maintain its functions and controls	social-ecological system management
Leeson and Subrick (2006)	Refers to a political economic arrangement's ability to produce social welfare-enhancing outcomes in the face of deviations from ideal assumptions about individual's motivations and information	political economic system
Levin and Lubchenco (2008)	The capacity of a system to absorb stresses and continue functioning	ecosystem management
Lien (2007)	The effects on the economic sustainability and risk efficiency of the system to a shock, represented by total crop failures in one of the 6 years in the planning period	social-economic systems
Roy (2010)	A capacity for withstanding " vague approximations" and/or "zones of ignorance" in order to prevent undesirable impacts, notably the degradation of the properties to be maintained	operational research
Roy (2010)	Is related to a process that corresponds to a concern: the need for a capacity for resistance or self-protection	operational research
Walker et al. (2005)	Robustness is not an intrinsic property of a system, but rather is highly contrived. That is, we want a very specific solution to be robust to a very well known set of uncertainties for a fairly well understood system	ecosystem management
Webb and Levin (2005)	The ability of the system to maintain its macroscopic functional features, such as species diversity or nutrient cycling, rather than the narrower and unattainable possibility of constancy	ecosystem management

Appendix 2: a framework of robustness, consisting of three organising principles.

	STATIC ENVIRONMENT		DYNAMIC ENVIRONMENT	
	Control	Adaptation	Control	Adaptation
Efficiency of function	 **Reliability** Fault tolerance Failure mode avoidance E.g. Taguchi, 1995; Clausing 2004; Clausing and Frey, 2005; Kato, 2007; Kamoshita, 2008	 **Elasticity** Engineering resilience Fail-safe design Homeostatic control systems E.g. Pimm, 1984; Kamoshita, 2004; Sowinski, 2005; Ten Napel et al., 2006	 **Insensitivity** Generalists Selective breeding Genetic modification E.g. Kanis, 2004; Knap, 2005; LNV, 2007; Star, 2008; Kitano, 2007; Pryce, 2009.	 **Invariance** Canalization Phenotypic robustness Mutational robustness E.g. Waddington, 1953; Scharloo, 1991; De Visser et al., 2003; Hermisson and Wagner, 2005
Persistence of functionality	 **Continuity** Inherent resistance Conservation E.g. Lamont, 2006; LNV, 1990	 **Amplitude** Ecological resilience Cyclical change E.g. Holling, 1986; Scheffer, 1998	 **Applicability** Biological robustness Planning under uncertainty Design for changeability E.g. Carlson and Doyle, 1999; Kitano, 2004, 2007; (Rosenhead, 1980; Best *et al.*, 1986; Driouchi *et al.*, 2009	 **Evolvability** Social-ecological resilience Developmental robustness Panarchy E.g. Levin, 1999; Gunderson and Holling, 2002; Walker et al., 2005; Keller, 2002

Appendix 3 Classification of demands of the Houden van Hennen Project

LAYING HEN

Need	Code	optimisation	avoid	resist	recover	other	Description of demand
		Relation					
Experience freedom, fresh air and elements like sun, water, earth and wind	Lo1					X	Being outside
fresh air to live in	lo2		X				MAC[1] dust particles in the air
	Lo3		X				MAC respiratory dust in the air
	Lo4	X					Optimal humidity level
	Lo5	X					Optimal concentration of O_2 in the air
	Lo6		X				MAC NH_3 in the air to prevent aversive behaviour
	Lo7		X				MAC CO_2 in the air
	Lo8		X				MAC SO_2 in the air
	Lo9		X				MAC H_2S in the air
	Lo10		X				MAC CO in the air
	Lo11		X				Ventilation to prevent heat stress
	Lo12		X				Ventilation to prevent heat stress
Adequate ambient living temperature for the laying hen	Lo13	X					Optimised feed efficiency in thermoneutral zone
Presence of light and an optimal light quality to perform ethological needs	Lo14		X				Avoid production of stress hormone corticosteron
	Lo15		X				Avoid averseness
	Lo16					X	Allow social recognition
	Lo17		X				Avoid fear during egg laying
	Lo18					X	Improve welfare during resting
	Lo19	X					Optimise foraging behaviour
	Lo20					X	Allow sunbathing and dust bathing

[1] *MAC: Maximum Acceptable Concentration;*

Day- and night rhythm	Lo21		X				Avoid abberant sleeping behaviour, eye handicaps, blindness
Noise	Lo22		X				Avoid noise stress
Orientation possibilities	Lo23					X	Allow proper orientation towards sun
	Lo24					X	Provide recognition points
	Lo25					X	Sufficient and adequate foraging space
	Lo26					X	Sufficient space for scraping
	Lo27					X	Adequate substrate for foraging
	Lo28					X	Quality of litter to scrape
saturation of hunger- and thirst feelings	LZ1	X					Optimal food composition
	LZ2		X				Avoid feather pecking
	LZ3		X				Avoid feather pecking
	LZ4	X					Optimise food distribution
	LZ5					X	EU standard space for food intake
	LZ6	X					Optimum water composition
	LZ7					X	Water supply
	LZ8	X					Optimise water distribution
	LZ9					X	EU standard space for water intake
To forage	LZ10					X	Sufficient foraging space
	LZ11					X	Forage substrate quality
Health (good functioning without suffering)	LG1		X				Exposure to germs of diseases
	LG2			X			Promote natural resistance
	LG3		X				Feather pecking, stress
Health improving living environment	LG4	X					Optimise living environment to improve health
movement possibilities	LB1					X	Sufficient space to flutter
	LB2					X	Sufficient space for turning
	LB3					X	Sufficient space to foraging

	LB4					X	Sufficient space for preening, wing stretching, leg stretching, bodyshaking, wingflapping
	LB5					X	Sufficient space for dustbathing
	LB6					X	Sufficient space for sunbathing
	LB7					X	Quality substrate for dustbathing
	LB8					X	Access to direct sunlight to facilitate sunbathing
Presence of conspecifics	LS1		X				Optimum group size to minimise feather pecking and aggression
Choice in distance to conspecifics	LS2		X				Sufficient space for social distance to avoid feather pecking and aggression
Possibilities of synchronizing behaviour	LS3					X	Sufficient space for synchronising
Performing sexual behaviour?	LS4					X	Unclear whether this is a real need of the laying hen
Performing of resting- and sleeping behaviour	LR1					X	Sufficient resting space
	LR2					X	Standing space per hen
	LR3	X					High situated sitting space
	LR4	X					Design criterion location of resting places
	LR5		X				Design of perch should avoid injuries and infections
	LR6		X				abberant sleeping behaviour, eye handicaps, blindness
Safety to flee	LV1					X	sufficient fleeing space
Hiding	LV2					X	Presence and amount of roosters per flock
	LV3					X	Presence and amount of hiding opportunities per flock
	LV4					X	Dimension of hiding-places
	LV5					X	Location of hiding-places
Performance of nesting behaviour and egg laying	LE1					X	Space for nesting behaviour per hen
	LE2					X	Design criterion laying nests
	LE3					X	Attractiveness of laying nests
	LE4					X	Approachableness laying nests
	LE5					X	Shelter and security in laying nest
	LE6		X				Avoid fear during egg laying
	LE7					X	Quality nesting material

FARMER

Need	Code	optimisation	avoid	resist	recover	other	Description of demand
		Relation					
Continuity of management	PO1	X					Business development: increasing scale
	PO2	X					Business development: specialisation
	PO3	X					Business development: diversification
product consistency	PO4					X	Meet quality demands
	PO5					X	Meet demands for food safety
	PO6	X					Be competitive with similar companies
	PO7					X	Availability of labour, market and raw products
	PO8					X	Earning capacity
	PO9					X	Quick depreciation of the system
	PO10					X	Meet demands of the IKB (tracking and tracing)
	PO11					X	Reliable and consistent rules (EU, NL, WTO)
	PO12					X	Commitment with turnover
	PO13				X		Flexibility in the husbandry system
income	PO14					X	Above average
	PO15					X	Sufficient to provide family with necessaries of life
profit	PO16					X	% of family income
Minimum amount of labour	PO17	X					Quantity of labour per egg or kg product
Producing as much as possible eggs	PO18	X					Minimum egg production per chicken / year
Entrepeneurship, way of living and acknowledgement	PO19					X	Innovation, operational management
	PO20					X	Skilled labour
	PO21					X	Entrepreneurship
	PO22					X	Reliability / chain responsibility

	PO23					X	Animal friendliness
	PO24					X	Openness / transparency of the husbandry system
	PO25					X	Collaboration
	PO26					X	Communicate / information
	PO27					X	Reasonable production
To produce undisturbed and manageable	PO28	X					Maximum number of floor eggs
	PO29		X				Absence of canabalism and feather pecking
Keeping productive laying hens alive	PO30		X				Hygienic animal house to exclude infections
	PO31		X				Exclude bacterium diseases
	PO32		X				Exclude virus diseases
	PO33		X				Exclude mold diseases
	PO34		X				Exclude parasitical diseases
	PO35	X					Suitable conditions for breeding and egg laying period
	PO36					X	Sufficient locomotion space
	PO37		X				Avoid feather pecking
	PO38		X				MAC germs of disease in water
	PO39		X				MAC solid particles in air
	PO40					X	Water supply
	PO41	X					Optimum water quantity
	PO42	X					Optimum water temperature
	PO43	X					Optimum water/food proportion
Sufficient resources to keep animals healthy in legal manner	PO44					X	
optimal housing climate for the productive laying hen	PO45	X					Exact environment temperature on each moment of the day on specific places
	PO46	X					Exact light intensity on each moment of the day on specific places
	PO47	X					Optimal humidity
	PO48	X					Minimum ventilation
	PO49	X					Maximum ventilation
	PO50	X					Exact air movement pattern
	PO51	X					Facilities regarding air outlet

As much as possible first quality eggs	PO52	X					Maximum acceptable amount of dust in the air
	PO53	X					Acceptable % second quality eggs
	PO54	X					Minimum % first quality eggs
	PO55		X				Exclude New Castle Disease
	PO56		X				Exclude infectious bronchitis
	PO57		X				Exclude egg drop syndrome
Disposal of the remaining material	PO58					X	Amount of manure
	PO59					X	Storage capacity for manure
	PO60					X	Amount of water
	PO61					X	Amount of air
To produce eggs	PO62	X					Minimum egg production
Socially justified animal keeping	PD1					X	Meet demands for animal welfare and environment
Act responsibly	PD2					X	
Transparency	PD3					X	Evidence of production laying hen
Farmer dignified animal keeping	PD4					X	Develop and maintain self-respect as animal keeper
Contact between animal and human	PD5					X	Contact possibilities
Working with animals, experience animals	PD6					X	
Be in contact with the nature of the animal	PD7					X	Interest and notion in character of the animal
Be part of nature	PD8					X	Presence of nature; to choose immaterial matter above material matters; natural habitat
Keep animals healthy	PD9					X	Animal health
Taking care of animals	PD10					X	Foresee in basic needs of the animal
Protect animals against harmful influences	PD11		X				Physical environment that offers protection
Offer animals possibilities to perform protective behaviour patterns	PD12	X					
Secure income	PA1	X					Wages above average
Generate farmer's satisfaction	PA2					X	Appreciation for accomplished work
	PA3					X	Visualise labour results

Produce undisturbed and manageable	PA4		X				Guard against disturbances in the laying hen system
	PA5	X					Avoid unnecessary labour
Job security in long term	PA6					X	operational management
Job delight and working convenience	PA7					X	Labour
	PA8					X	Suitable housing climate
	PA9					X	Interaction human / chicken
	PA10					X	Healthy chicken
	PA11		X				Maximum % ground eggs
	PA12					X	Clean eggs
	PA13	X					Optimised technical system
	PA14					X	Plannable working times
	PA15					X	Variation and diversity
Social contact	PA16					X	Contact with colleagues and other parties involved
Social freedom	PA17				X		Space to leave the farm without something going wrong
efficient working environment	PA18					X	Ergonomic work space and access
	PA19					X	Good lighting
	PA20					X	Make thermo comfort possible
Safe work environment	PA21	X					To have overview
	PA22			X			Construction does not collapse during calamities
	PA23					X	Safe machinery, equipment and passage
	PA24		X				Offer protection against the chickens
	PA25		X				Offer protection against noise
	PA26		X				Offer protection against tremors
	PA27		X				Prevent too much bending over and lifting of too heavy loads
Health	PA28		X				Offer protection against germs of diseases
Protection against too much dust	PA29		X				MAC total dust particles
	PA30		X				MAC respiratory dust

	PA31		X				MAC endotoxines
Protection against ammonia and other gasses and vapours	PA32		X				MAC NH_3 in air
	PA33		X				MAC CH_4 in air
	PA34		X				MAC CO in air
	PA35		X				MAC CO_2 in air
	PA36		X				MAC H_2S in air
	PA37		X				MAC NO_2 in air

CITIZEN

		Relation					
Need	**Code**	**optimisation**	**avoid**	**resist**	**recover**	**other**	**Description of demand**
Spatial classification	B1	X					Fresh air, no draft
	B2					X	Openings, windows
	B3					X	Transparent materials
	B4					X	View
	B5				X		Seek shelter against rain
freedom of movement	B6					X	Free access to outside facilities
	B7					X	Wide walking paths
Friendly appearance	B8					X	Round, friendly, organic shapes
	B9					X	Splashing water
	B10					X	From the outside recognisable egg or chicken shapes
	B11					X	Elements from the ‘farm in earlier times’
	B12					X	Shed shapes
	B13					X	Clean, but not sterile
	B14					X	Warm, soft and fresh shapes, colours sounds, smells and materials

Nature within the living environment	B15					X	Natural elements in the husbandry system
	B16		X				Day / night rhythm to avoid abberant sleeping behaviour, eye handicaps, blindness
Natural order	B17					X	Presence of rooster or alpha-hen
Natural resistance	B18			X			Rear hens that are adapted to the new husbandry system (robust hens)
	B19			X			stress resistance
Social structure within the flock	B20				X		Self-organising social structure
Species specific behaviour	B21					X	Possibilities for foraging
Various places for specific activities	B22					X	Provide feeding area, foraging area, sleeping area and playing area
Facilities	B23					X	Well working facilities
	B24	X					Well placed facilities
	B25					X	In- and outside areas
Diversity	B26					X	Different species of chickens
	B27					X	Presence of other animal species
	B28					X	Presence of other living elements (plants)
Need of citizen himself:	B29						
Transparency	B30					X	Understanding the management
	B31					X	Visibility of the chicken
	B32					X	Understanding the chicken activities

CONSUMER

Need	Code	Relation: optimisation	avoid	resist	recover	other	Description of demand
Correct egg yolk	C1	X					egg quality: colour
Good quality of the egg white	C2	X					egg quality: thickness of the egg white
	C3	X					Transparency
Correct dimension of air chamber	C4	X					Maximum size
Nice smell	C5	X					egg quality: smell
Quality of the egg shell	C6	X					egg quality: colour
	C7					X	Intact eggs
	C8			X			Firmness of the egg
	C9		X				Avoid contamination
	C10		X				Avoid blood or meat spots
	C11		X				Avoid nest rolling tracks
Clean egg	C12	X					Cleanness geared to consumer demands
	C13	X					Cleanness geared to consumer demands
Nice shape	C14	X					egg quality: shape
Nice size	C15	X					egg quality: large size
Uniformity	C16	X					Uniformity geared to consumer demands
Freshness	C17	X					egg quality: preservability
Egg pealability	C18	X					egg quality: good pealability
Safe egg	C19		X				food safety: avoid Dioxins
	C20		X				food safety: avoid Lasalocid (potential need)
	C21		X				food safety: avoid Nitrophen (potential need)
	C22		X				food safety: avoid Flumequine (potential need)
	C23		X				food safety: avoid Caffein (potential need)
	C24		X				food safety: avoid Salmonella enteritidis

	C25		X				food safety: avoid Salmonella typhimurium (potential need)
	C26		X				food safety: avoid residuals of medicines (potential need)
Adequate packaging	C27					X	Type of box geared to consumer demands
	C28					X	Number of eggs per box geared to consumer demands
	C29					X	Colour of package geared to consumer demands
	C30					X	Visibility of the eggs geared to consumer demands
Label	C31					X	Layout geared to consumer demands
	C32					X	Colour geared to consumer demands
	C33					X	Information geared to consumer demands
Good price	C34					X	Price geared to consumer demands
Health	C35	X					egg quality: natural high quality food source
Taste	C36	X					Egg quality: taste

NEED OF THE LAYING HEN ACCORDING TO DIFFERENT TYES OF CITIZENS

COSMOPOLITANS

		Relation					
Need	**Code**	**optimisation**	**avoid**	**resist**	**recover**	**other**	**Description of demand**
Dynamic	K1					X	Allow variation in activities
	K2					X	Provide possibilities to rest
	K3					X	Provide possibilities for activities being performed on each moment of the day
Privacy	K4					X	Provide possibilities for protection
	K5					X	Individual laying nests
	K6					X	Provide protected places to be alone
Individuality	K7					X	Allow species specific behaviour
	K8					X	Allow choice in activities
Wellness	K9			X			Healthy, strong and fit animals

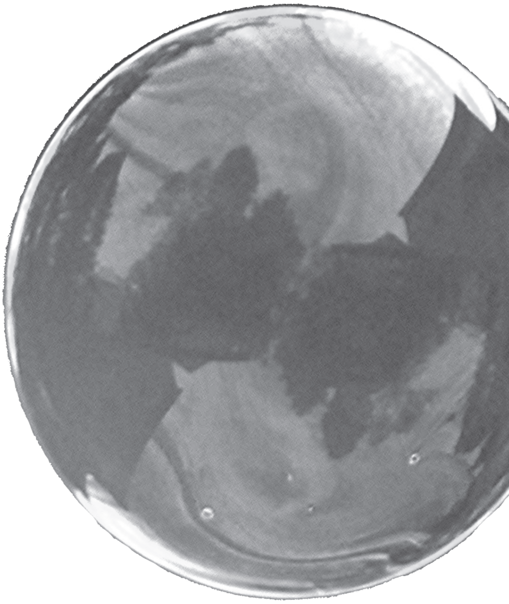
POST-MATERIALISTS

		Relation					
Need	**Code**	**optimisation**	**avoid**	**resist**	**recover**	**other**	**Description of demand**
Natural environment	P1					X	Contact with natural elements
	P2					X	Contact with (running) water
	P3					X	Contact with (natural) light

Need	Code	optimisation	avoid	resist	recover	other	Description of demand
Natural food	P4					X	Provide varied food with living elements, e.g. insects
Relative context	P5					X	Synergy between different components
Freedom	P6					X	Allow hen to go outside
	P7					X	Provide possibility to choose where to be
Natural principles and mechanisms	P8		X				Minimise human presence
	P9		X				Minimise human interference

TRADITIONAL CITIZENRY

		Relation					
Need	**Code**	**optimisation**	**avoid**	**resist**	**recover**	**other**	**Description of demand**
Care and attention for the animals	T1					X	Provide healthy food
	T2		X				Avoid stress
	T3		X				Avoid illness and/or unhappiness
Respectful treatment of animals	T4					X	Maintain integrity of the laying hen
	T5					X	Good methods for slaughtering
	T6		X				Minimise duration of transport (stress)
	T7					X	No cruelty
	T8					X	No grow hormones
'Back to earlier times'	T9					X	Provide free roaming possibility
	T10					X	Design with elements of farm in earlier days
	T11			X			Solid design of the building



About the author

Curriculum Vitae

Douwe Martijn de Goede was born in Amsterdam on March 10th 1977. He holds an MSc in Forestry and Nature Conservation with a minor in Philosophy from Wageningen University (2002) and an MA in Applied Ethics from Utrecht University (2006). In 2003 Douwe started to work as a project employee at Recreatie Noord-Holland NV, an independent implementing agency for development, management and exploitation of recreational provisions. From 2006 till 2008 he worked at Dienst Regelingen, an implementing agency of the former Dutch ministry of Agriculture, Nature and Food Quality. In 2008 Douwe started as a PhD candidate at the Centre for Methodical Ethics and Technology Assessment (META), since 2013 part of the Communication, Philosophy, and Technology (CPT) group of Wageningen University. From 2009 he combined his PhD with Academic Consultancy Coaching. Douwe lives in Geldermalsen with his wife and two children.

Publications

Journal papers

De Goede, D.M., B. Gremmen, T.B. Rodenburg, J. E. Bolhuis, P. Bijma, M. Scholten en B. Kemp, 2013. Reducing damaging behaviour in robust livestock farming, NJAS - Wageningen Journal of Life Sciences, Volume 66, p49-53;

De Goede, D.M., B. Gremmen en M. Blom Zandstra, 2013. Robust agriculture: Balancing between vulnerability and stability. NJAS – Wageningen Journal of life sciences, Volume 64-65, p1-7;

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Nabuurs, G.J., D.M. de Goede, B. Michie, M.J. Schelhaas, J.G. Wesseling, 2002. Long-term international impacts of nature-oriented forest management on European forests – An assessment with the EFISCEN model. Journal of World Forest resource Management 9(2): p101-129;

Nabuurs, M.J. Schelhaas; D.M. de Goede, 2001. Internationale gevolgen van geïntegreerd bosbeheer in Nederland; verwaarloost Nederland de rol van bos als natuurlijke hulpbron? Ned. Bosbouwtijdschr. 73 (5): p29-32.

Other publications

De Goede, D.M., J. Erens, E. Kapsomenou en M. Peters, 2013. Large scale insect rearing and animal welfare In: H. Röcklingsberg and P. Sandin: The Ethics of Consumption, the citizen, the market and the law. Wageningen Academic Publishers, p236-242

De Goede, D.M., B. Gremmen en M. Blom Zandstra, 2012. Adaptive capacities from an animal welfare perspective. In: Thomas Potthast and Simon Meisch (eds.); Climate change and sustainable development, Ethical perspectives on land use and food production. Wageningen Academic Publishers, p187-192.

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Clerkx, A.P.P.M., D.M. de Goede, M.E. Sanders, 2003. Bosdynamiek in bosreservaat Zeesserveld. Wageningen, Alterra, Research Instituut voor de Groene Ruimte, Alterra-rapport 668

Douwe de Goede

Wageningen School of Social Sciences (WASS)

Completed Training and Supervision Plan

Name of the learning activity	Department/Institute	Year	ECTS*
A) Project related competences			
Field Research Methods: Methods and Tools for Qualitative Data Analysis	Wageningen School of Social Sciences (WASS)	2008	2,3
WTMC Summer School 'A critical theory of technology'	Netherlands Graduate Research School of Science, Technology and Modern Culture (WTMC)	2008	4,2
The concept of nature and its cognates in social and natural sciences and humanities	Dutch-Flemish network for Philosophy of Science and Technology (NFWT)	2009	2,0
Innovation for Sustainability: Bridging theory into practice	TransForum and Graduate School Production Ecology & Resource Conservation (PE&RC)	2010	3,0
Investigating Technology	WASS	2011	4,0
Workshop Navigating Complex Socio-Environmental Processes	PE&RC	2011	0,3
'Robust Animal Production, Between Highly Optimised Tolerance and Complex Adaptive System Views'	WASS PhD day	2011	1,0
'Adaptive Capacities from an Animal Welfare Perspective'	10th Congress of the European Society for Agriculture and food Ethics (Eursafe), Tübingen	2012	1,0
B) General research related competences			
Introduction course	WASS	2008	1,5
Finalising research proposal	Centre for Methodical Ethics and Technology Assessment (META)	2008	2,0
Information Literacy and introduction Endnote	WASS	2008	0,6
META seminars and book reading	META	2008 - 2012	3,0
Scientific Writing	Wageningen Graduate Sschools (WGS)	2009 - 2010	1,5
Project- and Time Management	WGS	2010	1,5

*One credit according to ECTS is on average equivalent to 28 hours of study load

C) Career related competences/personal development

PhD competence assessment	WASS	2008	0,3
ACT Cursus voor procesbegeleiders	Wageningen University - Docenten Ondersteuning (DO)	2009	1,0
ACT Coaching of projects:	Wageningen University	2009 - 2013	4,0
• *DNA typing of the Dutch and Flemish cattle population*		*2009*	
• *Strategies for creating value in pig production chains*		*2009*	
• *Open Sesame*		*2010*	
• *Outdoor Pigs in the Netherlands*		*2011*	
• *The added value of nature and landscape for the business sector in Twente*		*2012*	
• *System to prevent fogging of windows in greenhouses with use of a wetting agent*		*2012*	
• *Large Scale insect rearing in relation to animal welfare*		*2012*	
• *How can we improve the implementation of results of sustainable crop protection research by growers?*		*2013*	
• *Development of the PURE Hub Concept applied to Markdal, Breda*		*2013*	
Total			33,2

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