Assessment of the Farm-Economic Impact of Reducing Antimicrobial Use in Livestock Production
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Jamal Luka Roskam

Thesis

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Abstract

The overall objective of this dissertation was to assess the scope for, and the farm-economic impact of reducing veterinary antimicrobial use (AMU). The dissertations' underlying assertion is that an assessment of these issues can help in understanding pathways for reducing veterinary AMU. First, a conceptual framework was developed that provides an integrated assessment of measures and strategies that can be applied within the supply chain in order to reduce both (the need for) AMU and the prevalence of (pathogenic) microorganisms, and consequently the risks of human exposure to AMR. The farmer, the farm and the animals are considered as main decision areas in order to reduce AMU successfully. In addition, a theoretical framework was developed for deriving the economic value of AMU and determining the factors that affect the economic value of AMU. Microeconomic theory postulates that the main determinants of the economic value of AMU are the prices of productive inputs, damage abatement inputs and outputs, the production technology, the damage abatement function, the risk attitude of the farmer and the variance of profit. The next step was to assess the relation between technical farm performance and AMU. The results indicate that farms have unique combinations of technical farm performance and AMU, and therefore require farm-specific strategies to reduce AMU successfully. Finally, the impact of farm-specific interventions on farm performance was assessed. The results indicate that successful strategies for reducing AMU need to target combined interventions regarding the farmer, the farm and the animals. Overall, this dissertation underlined that there are possibilities for reducing AMU without necessarily having negative consequences with respect to technical farm performance.

Table of Contents

Chapter 1

General Introduction

1.1. Background

Since the discovery of penicillin in 1928, various antimicrobial agents have been introduced, which are active against a wide range of infections caused by microorganisms such as bacteria, viruses, fungi and parasites. Previously deadly diseases have become routine disorders, which can be cured easily by using antimicrobials (AMU). The introduction of AMU in veterinary medicine in the 1950s completely changed the options for treating livestock diseases. Besides therapeutic treatments of clinically diseased animals, antimicrobial agents are also used for prophylactic purposes (i.e. prevention of livestock diseases), metaphylactic purposes (i.e. administration to clinically healthy animals that belong to the same herd or flock or administration to animals with clinical signs) and growth promotion (McEwen and Fedorka-Cray, 2002; Rushton *et al.*, 2014; Shea, 2004). In that respect, AMU provides a basis for improving animal health and productivity (Odonkor and Addo, 2011).

Despite the benefits of veterinary AMU, inappropriate use invariably leads to the development and spread of antimicrobial resistance (AMR), resulting in ineffectiveness of antimicrobials. The process of AMR development continued in all known cases after the introduction of new antimicrobial compounds (Levy, 1982). Within the last decades, there has been an increased awareness of the potential negative consequences that the development and spread of AMR among food producing animals can have on human health (e.g. Aarestrup *et al.*, 2008; Carattoli, 2008; Depoorter *et al.*, 2012; Mayrhofer *et al.*, 2006; Silbergeld *et al.*, 2008; Srinivasan *et al.*, 2008; Stine *et al.*, 2007; van Boxstael *et al.*, 2012; Verraes *et al.*, 2013; Zirakzadeh and Patel, 2005).

Figure 1.1 illustrates the complexity of AMR by showing all potential pathways among which humans can be exposed to AMR originating from livestock supply chains. From this Figure, three potential main pathways are delineated. First, the consumption of (contaminated) food products originating from the supply chain (Depoorter *et al.*, 2012; Mayrhofer *et al.*, 2006; van Boxstael *et al.*, 2012). Second, direct contact between humans and contaminated animals including pets, vermin and wildlife (Huijsdens *et al.*, 2006; van Cleef *et al.*, 2011a; van Cleef *et al.*, 2011b). Finally, environmental contamination due to the release of farm effluents and manure spreading (Boxall *et al.*, 2004) causing that resistant bacteria and genes are found in both water and soil systems (Benotti *et al.*, 2008; Blackwell *et al.*, 2007; Heberer, 2002) and in vegetables, seed, crops, fruit and cereals (Boxall *et al.*, 2006; Kumar *et al.*, 2005).

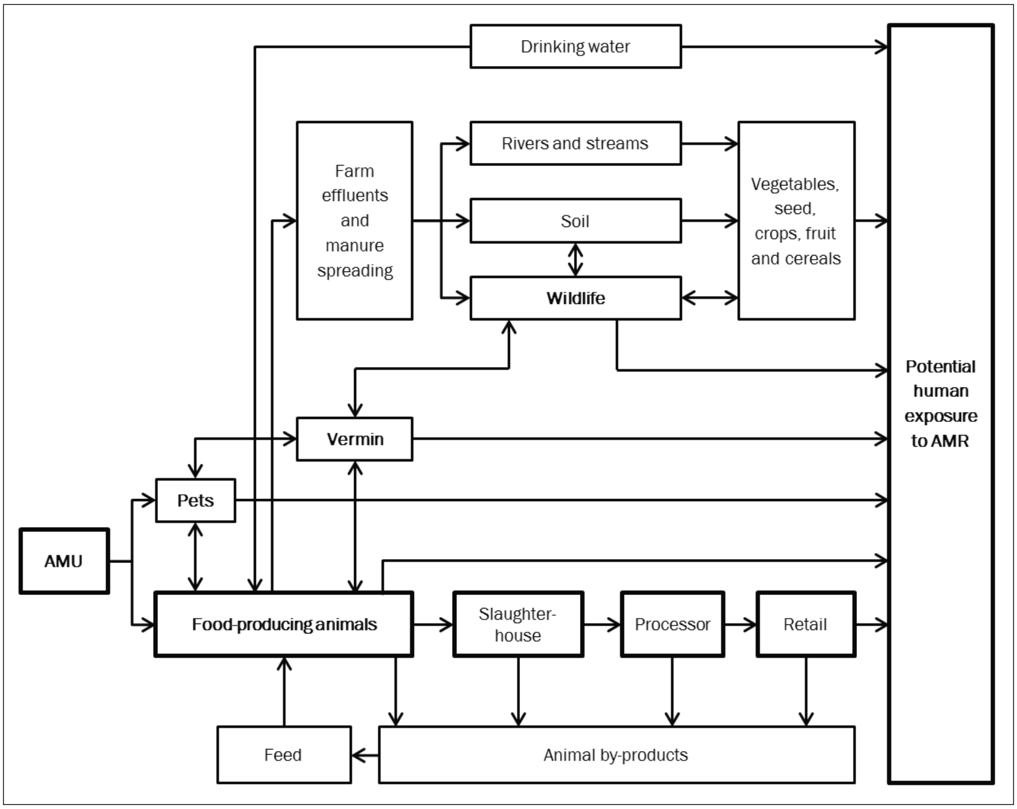

Figure 1.1. Potential pathways that pose potential risks for human exposure to AMR originating from livestock production chains (adapted from Doyle *et al.*, 2006).

Given the link between AMU and AMR, the use of antimicrobial growth promoters is controversial (Landers *et al.*, 2012) which resulted in a ban of antimicrobial growth promoters in the EU. Several European countries (including Denmark, France Norway and The Netherlands) have introduced general policies aimed at reducing non-human AMU. These countries all have formal reduction targets, up to 50 percent, expressed as percentage of previous use (Rushton *et al.*, 2014). These reduction targets were not based on any evidence-based dose (AMU) – effect (AMR) relation. However, faced with increasing public pressure and concerns, decisions need to be taken

(Speksnijder *et al.*, 2015c). In the case of The Netherlands there has been success in reaching the target reductions and this resulted in a new target reduction of 70% between 2009 and 2015 (Speksnijder *et al.*, 2015c). Although reductions have been realized, there are still considerable variations in AMU both within and between countries (European Medicines Agency, 2017). Hence, there are still possibilities for reducing AMU.

1.2. Problem statement

EU policy makers have identified prudent AMU (also known as responsible use) in veterinary medicine as one of the main pathways towards reducing AMR (European Commission, 2015). Prudent use principles describe criteria for best practice regarding AMU, and cover issues like registration and legal basis, need for diagnosis, selection of appropriate antimicrobial substance, formulation and spectrum, right dosage as well as emphasis on AMR testing (Rushton *et al.*, 2014). Prudent AMU should lead to more rational and targeted AMU to maximise the therapeutic effect and minimise the development of AMR. The final outcome of prudent use should be an overall reduction in AMU, achieved mainly by limiting AMU to those situations where they are deemed necessary (European Commission, 2015).

Current veterinary AMU generates short-term benefits for various actors in livestock production systems due to the prevention and treatment of livestock diseases, and for society as whole through a greater availability of livestock products, and increased animal health and welfare. In addition, AMU improved public health by controlling animal diseases and preventing transmission of (zoonotic) pathogens from animals to humans (Hao *et al.*, 2014). However, excessive AMU could lead to AMR resulting in negative consequences for human health. The need for AMU is heavily influenced by husbandry practices and its direct link to animal health (Rushton *et al.*, 2014), which limits the scope for reducing AMU. Yet there are major gaps in knowledge, data and information regarding the possibilities for reducing AMU as well as the farm-economic impact of current and reduced AMU. Knowledge on these issues is needed to support decision making on international and national public policy as well as in setting private standards in order to reduce veterinary AMU (Rushton *et al.*, 2014).

1.3. Objective

The overall objective of this dissertation was to assess the scope for, and the farm-economic impact of reducing veterinary AMU. The dissertations' underlying assertion is that an assessment of these issues can help in understanding pathways for reducing veterinary AMU. To achieve the overall objective, four sub-objectives were defined:

1. to develop a conceptual framework that provides an integrated assessment of the measures and strategies that can be applied within the supply chain in order to reduce both (the need for) AMU and the prevalence of (pathogenic) microorganisms, and consequently the risks of human exposure to AMR;
2. to develop a theoretical framework for deriving the economic value of AMU and determining the factors that affect the economic value of AMU;
3. to assess the relation between technical farm performance and AMU;
4. to assess the impact of interventions, aimed at reducing AMU, on farm performance.

1.4. Outline of the dissertation

This dissertation comprises a general introduction (Chapter 1), four research chapters (Chapters 2-5), and a general discussion (Chapter 6). The structure of the dissertation is presented in Figure 1.2. Like shown in the Figure, Chapter 2 is focussed on the level of the supply chain (i.e. beyond-farm), while Chapter 3-5 are focussed at the on-farm level.

Chapter 2 presents a conceptual framework that provides an integrated assessment of the measures and strategies that can be applied to reduce both (the need for) AMU and the prevalence of pathogenic microorganisms in order to reduce the risks for human exposure to AMR.

Chapter 3 provides a theoretical framework regarding the economic value of AMU. The framework indicates which factors affect the economic value. In addition, the findings are used to develop policy recommendations.

Chapter 4 assesses the relation between farm performance and AMU. Farm performance is determined using Data Envelopment Analysis; subsequently groups of farms with similar characteristics are obtained using cluster analysis. Thereafter, the clusters are compared to examine whether there are differences between the clusters.

Chapter 5 examines the effect of intervention on technical and economic farm performance. The interventions in this study were specifically aimed at reducing AMU.

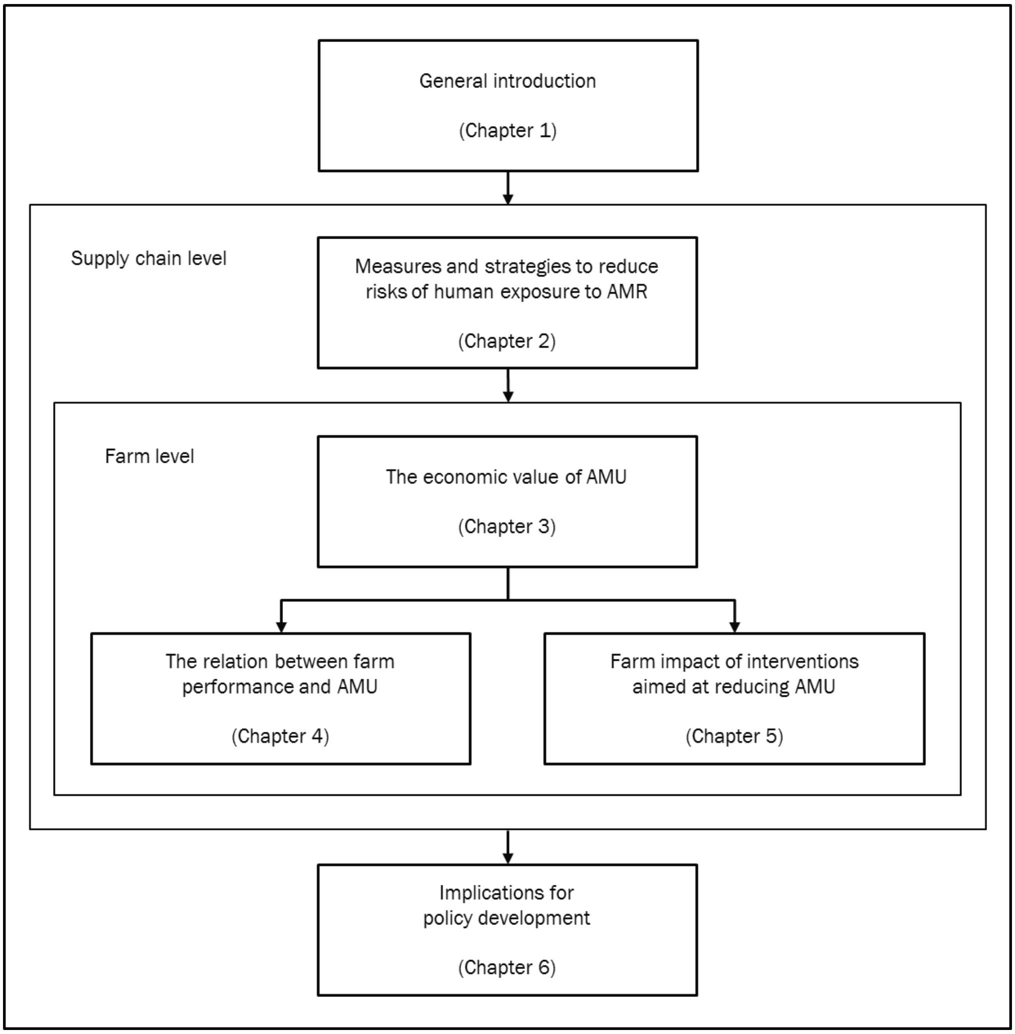

Figure 1.2. Structure of the dissertation

Finally, *Chapter 6* synthesizes the results, elaborates implications for business stakeholders and policy makers, reflects on the approaches and methods used in this dissertation, outlines directions for future research, and finalizes with the main conclusions of this dissertation.

Chapter 2

Economic Decision-Making to Reduce the Risks of Human Exposure to Antimicrobial Resistance: A Conceptual Framework for Livestock Supply Chains

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Abstract

Antimicrobial resistance is one of the biggest health threats for both humans and animals. This justifies the need for a conceptual framework that provides an integrated assessment of the measures and strategies that can be applied within the supply chain in order to reduce the risks of human exposure to antimicrobial resistance. The aim of this paper was therefore to provide a comprehensive supply chain based conceptualization that describes the main measures and strategies to reduce the risks of human exposure to antimicrobial resistance. The conceptual framework presented in this study makes a distinction between the on-farm and the beyond-farm decision-making context. The on-farm decision-making context focuses on the strategies that can reduce (the need for) antimicrobial use. The beyond-farm decision-making focuses on the prevalence of (pathogenic) microorganisms. A panel consisting of Dutch policy makers assessed the framework on various aspects including correctness, completeness and consistency. It is concluded that the conceptual framework provides a sound theoretical basis for economic decision-support for policy makers in order to reduce the risks of human exposure to antimicrobial resistance originating from livestock supply chains.

Keywords: Antimicrobial use; policy support; livestock production

2.1. Introduction

Farmers worldwide use large amounts of antimicrobial agents. Besides use for therapeutic treatments of clinically diseased animals, antimicrobial agents are used for prophylactic purposes (i.e. disease prevention), metaphylactic purposes (i.e. administration to clinically healthy animals that belong to the same flock or administration to animals with clinical signs) and growth promotion (McEwen and Fedorka-Cray, 2002; Rushton *et al.*, 2014; Shea, 2004). However, various studies found evidence for the link between antimicrobial use (AMU) in livestock production and the presence of antimicrobial resistant (pathogenic) microorganisms in humans (e.g. Carattoli, 2008; Depoorter *et al.*, 2012; Mayrhofer *et al.*, 2006; Silbergeld *et al.*, 2008; Srinivasan *et al.*, 2008; Stine *et al.*, 2007; van Boxstael *et al.*, 2012; Zirakzadeh and Patel, 2005). It has become clear that antimicrobial resistance (AMR) poses a threat to continued AMU in veterinary medicine. This resulted in various efforts to reduce inappropriate and excessive AMU in livestock production with the EU ban on the use of antimicrobial growth promoters since 2006 as main European measure. Despite the efforts made to combat inappropriate AMU, the overall level of AMU remained relatively high, which provides favourable conditions for the selection, spread and persistence of AMR. Therefore, national and international governments obliged farmers to increase reductions in AMU. In that respect, all resources available should be allocated as such that both the risks of human exposure to AMR and the costs of the measures and strategies are minimized.

Previous studies have analysed the problem of AMR. Most of these studies primarily focus on the genetic basis of AMR (e.g. Catry *et al.*, 2003; Kehrenberg *et al.*, 2001), the occurrence of AMR (e.g. Aarestrup *et al.*, 2001; Normanno *et al.*, 2007), (side-) effects of AMU (e.g. Aarestrup and Wegener, 1999; McEwen and Fedorka-Cray, 2002), the prevention of AMR (e.g. Gustafson and Bowen, 1997; Roca *et al.*, 2015) and alternative ways to prevent and combat zoonotic diseases in order to lower AMU (e.g. Ezema, 2013; Paul-Pierre, 2009; Postma *et al.*, 2015; Rojo-Gimeno *et al.*, 2016). In addition, Hudson *et al.* (2017) reviewed potential transmission routes of AMR bacteria/genes in agriculture to human infection. From these studies, it can be concluded that AMR is a complex agricultural problem. These kind of problems require a conceptual framework to provide an integrated assessment of, in this specific case, the risks for human exposure to AMR (Jabareen, 2009; Liehr and Smith, 1999; Schut *et al.*, 2015), and that allows for combining both theoretical and empirical findings regarding the problem (Imenda, 2014). First, such a framework should provide a systematic overview of the main factors and decision alternatives (i.e. potential measures) that contribute to the problem. Moreover, it should provide a solid basis for the formulation of the appropriate policy and analysis questions, and elucidate the right questions regarding cost and risk trade-offs, all in the appropriate economic decision-making context. In that respect, such a framework can support the process of finding and analysing potential measures and strategies for reducing the potential risks for human exposure to AMR by considering the economic consequences of the applying the measures and strategies (including to whom the additional costs accrue). Such a holistic and integrated conceptualization of the problem of AMR is currently missing.

The aim of this study was to provide a comprehensive supply chain based conceptualization that describes the main measures and strategies to reduce both (the need for) AMU and the prevalence of (pathogenic) microorganisms, and consequently the risks of human exposure to AMR. The focus of the framework is on poultry and pig production since these supply chains are major contributors to the global meat production (Rushton *et al.*, 2014) and because poultry and pig meat are major reservoirs of food-borne pathogens and commensals (Leverstein-van Hall *et al.*, 2011; Rushton *et al.*, 2014; Weese, 2010; WHO, 2014).

2.2. Conceptual framework

The conceptual framework developed in this paper makes a distinction between the on-farm and the beyond-farm decision-making context regarding the possible actions to reduce the risks of human exposure to AMR. The on-farm decision-making context focuses on (the need for) reducing AMU, whereas the beyond-farm context focuses on reducing the prevalence of (pathogenic) microorganisms, which can be either resistant or non-resistant.

2.2.1. On-farm decision-making context

The on-farm decision-making context is shown in Figure 2.1. The Figure consists of four different layers: decision-makers, decision areas, treatment decisions, and decision objects. The first layer makes a distinction between two different decision-makers. The first group of decision-makers, i.e. the policy makers, include (supra-) national governments and other semi-governmental authorities. This group of stakeholders has the power to develop, implement and enforce laws, policies, rules and regulations. Hence, they determine the decision space of the farmers, which are the other decision-makers included in the Figure. Within this decision space, farmers can apply various measures and strategies in order to reduce (the need for) AMU. Various service providers (including veterinarians and the feed industry) can support farmers in making their decisions. However, the farmer holds the prime responsibility for the on-farm decisions. In that respect, it is important to understand the behaviour of farmers, which is determined by aspects including their awareness; their beliefs and attitudes; their knowledge, skills and experience; and their objectives. Various economic theories have endorsed the importance of behaviour, e.g. the theory of planned behaviour (Ajzen, 1991) and the von Neumann-Morgenstern expected utility theorem (Von Neumann and Morgenstern, 1953). In practice, financial motives dominate the decision-making of farmers, like shown by Gocsik *et al.* (2015). Therefore, it is assumed that a rational farmer aims to maximize its own income (Kay *et al.*, 2011) by minimizing the increase in production costs resulting from the applied measures and strategies to reduce (the need for) AMU.

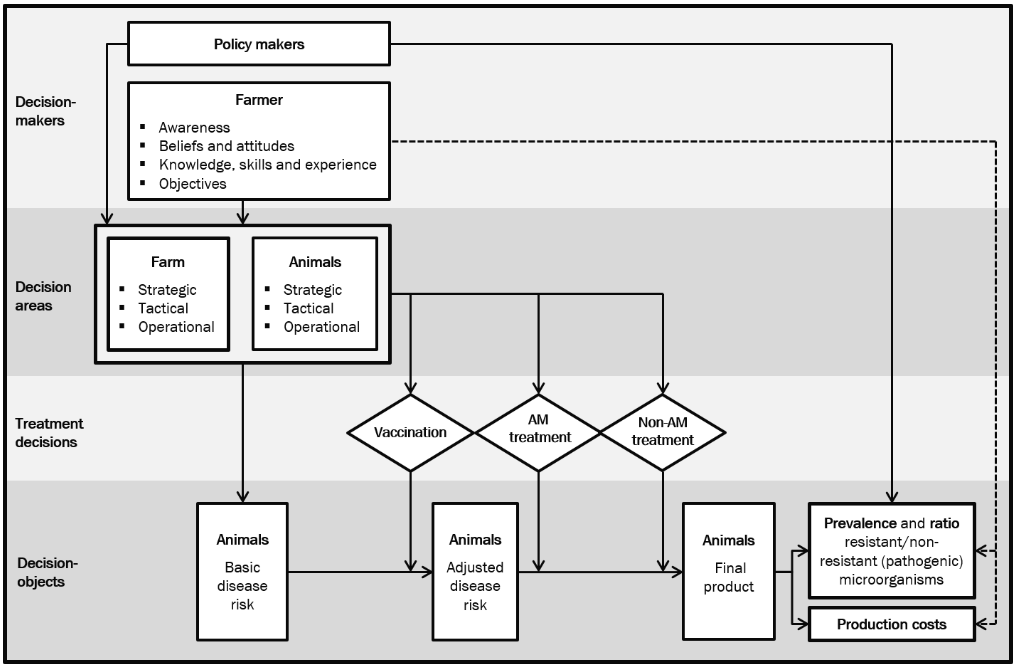

Figure 2.1. The on-farm decision-making context

The second layer of Figure 2.1 comprises the decision areas of the farmer. Two decision areas, i.e. farm and animals, and three decision types, i.e. strategic, tactical and operational decisions, are distinguished. Strategic decisions are long-term decisions with a time horizon of 5-10 years that involve relatively large investments, which affect the production costs over a number of years; these imply long term and (often)-risky financial commitments. Tactical decisions are midterm decisions within a time horizon of a year or a production cycle, and generally involve less investment costs. Hence, tactical decisions involve less financial risks compared to strategic decisions. Operational decisions are day-to-day decisions that fit within the strategic and tactical decision-making context. Table 2.1 describes the main economic decision issues to reduce (the need for) AMU for both pig production (Bokma-Bakker *et al.*, 2014; Groot *et al.*, 2011a; Houben and van der Wielen, 2015) and poultry production (Groot *et al.*, 2011b) by making a distinction between the type of decision and the decision area.

Table 2.1 Catalogue of economic decision issues that can be taken on-farm in order to reduce (the need for) AMU

Type of Decision	Decision areas	
	Farm	**Animal**
Strategic	Location of the farm Farm layout Outside (i.e. external biosecurity/ keeping diseases outside the farm) – Inside (i.e. internal biosecurity/ avoid spread of diseases on-farm) Farm management Production management – Farm management concept	Animal characteristics Animal genetics – Health status (e.g. specific pathogen free animals) Disease management Animal management operations
Tactical	Farm layout Maintenance of buildings – Cleaning and decontamination protocol – Pests and vermin control – Avoid introducing diseases on dispatch to the slaughterhouse Farm management Farm visit by consultant – Evaluation animal health – Monitoring and evaluating nutrition (i.e. quantity, quality and access) – Checking water and water supply system (including quantity, quality and access) – Checking the climate control system (including temperature, airflow, humidity and air quality) – Checking other factors (including litter quality)	Animal characteristics Number of animals – Stocking density Disease management Scheduling periodic activities – Individual or group treatment – Use of antimicrobial agents - Use of preventive measures (including vaccination, pain-killers, zinc-oxide and copper) – Use of natural products (including organic acids phytogenic substances, natural growth promoters, herbs, probiotics, prebiotics, and enzymes) – Use of feed additives – Selection of animal breeder – Supply and despatching frequency (e.g. all-in-all-out principle)
Operational	Adaption to and implementation of strategic and tactical decisions	Daily observation, monitoring and treatment

The location of the farm, the farm layout and the production system management are three important issues regarding the decision area of the farm. Decisions regarding the location of the farm are strategic decisions. A number of environmental features (including the density and proximity of neighbouring farms, and the type and size of the neighbouring farms) characterizes the location of the farm. Those features are important determinants of both the frequency of occurrence and the magnitude of diseases (Rivas *et al.*, 2003). Hence, the location of the farm determines the external disease risk. The farm layout consists of the internal and external biosecurity in which the focus is on avoiding the introduction and spread of diseases on the farm. The farmer controls all its activities through farm management. Within the decision area animal, distinction is made between animal related decisions (i.e. with respect to the animal itself) and disease management related decisions.

The third layer of Figure 2.1 incorporates the decisions regarding the treatment of animals. Three treatment possibilities are distinguished: vaccination, therapeutic treatment with antimicrobial agents and non-antimicrobial treatments. Treatment decisions have major impacts on the prevalence of and ratio between antimicrobial resistant and non-resistant (pathogenic) microorganisms. In many cases, veterinarians have to decide whether the animals can be treated with an antimicrobial, and if so, which antimicrobial agent and by what route of administration (e.g. in feed or in drinking water). The cost of the drug and the severity of the disease often determine the type of antimicrobial agent that is used. It is assumed that non-antimicrobial treatments are beneficial for preventing AMR emergence. However, it is likely that the replacement of AMU for non-antimicrobial treatments will increase the production costs, particularly in the short-term.

The fourth layer of Figure 2.1 reflects on the various stages of the decision object, i.e. the animals. The basic disease risk is determined by the entire complexity and variety of decisions that are taken with respect to the farm and the animals. The disease risk is adjusted when animals are vaccinated. All measures and strategies, either antimicrobial-related or not, have both short-term and long-term effects. The application of those measures and strategies can affect, either directly or indirectly, the technical and economic performance. Hence, the application of on-farm measures and strategies can affect both the production costs, and the risks of human exposure to AMR.

2.2.2. Beyond-farm decision-making

Livestock supply chains usually consist of the following stages: farm, transport, slaughterhouse, processor, retailer and consumer. Hence, compared to the on-farm decision-making context, more stakeholders are involved in the beyond-farm stage. Asymmetry in costs and benefits among chain actors and other stakeholders is common in livestock supply chains

(Michalski *et al.*, 2013). Moreover, there is a high level of interdependency among the different partners within the supply chain (Ziggers and Trienekens, 1999).

Figure 2.2 shows the main stages of a livestock supply chain. This study limits itself to the retail level when discussing potential measures and strategies. Although improper storage and/or improperly prepared food at consumer level adds to the level of prevalence (Doyle *et al.*, 2006), there are no supply chain based policy measures to control food preparation by consumers.

Policy makers, including governments and other (semi-) governmental health authorities, determine the decision space of the supply chain actors. However, actors are free to make their own decisions within those boundaries.

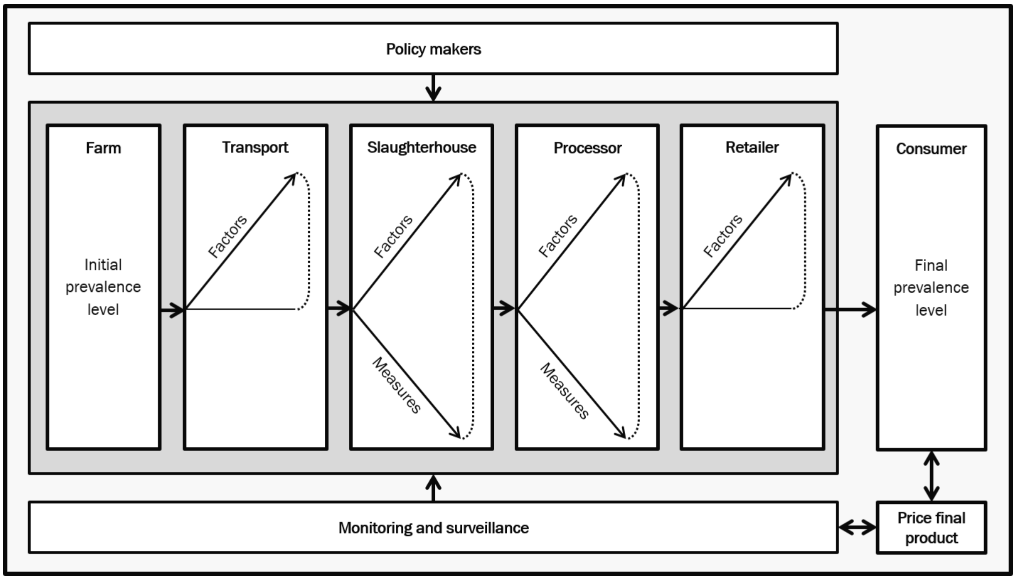

Figure 2.2. The beyond-farm decision-making context with factors and measures that can affect the prevalence of (pathogenic) microorganisms

The flowchart presented in Figure 2.2 starts with the transport of animals from the farm to the slaughterhouse. These animals, aimed for human consumption, leave the farm with a given pathogenic 'load', determined by the *prevalence* of (pathogenic) microorganisms and the *ratio* antimicrobial resistant and non-resistant (pathogenic) microorganisms. The ratio of antimicrobial resistance and non-resistant (pathogenic) microorganisms is assumed to remain unaffected, especially after slaughtering. At each stage of the chain, the prevalence of (pathogenic) microorganisms can be affected, either negatively through factors that increase the prevalence level (e.g. cross-contamination) or positively through measures that decrease the prevalence level (e.g. decontamination treatments). An overview of these factors and measures is presented in Table 2.2 for both pig and poultry production.

Table 2.2. Factors and measures beyond-farm that can affect the prevalence of (pathogenic) microorganisms in pig and poultry production

Factors and measures	Pig production	Poultry production
Prevalence influencing factors (Southern *et al.*, 2006)	Transport Stress incidents – Vehicle cleanliness in transit – Crate density and space allowance – Physical hazards during transport – Length of time in transit and number of rest stops – Facilities for in-transit monitoring – Driving and vehicle conditions Slaughterhouse Lairage conditions – Sanitary and hygienic protocols Processor Sanitary and hygienic protocols Retailer Sanitary and hygienic protocols – Storage conditions	Identical to pig production
Measures to counteract (pathogenic) microorganisms (Loretz *et al.*, 2010; Loretz *et al.*, 2011)	Slaughterhouse / processor Physical decontamination treatments (including scalding and singeing, chilling, water spraying, steam, and ultraviolet light) – Chemical decontamination treatments (including organic acids and other chemical treatments)	Slaughterhouse / processor Physical decontamination treatments (including water based treatments, irradiation, ultrasound, air chilling, and freezing) – Chemical decontamination treatments (including organic acids, chlorine-based treatments, and phosphate-based treatments)

During the transport of animals from farm to slaughterhouse, various physical, microbial and environmental hazards may adversely affect the microbial quality in the animals (Southern *et al.*, 2006). Additionally, the stress level can increase in case of adverse transportation conditions, which potentially causes increased pathogen multiplication in carrier animals through which other animals can be exposed as well (Southern *et al.*, 2006). In subsequent stages of the chain, the prevalence of (pathogenic) microorganisms can increase through improper storage conditions (Quintavalla and Vicini, 2002). Contaminated carcasses or food products can contaminate each other through cross-contamination (Pérez-Rodríguez *et al.*, 2008). Good sanitary and hygienic processes are the basis for controlling microbial contamination and avoiding cross-contamination (Buncic and Sofos, 2012). However, total prevention of increased microbial cross-contamination is out of reach under commercial conditions, even when best hygiene measures are applied (Buncic and Sofos, 2012). Therefore, there is a need for specific targeted measures.

Loretz *et al.* (2010) described the intervention possibilities beyond-farm for poultry carcasses, where Loretz *et al.* (2011) described the intervention possibilities for pig carcasses. Examples of intervention possibilities are psychical treatments (including hot water spraying, irradiation, steam treatment, ultrasound, ultraviolet light, air chilling, or freezing) and chemical interventions (including lactic, acetic and organic acids, and chlorine-based or phosphate-based treatments). Those interventions differ in terms of effectiveness and welfare effects. In addition, there is a legal ban on certain intervention possibilities, e.g. the EU ban on the use of organic acids (European Parliament & Council of the European Union, 2004). At the retail level, there are no intervention possibilities to reduce the prevalence of (pathogenic) microorganisms. However, inappropriate storage conditions can increase the prevalence level (Arvanitoyannis and Stratakos, 2012).

Monitoring and surveillance is possible throughout the whole supply chain. A generally accepted example of a widely applied monitoring and surveillance approach is the *Hazard Analysis and Critical Control Points (HACCP)* approach. This preventive approach involves the identification and control of potential food safety hazards.

2.3. Compliance, effectivity and governance

The implementation of measures and strategies to reduce the risks of human exposure to AMR is not straightforward and might come with considerable additional costs originating from increased production costs, reduced output or a combination of both. This could pose a temptation for stakeholders to non-comply with (legal) obligations. Such risks of (partial) non-compliance might reduce the effectiveness of measures and strategies. Various authors used a compliance model that describes the decision-making process within firms (Baron and Baron, 1980; French and Neighbors, 1991; Henson and Heasman, 1998; Loader and Hobbs, 1999; McKean, 1980; Sproull, 1981). According to Rugman and Verbeke (1998), and Henson and Caswell (1999) responses in terms of compliance depend on the following aspects:

- *Expected economic benefits*. Generally, there will only be a natural tendency to comply with policies when the total costs of compliance are lower than the (commercial) benefits of non-compliance (van der Meulen and Bremmers, 2013);
- *Driver of compliance*. Firms can be stimulated to comply by providing financial incentives (e.g. grants for the antibiotic-free meat production), or through sanctions in case of non-compliance (e.g. financial penalties for using certain antimicrobials agents);
- *Strength of enforcement authorities*. Firms always take into account the likelihood of being caught in case of non-compliance. In that respect, penalties, monitoring and control could enforce compliance (Bremmers *et al.*, 2008).

The development of an appropriate mix of the above-mentioned aspects helps in regulating compliance. Two regulation views are distinguished: one from the public side and one from the private side (Henson and Caswell, 1999). On the public side, Henson and Caswell (1999) distinguished direct ex-ante regulation (i.e. standards, inspection, product testing and other programmes to ensure good food quality) and product liability (i.e. ex-post regulation to discourage food production of insufficient quality). Product liability is not easy to implement due to existing problems with food traceability (Pouliot and Sumner, 2008). On the private side, Henson and Caswell (1999) distinguished self-regulation (i.e. internal control systems that assure product quality where the firm sets, monitors and self-certifies control parameters) and certification (i.e. setting quality standards). Certification could be attractive since consumers are willing to pay more for products when the food safety is enhanced (Dickinson and Bailey, 2002; Hobbs *et al.*, 2005). Governmental authorities can stimulate and facilitate private initiatives of self-regulation and certification by providing (financial) incentives.

If the prevailing aim is reducing risks of human exposure to AMR, which can result in reduced AMU with coinciding increased production costs, non-compliance is a critical risk factor. The risk governance literature has looked at engaging people at different levels (Johansson *et al.*, 2009). However, ensuring accountability and establishing trust between stakeholders at different levels is rather complex (Drott *et al.*, 2013; Gilmour *et al.*, 2011). Hence, minimizing non-compliance requires additional costs, e.g. improved governance, monitoring and control; moreover, they accrue to different stakeholders. Such additional costs should be included in future analyses.

2.4. Validation of the framework

A panel of policy makers tested the practical usability of the framework during two organized workshops. Due to logistical and budgetary constraints, the panel only comprised Dutch policy makers. The panel included policy makers from the Dutch Product Boards for Livestock, Meat and Eggs, the Dutch Ministry of Economic Affairs, the Dutch Animal Health Service, The Netherlands Food and Consumer Product Safety Authority, and the Dutch Agricultural and Horticultural Organisation (i.e. one policy maker from each organisation). Hence, the panel consisted of policy makers from the main organisations involved in the Dutch livestock production sector. First, the panel received the framework electronically. The first workshop started with a presentation about the framework. Afterwards, the panel assessed the framework on different aspects including correctness, completeness and consistency. The outcome of the first workshop was that the Figures with respect to the on-farm and beyond-farm decision-making context were too complex. Hence, the Figures were adapted after the first workshop. The modified framework was presented during the second workshop. Again, the panel assessed the framework on similar aspects as in the first workshop. The panel addressed some minor remarks, including the suggestion to simply elements in Figure 1 and 2. According to the feedback received from the panel, the framework was adapted and finalized after the second workshop.

2.5. Conclusions, discussion and future outlook

The aim of this study was to provide a comprehensive supply chain based conceptualization that describes the main measures and strategies to reduce (the need for) AMU, and consequently to reduce the risks of human exposure to AMR. This paper framed the on-farm and beyond-farm decision-making context to assess potential risks of human exposure to AMR from a holistic view. In that respect, the conceptualization presented in this study is a qualitative basis for future bio-economic modelling and quantitative analyses. Specifically, such models and analyses need to include the potential risks and the potential benefits associated with AMU. Rushton (2015) already emphasized the need for impact assessments in future research. Those assessment analyses have the value to identify bottlenecks in the management of AMU and potential impacts in terms of residues or AMR emergence. Hence, assessment analyses have to include evaluations of potential interventions for reducing AMU and can reveal potential unintended consequences.

The preferred tool for impact assessment analyses is the comparison between the benefits of veterinary AMU on the one hand, and both the financial costs and the risks of AMR emergence on the other hand (Rushton, 2015). However, on the costs side, not all expenditure costs are equal. Variable and fixed costs are distinguished. Variable costs vary according to the level of production and are farm-specific (Rushton, 2009). Fixed costs are difficult to assign to certain activities and are investments made to last for a long period of time (Rushton, 2009). Tisdell (2009) emphasized the need to invest in fixed cost elements to tackle AMR emergence. In addition, one should realize that although veterinary AMU is common, the institutional environment in which they are used is variable (Rushton *et al.*, 2014) which again affects the efficacy of measures.

Results of future analyses can contribute to the process of developing new policy guidelines to support the economic decision-making on reducing AMR in order to reduce the risks of human exposure to AMR. The conceptual framework presented in this study is a qualitative basis for future impact assessment analyses.

Acknowledgements

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Chapter 3

The Economic Value of Antimicrobial Use in Livestock Production

J.L. Roskam, A.G.J.M. Oude Lansink, and H.W. Saatkamp

Abstract

A theoretical framework was developed to assess the economic value of antimicrobial use. Three situations are distinguished: 1) a baseline model for a farm with a conventional production system; 2) an extension including the impact of production system improvements; and 3) an extension including risk and risk attitude impacts. The framework shows that the economic value is negatively affected by the price of productive inputs and damage abatement inputs, and positively affected by the output price, the input-output combination, the damage abatement effect, risk aversion and variance of profit. Additionally, policy recommendations are derived to reduce AMU in livestock production.

Keywords: Antimicrobial use; Damage Abatement; Economic Value

3.1. Introduction

Antimicrobial agents (AMs) have played an important role in improving the productivity of worldwide livestock production by reducing the impact of livestock diseases. Various purposes of antimicrobial use (AMU) are distinguished (McEwen and Fedorka-Cray, 2002; Page and Gautier, 2012; Rushton *et al.*, 2014; Stärk, 2013): therapeutic purposes (i.e. treatment of diseased animals), prophylactic purposes (i.e. disease prevention), metaphylactic purposes (i.e. administration to clinically healthy animals that belong to a herd or flock with clinical signs) and growth promotion. A major drawback of AMU is the emergence of antimicrobial resistant pathogens in food-producing animals. Contamination of food products with resistant pathogens can cause antimicrobial resistance (AMR), which could reduce antimicrobial effectiveness in humans (Marshall and Levy, 2011). AMR is therefore considered as a major global health threat (O'Neill, 2015; WHO, 2014).

Various studies provide evidence of a relation between AMU in livestock production and the prevalence of resistant pathogens in humans (e.g. Carattoli, 2008; Depoorter *et al.*, 2012; Mayrhofer *et al.*, 2006; Silbergeld *et al.*, 2008; Srinivasan *et al.*, 2008; Stine *et al.*, 2007; van Boxstael *et al.*, 2012; Zirakzadeh and Patel, 2005). Hence, there is an urgent need for reducing AMU in livestock production to a minimum required to guarantee animal health but still be compatible with sustainable animal production (Aarestrup *et al.*, 2008; Angulo *et al.*, 2009; McEwen, 2006; Prescott, 2008; Speksnijder *et al.*, 2015b). Currently, there is no agreement about what this minimum should be. Different measures have contributed to reductions in AMU, including a European ban in 2006 on the use of antimicrobial growth promoters.

Successful measures have led to a significant reduction in veterinary AMU in countries such as the Netherlands and Denmark. However, large variations remain in AMU between countries and individual farms. This suggests possibilities for further reductions in AMU, in particular for farmers with intensive AMU. The individual farmer should therefore be at the core of any effort to reduce AMU. An understanding of the EV_{AMU} and the factors that affect the EV_{AMU} is essential, as this knowledge can be utilized to derive concrete policy recommendations to influence the EV_{AMU} in order to reduce AMU.

The objective of this study was twofold. First, to develop a theoretical framework to derive the EV_{AMU} and to determine the factors that affect the EV_{AMU}. Second, to utilize the framework as a theoretical basis for policy recommendations to reduce AMU in livestock production. The emphasis in the theoretical framework presented in this study is on meat production, including broiler and fattening pig production.

3.2. The concept of damage abatement

The production function expresses the technical relationship between inputs used and outputs produced (Case *et al.*, 1999; Krugman and Wells, 2013). This section provides different production function specifications that explicitly account for the role of damage abatement inputs. Damage-control agents do not enhance productivity directly, in contrast to the production factors known as productive inputs (Lichtenberg and Zilberman, 1986). Hence, damage abatement inputs are defined as inputs that reduce damage rather than increase output, whereas productive inputs are inputs that increase output directly (Oude Lansink and Carpentier, 2001). The traditional specification of the production function is:

$$y = F(x, z) \tag{3.1}$$

where x is a vector of productive inputs and z a vector of damage abatement inputs. $F(\cdot)$ is assumed to possess the standard production function properties, in particular concavity in (x, z). Hence, the traditional production function specification treats x and z symmetrically.

Damage abatement specifications differ from the traditional specification in the asymmetric treatment of productive inputs and damage abatement inputs. The concept of damage abatement inputs was introduced in the agricultural economics literature by Hall and Norgaard (1973) and Talpaz and Borosh (1974). Lichtenberg and Zilberman (1986) specified an output damage abatement production function that is consistent with the concept of damage abatement and that allows damage abatement inputs to reduce losses from potential output. Following

Lichtenberg and Zilberman (1986), the specification of the output damage abatement production function is:

$$y = F(x) \cdot D(z) \tag{3.2}$$

where $F(\cdot)$ is a production function that gives the potential output (y) from the productive input vector x and $D(\cdot)$ is a damage abatement function that gives the level of damage abatement from the damage abatement input vector z. Following Oude Lansink and Carpentier (2001), properties of the output damage abatement production function are:

$$D(z) \geq 0 \tag{3.3a}$$

$$0 \leq D(z) \leq 1 \tag{3.3b}$$

Property (3.3a) implies that damage abatement inputs are not strictly essential inputs, i.e. positive damage abatement is possible at zero levels of damage abatement inputs. Property (3.3b) implies that the damage abatement function is defined as a fraction between zero and one. $D(z) = 1$ indicates that the destructive capacity is completely eliminated, i.e. losses are zero and actual output equals potential output (Lichtenberg and Zilberman, 1986). A damage abatement of zero denotes the output obtainable under maximum destructive capacity, i.e. actual output equals minimum output (Lichtenberg and Zilberman, 1986).

The concept of damage abatement has been applied to pesticides (i.e. fungicides, herbicides and other pesticides) (Lichtenberg and Zilberman, 1986; Oude Lansink and Carpentier, 2001). The concept of damage abatement also applies to AMU in livestock production since AMU can reduce the damage caused pathogenic diseases.

The theoretical framework proposed in this study follows the output damage abatement production function specification of Lichtenberg and Zilberman (1986). This specification assumes that no interdependence exists between productive inputs and damage abatement inputs. Oude Lansink and Carpentier (2001) introduced an alternative specification to capture the potential interdependence between productive inputs and damage abatement inputs i.e. that damage abatement inputs affect the productivity of productive inputs. However, this assumption is arguable in the case of AMU, as an effect of AMU on the productivity of productive inputs (including feed) is similar to growth promotion, which is prohibited in the EU.

3.3. Theoretical framework

The theoretical framework presented in this study assesses the EV_{AMU} for individual farmers in three specific situations: 1) a baseline model that examines the EV_{AMU} for a specific farm with a conventional production system, 2) an extension of the baseline model that includes the impact of production system improvements and 3) another extension of the baseline model that includes the impact of risk and risk attitude.

3.3.1. Baseline model

The starting point of the baseline model is the production function, which expresses the relationship between the output *meat* (y-axis) and the main productive input *feed* (x-axis) (see Figure 3.1). The production function slopes upwards because more meat is produced when more feed is used. The marginal product of feed declines when more feed is used, i.e. the marginal product of feed drops as the amount of feed used increases, and therefore there are diminishing returns to feed (Krugman and Wells, 2013).

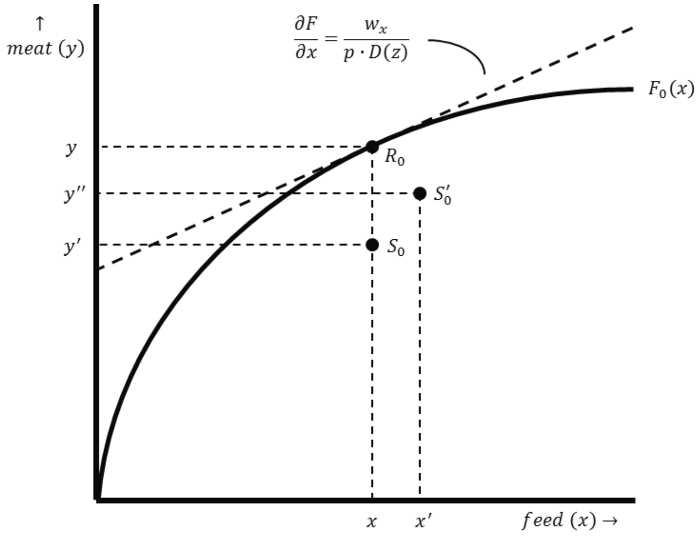

Figure 3.1. The production function of a farm with a conventional production system. *Production function* $\mathbf{F_0(x)}$ *illustrates the relation between the output meat* $(\mathbf{y})$ *and the productive input feed* $(\mathbf{x})$ *for a specific farm with a conventional production system. The dashed line represents the isoprofit line. The slope of this line is* $\frac{\partial \mathbf{F}}{\partial \mathbf{x}} = \frac{\mathbf{w_x}}{\mathbf{p} \cdot \mathbf{D(z)}}$*. Point* $\mathbf{R_0}$ *shows the optimal input-output combination* $(\mathbf{x}, \mathbf{y})$ *for a production level without damage. Point* $\mathbf{S_0}$ *shows the input-output combination* $(\mathbf{x}, \mathbf{y'})$ *with maximum damage and no AMU. Point* $\mathbf{S_0'}$ *shows the input-out combination* $(\mathbf{x'}, \mathbf{y''})$ *resulting from optimal damage abatement.*

Neoclassical economics is based on a number of assumptions. In the baseline model, farmers are assumed to maximize profit. Letting p denote the price of output; w_x denote the price of productive inputs; and w_z denote the price of damage abatement inputs, the relevant profit-maximization problem is expressed as:

$$\max_{x,z} \pi = p[F(x) \cdot D(z)] - w_x \cdot x - w_z \tag{3.4}$$

According to the conventional profit maximization criterion, the optimal input-output combination is denoted as point R_0 in Figure 1. At this point, the production function is tangent to the isoprofit line. This involves a tangency condition in which the slope of the production function (i.e. the marginal product of productive input use) equals the slope of the corresponding isoprofit line. This point is found by taking the first derivative of π with respect to x; setting it equal to zero and then rewriting it in terms of $\frac{\partial F}{\partial x}$ (see Equations 3.5 and 3.6).

$$\frac{\partial \pi}{\partial x} = p\left(\frac{\partial F}{\partial x} \cdot D(z)\right) - w_x = 0 \tag{3.5}$$

$$\frac{\partial F}{\partial x} = \frac{w_x}{p \cdot D(z)} \tag{3.6}$$

Equations (3.5) and (3.6) show that the marginal product of productive input use is determined by w_x, p and $D(z)$. A rational farmer starts using more (less) productive inputs when the price of productive inputs decreases (increases) and/or the output price increases (decreases), *ceteris paribus (cet. par.)*. Hence, the marginal product will increase (decrease) when w_x decreases (increases), *cet. par.* In addition, the marginal product will increase (decrease) when p increases (decreases), *cet. par.* The same effect applies to $D(z)$, *cet. par.*

Point R_0 is located on the production function. At this point, losses are zero and the actual output level equals potential output. However, damage is inherent to livestock production. Input-output combinations are therefore located *below* the production function, excluding exceptional cases. At point S_0, there is a basic level of damage abatement without AMU. A graphical representation of the damage abatement function is shown in Figure 2 with the damage abatement effect on the y-axis and the use of damage abatement inputs on the x-axis. The damage abatement function only distinguishes the effect of AMU. Optimal AMU results in a shift of the input-output combination, since an economically rational producers' response is to increase productive input use and production intensity from point S_0 to point S_0' (see Figure 3.1).

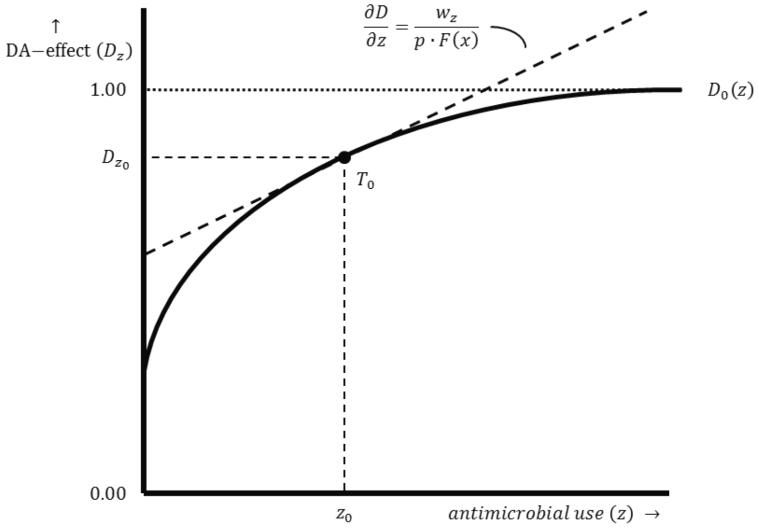

Figure 3.2. The damage abatement function of a farm with a conventional production system. *Damage abatement function* $\mathbf{D_0(z)}$ *illustrates the relation between the damage abatement effect* $(\mathbf{D_z})$ *and the damage abatement input use* $(\mathbf{z})$ *for a farm with a conventional production system. The dashed line represents the isoprofit line. The slope of this line is* $\frac{\partial \mathbf{D}}{\partial \mathbf{z}} = \frac{\mathbf{w_z}}{\mathbf{p \cdot F(x)}}$. *Point* $\mathbf{T_0}$ *shows the optimal damage abatement effect* $\left(\mathbf{D_{z_0}}\right)$ *resulting from an optimal level of AMU* $(\mathbf{z_0})$.

The optimal damage abatement effect and the optimal level of damage abatement input use are determined by the damage abatement function. The point where the damage abatement function is tangent to the isoprofit line determines the level of damage abatement input use that generates optimal damage abatement (see point T_0 in Figure 3.2). This involves a tangency condition in which the slope of the damage abatement function (i.e. the marginal product of the damage abatement input use) equals the slope of the corresponding isoprofit line. This point is found by taking the first derivative of π with respect to z; setting it equal to 0 and rewriting it in terms of $\frac{\partial D}{\partial z}$ (see Equations 3.7 and 3.8).

$$\frac{\partial \pi}{\partial z} = p\left(F(x) \cdot \frac{\partial D}{\partial Z}\right) - w_z = 0 \tag{3.7}$$

3

$$\frac{\partial D}{\partial z} = \frac{w_z}{p \cdot F(x)} \tag{3.8}$$

Equations (3.7) and (3.8) show that the marginal product of damage abatement input use is determined by w_z, p and $F(x)$. A rational farmer uses more (less) damage abatement inputs (i.e. AMs) when the price of damage abatement inputs decreases (increases) and/or the price of output increases (decreases), *cet. par.* Hence, the marginal product will increase (decrease) when w_z decreases (increases), *cet. par.* In addition, this value will increase (decrease) when p increases (decreases), *cet. par.* The same effect applies to $F(x)$, *cet. par.*

The EV_{AMU} is determined by comparing, for an individual farmer, the income obtained from production with a basic level of damage-abatement without AMU (see production point S_0 in Figure 3.1) with the income obtained from production with optimal damage-abatement including optimal AMU (see production point S_0' in Figure 3.1). These income levels are determined by the marginal product of productive input use and the marginal product of damage abatement input use. Letting Δy denote the change in output resulting from optimal AMU and Δx denote the change in productive input use resulting from optimal AMU, the EV_{AMU} is expressed as:

$$EV_{AMU} = \Delta y \cdot p - \Delta x \cdot w_x - z \cdot w_z \tag{3.9}$$

The EV_{AMU} of Equation (3.9) is equal to the change in individual producer surplus, obtained by comparing the level of production with and without optimal AMU (i.e. comparing point S_0 and S_0'). The EV_{AMU} is determined by both the marginal product of the productive input use and the marginal product of the damage abatement input use. The EV_{AMU} is negatively affected by w_x and w_z, and positively affected by p, $f(x)$ and $D(z)$. In the short run, $f(x)$ and $D(z)$ are fixed, while p, w_x and w_z are variable. Hence, p, w_x and w_z determine the EV_{AMU} in the short run.

3.3.2. The impact of production system improvements

Successful and consistent implementation of preventive measures (e.g. biosecurity improvement) can reduce the prevalence and incidence of livestock diseases and mitigate their impact (Speksnijder *et al.*, 2015a). Production system improvements therefore reduce the need for AMU but the production costs (either fixed or variable costs) are likely to increase at the same time.

Such improvements increase the potential output, which results in an upward shift of the production function. This is shown in Figure 3.3, in which production function $f_0(x)$ corresponds to a farm with a conventional production system and production function $f_1(x)$ to a farm with an improved production system. The mathematical derivation of the optimal input-output combination is the same for both production systems (see Equations 5 and 6). However, as illustrated in Figure 3.3, the optimal input-output combination for a farm with an improved production system (x_1, y_1) differs from the optimal input-output for a farm with a conventional production system (x_0, y_0).

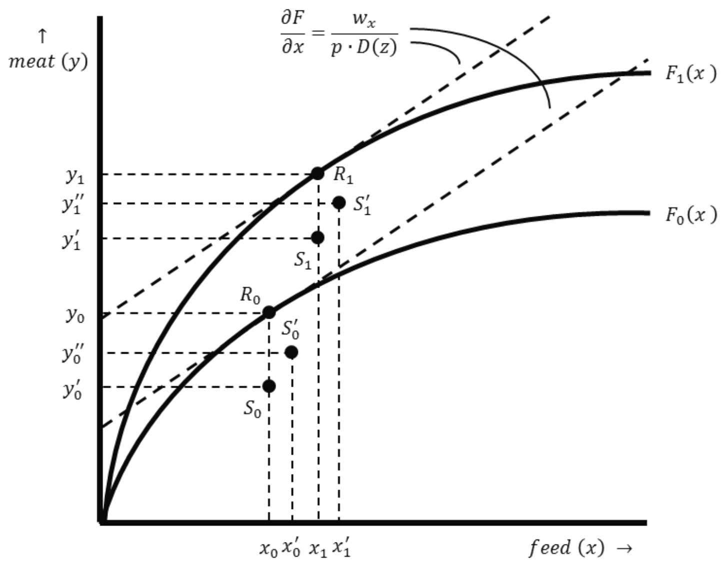

Figure 3.3. The production functions of a farm with a conventional production system and a farm with an improved production system. *Production function* $\mathbf{F_0(x)}$ *illustrates the relation between the output meat* $(\mathbf{y})$ *and the productive input feed* $(\mathbf{x})$ *for a farm with a conventional production system, while production function* $\mathbf{F_1(x)}$ *illustrates the same input-output relation for a farm with an improved production system. The dashed lines represent isoprofit lines. The slope of these lines is* $\frac{\partial \mathbf{F}}{\partial \mathbf{x}} = \frac{\mathbf{w_x}}{\mathbf{p \cdot D(z)}}$. *Point* $\mathbf{R_0}$ *shows the optimal input-output combination* $(\mathbf{x_0}, \mathbf{y_0})$ *for a farm with a conventional production system without damage, while point* $\mathbf{R_1}$ *shows the optimal input-output combination* $(\mathbf{x_1}, \mathbf{y_1})$ *for a farm with an improved production system. Point* $\mathbf{S_0}$ *shows the input-output combination* $(\mathbf{x_0}, \mathbf{y_0'})$ *for a farm with a conventional production system in a situation with*

maximum damage and no AMU, while point $\mathbf{S_1}$ *shows the input-output combination* $(\mathbf{x_1}, \mathbf{y_1'})$ *for a farm with an improved production system in the same situation. Point* $\mathbf{S_0'}$ *shows the input-out combination* $(\mathbf{x_0'}, \mathbf{y_0''})$ *for a farm with a conventional production system resulting from optimal damage abatement, while point* $\mathbf{S_1'}$ *shows the input-out combination* $(\mathbf{x_1'}, \mathbf{y_1''})$ *for a farm with an improved production system.*

The likely impact of production system improvements on the use of damage abatement inputs (i.e. AMs) is shown in Figure 3.4. Production system improvements are assumed to result in an outward shift of the damage abatement function since the level of damage abatement without AMU becomes higher. In addition, the damage abatement function is steeper since the maximum attainable damage abatement effect can be reached more quickly with AMU due to the production system improvements. The mathematical derivation of the optimal damage abatement effect and the optimal damage abatement input use is the same for both production systems and therefore similar to Equations (3.7) and (3.8). However, as Figure 3.4 shows, the optimal damage abatement effect is higher for a farm with an improved production system (D_{z_1}) compared to a farm with a conventional production system (D_{z_0}), while the optimal level of damage abatement input use (i.e. AMU) is lower for a farm with an improved production system (z_1) compared to a farm with a conventional production system (z_0).

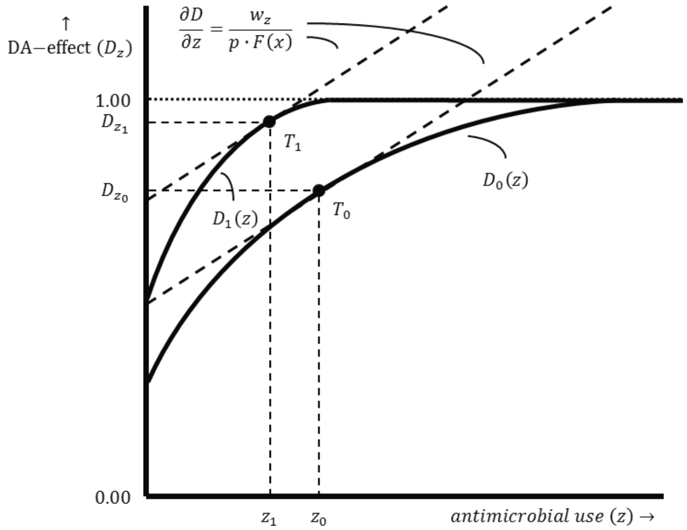

Figure 3.4. The damage abatement functions of a farm with a conventional production system and a farm with an improved production system. *Damage abatement function* $\mathbf{D_0(z)}$ *shows the relation between the damage abatement effect* $(\mathbf{D_{z_0}})$ *and the damage abatement input use* $(\mathbf{z_0})$ *for a farm with a conventional production system, while damage abatement function* $\mathbf{D_1(z)}$ *illustrates the relation between the damage abatement effect* $(\mathbf{D_{z_1}})$ *and the damage abatement input use* $(\mathbf{z_1})$ *of a farm with an improved production system. The dashed lines represent isoprofit lines. The slope of these lines is* $\frac{\partial \mathbf{D}}{\partial \mathbf{z}} = \frac{\mathbf{w_z}}{\mathbf{p \cdot F(x)}}$. *Point* $\mathbf{T_0}$ *shows the optimal damage abatement effect* $(\mathbf{D_{z_0}})$ *resulting from an optimal level of AMU* $(\mathbf{z_0})$*, while point* $\mathbf{T_1}$ *shows the optimal damage abatement effect* $(\mathbf{D_{z_1}})$ *resulting from an optimal level of AMU* $(\mathbf{z_1})$*.*

The EV_{AMU} in the situation with production system improvements is determined for two situations. First, the EV_{AMU} is determined for a farm that made investments in production system improvements by comparing input-output combinations S_1 and S_1' (see Figure 3). The expression of the EV_{AMU} in such a situation is therefore similar to Equation (3.9). Second, the EV_{AMU} is different for a farmer with a conventional production system who considers investing in production system improvements. Assuming the investments take place, and letting Δy denote the change in output in the situation with and without production system investments; Δ production costs denote the change in production costs associated with the investment; Δx denote the change in productive input use; and Δz denote the change in AMU, the $\mathrm{EV_{AMU}}$ is expressed as:

$$\mathrm{EV_{AMU}} = \Delta y \cdot p - \Delta \text{ production costs} - \Delta x \cdot w_x - \Delta z \cdot w_z \tag{3.10}$$

Equation (3.10) shows that a rational farmer will only invest in production system improvements when the $\mathrm{EV_{AMU}}$ is positive (i.e. Δ production costs $< [\Delta y \cdot p - \Delta x \cdot w_x - \Delta z \cdot w_z]$). Compared to the baseline model, an additional determinant of the $\mathrm{EV_{AMU}}$ is the change in annual production costs resulting from the investments in production system improvements.

3.3.3. The impact of risk and risk attitude

In the baseline model and the extension with the impact of production system improvements, the impact of risk and risk attitude were not taken into account. However, risk and uncertainty do affect the $\mathrm{EV_{AMU}}$. In *von Neumann-Morgenstern utility theory* (Von Neumann and Morgenstern, 1953), it is assumed that farmers aim to maximize the expected utility of income instead of income itself. Uncertainty enters through production risks, i.e. stochastic production (especially with respect to input-output quantities). Risk preferences of the farmer are implemented by assuming a *mean-variance utility function*, introduced by Markowitz (1952), in which the certainty equivalent of a farmer is expressed in terms of the mean and the variance. This function assumes linear mean-variance risk preferences, which imply *constant absolute risk aversion*, i.e. the preferred option in a risky choice situation is unaffected by the addition or subtraction of a constant amount to all pay-offs (Hardaker *et al.*, 2015). Following Sargent (1979), the farmer maximizes mean profit minus the risk premium (i.e. the variance multiplied by a constant denoted as α). The larger the α, the more risk averse the farmer is. Hence, the utility of the farmer is increasing in mean profit and decreasing in the variance of profit. The more risk averse a farmer is, the higher the rate of decrease in utility with respect to the variance of profit. Letting $\bar{\pi}$ denote the mean profit; α denote the measure of risk aversion; and σ_π^2 denote the variance of profit, the expected utility of the farmer is expressed as:

$$E[U(\pi)] = \bar{\pi} - \frac{1}{2}\alpha \cdot \sigma_\pi^2 = \overline{p\big(F(x) \cdot D(z)\big) - w_x \cdot x - w_z \cdot z} - \frac{1}{2}\alpha \cdot \sigma_\pi^2$$

According to the conventional profit maximization criterion, the optimal input-output combination is denoted at point R_0 in Figure 3.5. At this point, the production function is tangent to the isoprofit line. However, under utility maximization, the optimal input-output combination is determined by point R_1, where the production function is tangent to the iso-utility line (see Figure 3.5). This point is found by taking the first derivative of $u(\pi)$ with respect to x; setting it equal to 0 and rewriting it in terms of $\frac{\partial F}{\partial x}$ (see Equations 3.12 and 3.13).

$$\frac{\partial u(\pi)}{\partial x} = p\left(\frac{\partial F}{\partial x} \cdot D(z)\right) - w_x - \frac{\frac{1}{2}\alpha \cdot \partial\sigma_\pi^2}{\partial x} = 0 \tag{3.12}$$

$$\frac{\partial F}{\partial x} = \frac{w_x}{p \cdot D(z)} + \frac{\frac{\frac{1}{2}\alpha \cdot \partial\sigma_\pi^2}{\partial x}}{p \cdot D(z)} \tag{3.13}$$

3

Equation (3.13) shows that the marginal product of productive input use is determined by $w_x, p, D(z)$, α and σ_π^2. The effects of w_x, p and $D(z)$ on the marginal product are similar to the standard profit maximization situation. As α is assumed to be positive, the more risk averse a farmer is, the lower the marginal product of productive input use, *cet. par.* The effect of σ_π^2 on productive input use can be positive (i.e. when a higher variance in profit results in higher productive input use) or negative (i.e. when a higher variance in profit results in lower productive inputs use), *cet. par.* Both effects are shown in Figure 3.5, where a positive (negative) effect results in a higher (lower) input-output combination compared to the initial situation.

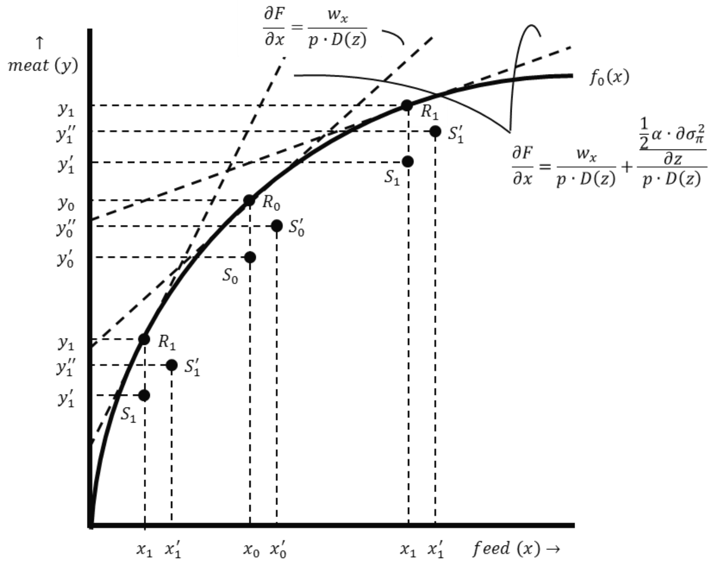

Figure 3.5. The optimal input-output combinations of risk neutral and risk averse farmers. *Production function* $\mathbf{F_0(x)}$ *illustrates the relation between the output meat* $(\mathbf{y})$ *and the productive input feed* $(\mathbf{x})$ *for a farm with a conventional production system. The dashed lines represent isoprofit lines; the slope of one of these lines is* $\frac{\partial \mathbf{F}}{\partial \mathbf{x}} = \frac{\mathbf{w_x}}{\mathbf{p} \cdot \mathbf{D(z)}}$*, while the slope of the other isoprofit lines is* $\frac{\partial \mathbf{F}}{\partial \mathbf{x}} = \frac{\mathbf{w_x}}{\mathbf{p \cdot D(z)}} + \frac{\frac{\frac{1}{2}\alpha \cdot \partial \sigma_\pi^2}{\partial \mathbf{x}}}{\mathbf{p \cdot D(z)}}$*. Point* $\mathbf{R_0}$ *shows the optimal input-output combination* $(\mathbf{x_0}, \mathbf{y_0})$ *for a risk neutral farmer with a conventional production system, while point* $\mathbf{R_1}$ *shows the optimal input-output combination* $(\mathbf{x_1}, \mathbf{y_1})$ *for a risk averse farmer. Point* $\mathbf{S_0}$ *shows the input-output combination* $(\mathbf{x_0}, \mathbf{y_0'})$ *for a risk neutral farmer in a situation with maximum damage and no AMU, while point* $\mathbf{S_1}$ *shows the input-output combination* $(\mathbf{x_1}, \mathbf{y_1'})$ *for a risk averse farmer. Point* $\mathbf{S_0'}$ *shows the input-out combination* $(\mathbf{x_0'}, \mathbf{y_0''})$ *for a risk neutral farmer resulting from optimal damage abatement, while point* $\mathbf{S_1'}$ *shows the input-out combination* $(\mathbf{x_1'}, \mathbf{y_1''})$ *for a risk averse farmer.*

The optimal damage abatement effect and the level of optimal damage abatement input use is found at the point where the damage abatement function is tangent to the iso-utility line (see point T_1 in Figure 3.6). This point is found by taking the first derivative of $u(\pi)$ with respect to z; setting it equal to 0 and rewriting it in terms of $\frac{\partial D}{\partial z}$ (see Equations 3.14 and 3.15).

$$\frac{\partial u(\pi)}{\partial z} = p\left(F(x) \cdot \frac{\partial D}{\partial z}\right) - w_z - \frac{\frac{1}{2}\alpha \cdot \partial\sigma_\pi^2}{\partial z} = 0 \tag{3.14}$$

$$\frac{\partial D}{\partial z} = \frac{w_z}{p \cdot F(x)} + \frac{\frac{\frac{1}{2}\alpha \cdot \partial\sigma_\pi^2}{\partial z}}{p \cdot F(x)} \tag{3.15}$$

The marginal product of damage abatement input use is determined by w_z, p, $F(x)$, α and σ_π^2. The effects of w_z, p and $F(x)$ on the marginal product are similar to the standard profit maximization situation. As α is assumed to be positive, the more risk averse a farmer, the lower the marginal product of damage abatement input use, *cet. par.* The effect of σ_π^2 on damage abatement input use (i.e. AMU) can be positive (i.e. when a higher variance in profit results in more intensive AMU) or negative (i.e. when a higher variance in profit results in less intensive AMU), *cet. par.* However, since damage abatement input use reduces damage, it is clear that damage abatement input use (i.e. AMU) reduces σ_π^2. Therefore, the more risk averse a farmer, the more damage abatement inputs are used to reduce σ_π^2.

The EV_{AMU} is obtained by extending Equation (3.9) with the change in α and σ_π^2:

$$\text{EV}_{\text{AMU}} = \Delta y \cdot p - z \cdot w_z - \Delta \text{x} \cdot w_x - \Delta\left(\frac{1}{2}\alpha \cdot \sigma_\pi^2\right) \tag{3.16}$$

Similar to the baseline model, the EV_{AMU} is affected by the determinants p, w_x, w_z, $F(x)$ and $D(z)$. In the short run, $F(x)$ and $D(z)$ are fixed, while p, w_x and w_z are variable. Hence, p, w_x and w_z determine whether the EV_{AMU} is positive in the short run. In addition, the EV_{AMU} is affected by α and σ_π^2. The higher the risk aversion of a farmer, the higher the EV_{AMU}. Similarly, an increase in σ_π^2 also increase the EV_{AMU}.

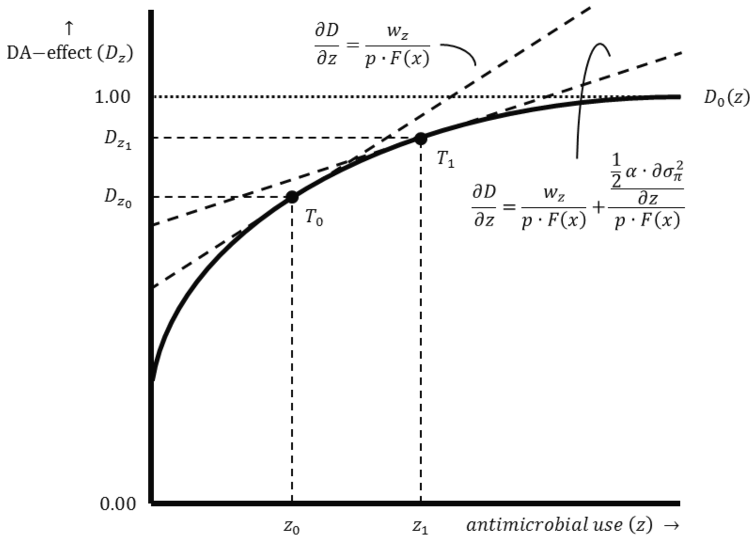

Figure 3.6. The optimal damage abatement effect of risk-neutral and risk-averse farmers. *Damage abatement function* $\mathbf{D_0(z)}$ *illustrates the relation between the damage abatement effect* $(\mathbf{D_z})$ *and the damage abatement input use* $(\mathbf{z})$ *for a farm with a conventional production system. The dashed lines represent isoprofit lines. The slope of one of these lines is* $\frac{\partial \mathbf{D}}{\partial \mathbf{z}} = \frac{\mathbf{w_z}}{\mathbf{p \cdot F(x)}}$. *The slope of the other isoprofit line is* $\frac{\partial \mathbf{D}}{\partial \mathbf{z}} = \frac{\mathbf{w_z}}{\mathbf{p \cdot F(x)}} + \frac{\frac{\frac{1}{2}\alpha \cdot \partial \sigma_\pi^2}{\partial \mathbf{z}}}{\mathbf{p \cdot F(x)}}$. *Point* $\mathbf{T_0}$ *shows the optimal damage abatement effect* $\left(\mathbf{D_{z_0}}\right)$ *for a risk neutral farmer, resulting from an optimal level of AMU* $(\mathbf{z_0})$. *Point* $\mathbf{T_1}$ *shows the optimal damage abatement effect* $\left(\mathbf{D_{z_1}}\right)$ *for a risk averse farmer, resulting from an optimal level of AMU* $(\mathbf{z_1})$.

3.4. Policy recommendations

The theoretical elaboration on the EV_{AMU} provides some important policy implications. Policy measures can be developed to affect the EV_{AMU} in order to reduce AMU in livestock production. In this section, policy recommendations are described for the three distinct situations included in the framework presented in section 3.

3.4.1. Baseline model

The baseline model showed that the EV_{AMU} is influenced in the short run by the output price, the price of productive inputs and the price of damage abatement inputs. Governments can therefore use price instruments to influence the EV_{AMU}. *Pricing of AMs* is the most obvious way to affect the EV_{AMU}, because an increase in the price of AMs increases the costs of AMU and reduces the EV_{AMU} for an individual farmer, i.e. AMU becomes less attractive. Future research should examine how large the price increase needs to be to adversely affect the EV_{AMU} in order to reduce AMU in livestock production.

Another instrument that can affect the EV_{AMU} is *product differentiation*, which provides incentives to farmers with a conventional production system to produce food products without AMU. Product differentiation should be an industry-led initiative, in which retailers decide to sell labelled meat products from animals raised without AMU. Producers of such food products receive higher premiums. If these premiums are passed on to the farmer, these premiums can help to offset higher production costs resulting from reductions in AMU. A recent example is McDonald's USA, who is pressing their meat suppliers to reduce AMU (McDonald's, 2015b). In addition, McDonald's developed a Global Vision for Antimicrobial Stewardship in Food Animals (McDonald's, 2015a). A drawback of introducing product differentiation is the likelihood of creating a two-tier food system with premium products from animals raised without AMU and meat products from animals raised with AMU. The risk is that the majority of consumers will continue buying the latter type of products, which do not pose a solution to the problem of AMR. Especially since consumers often over-claim their tendency to buy premium products, resulting in a value-action gap. Reinforcement of consumers' awareness of the problem of AMU in livestock production is therefore needed to ensure their willingness to buy premium products.

3.4.2. Production system improvements

The first extension of the baseline model reflected the impact of production system improvements. The farmer is essential in this respect, as the farmer makes the decisions about investments in production system improvements. Veterinarians and other farm advisors can facilitate farmers in this decision-making process by counselling, persuading, encouraging and stimulating farmers to invest in production system improvements (Ellis-Iversen *et al.*, 2010; Speksnijder *et al.*, 2015a). National and/or supra-national governments can promote investments in production system improvements directly or indirectly.

Direct stimulation is possible by providing subsidies for livestock farmers, for example via the Single Farm Payments scheme within the EU Common Agricultural Policy (CAP). Single Farm Payments can be linked to the obligation of responsible AMU and the obligation to meet particular targets with respect to reductions in AMU.

Indirect stimulation is possible through the introduction of accelerated depreciation, in which an asset loses book value at a faster rate than the traditional depreciation method. Generally, accelerated depreciation allows greater deductions of an asset and is used to minimize taxable income in the early years in exchange for increased taxable income in future years. This is a valuable tax incentive, which can encourage farmers to purchase new assets to improve the production system. It is therefore assumed that the introduction of accelerated depreciation will stimulate farmers to invest in production system improvements to reduce AMU. Recent examples related to environmental issues are the MIA scheme, which offers a tax refund on environmental investment, and the Vamil scheme, which provides possibilities for voluntary depreciation on environmental investment. Preference is given to indirect governmental support instead of direct support since indirect stimulation prevents that farmers entirely depend on governmental subsidies.

3.4.3. Risk and risk attitude

The second extension of the baseline model elaborated the impact of risk and risk attitude. Livestock farmers face various types of risk (Hardaker *et al.*, 2015). Price risks caused by volatility of input and output prices are perceived as the main source of risk among Dutch livestock farmers (Meuwissen *et al.*, 2001; Pennings and Smidts, 2000). Risk and risk attitude can be influenced in several ways. A distinction is made between recommendations to reduce *objective risks* and recommendations to reduce *perceived risks*. Interventions are assumed the main instrument to reduce both types of risks. Regarding human health care, Davey *et al.* (2013) distinguish *persuasive*, *restrictive* and *structural interventions*. This categorization is also applicable to livestock production, where persuasive interventions include changing the professional behaviour of farmers, restrictive interventions relate to restricting the freedom of prescribers to select and use AMs and structural interventions are similar to production system improvements.

Reducing *objective risks* can be achieved through structural interventions aimed at farm system improvements, such as providing better information to farmers in order to reduce the need for AMU (see section 4.2). An example is the introduction of precision livestock farming to support risk reduction by offering a management tool that enables a farmer to monitor animals automatically by using sensors, cameras and microphones (Armstrong *et al.*, 2014). Clinical signs of livestock diseases are detected earlier to enable quick countermeasures (Armstrong *et al.*, 2014). However, technology only provides a supportive tool and farmers still have to make decisions and take actions on-farm (Berckmans, 2014). Hence, perceived risks of farmers are also very important.

Perceived risks can be reduced by using persuasive interventions to affect the risk aversion of farmers. The framework has shown that the higher the degree of risk aversion, the higher the AMU. A better understanding of the risk perception of individual farmers can help to identify the underlying causes of risk aversion. This information is needed to design effective and structural solutions for reducing the degree of risk aversion. The impact of risks can also be reduced by sharing risks among a large group of farmers through insurance. Averaging risk reduces overall risk and provides opportunities to manage risks. To benefit from insurance as a farmer, membership is compulsory and the annual fee is related to the number of animals kept. Insurance with the intention to accumulate funds to compensate farmers for losses incurred from livestock diseases is possible through private insurance schemes (set up by farmers' organizations), cost-sharing schemes or insurance programs subsidized by governmental agencies (Otte *et al.*, 2004).

Using the approaches and tools outlined above to reduce objective and perceived risks and thereby reduce AMU in livestock production, a comprehensive herd health plan can be developed that is supported by all relevant farm advisors to ensure farmers' compliance (Speksnijder *et al.*, 2015b).

3.5. Concluding remarks and future outlook

The aim of this study was to develop a theoretical framework for assessing the EV_{AMU} and to determine the factors that affect the EV_{AMU}. Furthermore, the framework was used to derive policy recommendations to reduce AMU in livestock production by influencing the EV_{AMU}. The framework showed that the EV_{AMU} is negatively affected by the price of productive inputs and the price of damage abatement inputs, and positively affected by the price of output, the input-output combination and the damage abatement effect. In addition, the framework showed that the EV_{AMU} is positively affected by the degree of risk aversion and the variance of profit. An understanding of the EV_{AMU} and the factors that affect this EV_{AMU} can help policy makers to reduce AMU in livestock production.

Although the theoretical framework includes a broad set of situations and factors that affect the EV_{AMU} for individual livestock farmers, other situations (and factors) may also affect the EV_{AMU}. Furthermore, situations can be intertwined in reality. For example, the general perception of farmers is that the costs of non-antimicrobial alternatives and production system improvements are outweighed by the effect and costs of current AMU (Coyne *et al.*, 2014; Laanen *et al.*, 2014; Speksnijder *et al.*, 2015b). Hence, risk affects the decisions of individual farmers to invest in production system improvements.

This study provides policy recommendations to reduce AMU in livestock production. However, there are currently no global targets for reducing AMU and there is no understanding of how to set such targets. Hence, agreement is still needed about the level of AMU that is responsible and sustainable in the long run. A complete ban would have serious effects on animal health, animal welfare and productivity (Woolhouse *et al.*, 2015). Adverse effects of a ban on AMU would be at least partially softened if cost-effective non-antimicrobial alternatives were available. However, such alternatives (including probiotics and prebiotics) are still experimental (Laxminarayan *et al.*, 2013) and their efficacy is unclear and likely to be variable (Woolhouse *et al.*, 2015). Hence, more research is urgently needed on the effects of reducing AMU and potential alternatives to AMU in livestock production. Although there is not yet a consensus about an acceptable level of AMU in livestock production from both an economic and veterinary point of view, there is general agreement that AMU needs to be reduced. The theoretical framework presented in this study provides a solid theoretical basis for understanding the behaviour of individual farmers with regard to AMU and therefore for developing effective policies that can reduce AMU in livestock production.

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Chapter 4

The Relation between Technical Farm Performance and Antimicrobial Use of Belgian Broiler Farms

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Abstract

The aim of the present study was to explore the relation between both farm performance and antimicrobial use of Belgian broiler farms. Farm performance was expressed as technical efficiency, obtained by using a bootstrap Data Envelopment Analysis. Antimicrobial use was expressed as treatment incidence. Cluster analysis is used to obtain groups of farms with similar characteristics regarding technical farm performance and antimicrobial use. Results indicate that the farms within the different clusters combine different technical farm performance and different levels of antimicrobial use. Between the clusters, significant differences were found with respect to technical farm performance, AMU, resource intensity of feed, resource intensity of the number of day-old chicks at set-up, the number of antimicrobial treatments, the number of antimicrobial treatments related to either gut health or combined problems, and the number of antimicrobial treatments with orange active substances. The observed differences and similarities between farms are important to take into account policies that are aimed at declining veterinary antimicrobial use further.

Key words: Poultry production; Veterinary antimicrobial use; Technical efficiency; Data Envelopment Analysis; Cluster Analysis

4.1. Introduction

Antimicrobial agents are widely used in veterinary medicine for therapeutic treatment, metaphylaxis, prophylaxis and growth promotion (McEwen and Fedorka-Cray, 2002; van den Bogaard and Stobberingh, 1999). The advantages generated from veterinary antimicrobial use (AMU) exceed more than just animal health and welfare, as it has resulted in economic benefits for food animal producers through increased production efficiency and a more secure health for the general public (Hao *et al.*, 2014). Although AMU provides clear benefits, it simultaneously results in clear risks due to the enrichment of antimicrobial resistant microorganisms. There is a broad consensus that excessive and inappropriate AMU enriches the development, selection and spread of antimicrobial resistance (AMR). Subsequently, resistant microorganisms can be transferred from agricultural settings to humans (Aarestrup and Wegener, 1999; Aarestrup *et al.*, 2008; Singer *et al.*, 2003). This has resulted in increased societal and political pressure to reduce AMU.

Given the link between AMU and AMR, the use of antimicrobial growth promoters is banned in the European Union (Landers *et al.*, 2012). Several European countries (including Denmark, France Norway and The Netherlands) have introduced general policies aimed at reducing non-human AMU with formal reduction targets expressed as percentage of previous use (Rushton *et al.*, 2014). These reduction targets were not based on any evidence-based dose (AMU) – effect (AMR) relation. However, faced with increasing public pressure and concerns, the focus of national and supra-national governments is on further reductions of AMU (Speksnijder *et al.*, 2015c). The generic policies already picked up the “low-hanging fruit” regarding AMU. In order to go beyond the “low-hanging fruit”, the focus need to be shifted from generic measures towards individual farm conditions. From that perspective, insights in the relation between technical farm performance and AMU of individual farms are needed.

The aim of the present study was therefore to explore the relation between technical farm performance and AMU. Some studies already investigated the link between AMU and technical farm performance. Collineau *et al.* (2017) conducted a cross-sectional study among farrow-to-finish pig farms in Belgium, France, Germany and Sweden in which “top-farms” were allocated and compared with "regular-farms" in terms of farm characteristics, biosecurity and health status. Top-farms were ranked based on the combination of their level of AMU and their level of technical performance (expressed by the number of weaned pigs per sow and per year). In addition, other studies did not find any significant associations between technical performance indicators and AMU in broiler and pig farms (e.g. Chauvin *et al.*, 2005; van der Fels-Klerx *et al.*, 2011).

This study differs from previous studies in the sense that a multidimensional performance indicator of technical farm performance is used instead of a one-dimensional performance indicator, like the number of weaned pigs per sow and per year used by Collineau *et al.* (2017). A multidimensional indicator can include more inputs that are needed to produce a defined level of output. In the present study, multiple flock observations per farm are used to provide an appropriate assessment of both technical farm performance and AMU instead of using single flock or herd observations. In addition, specific differences between farms with respect to various indicators related technical farm performance and AMU are tested.

4.2. Materials and Methods

4.2.1. Data

The data used in the present study is collected in the context of the European "Ecology from farm to fork of microbial drug resistance and transmission" (EFFORT) project. The Belgian broiler farms included in this study are conventional farms. Hence, the intended slaughter age is lower than 60 days and the average growth per day is higher than 55 grams per day. Additionally, the stocking density is 10 birds or more per square meter, and each stable houses between 10,000 and 40,000 birds. In total, data was collected from 251 flocks from 39 Belgian broiler farms. First, the data was screened for the availability of data regarding the number of animals delivered to the slaughterhouse (including their mean weight measured in kilograms), the number of animals at set-up (calculated by correcting the number of animals slaughtered via mortality) and the total amount of feed used (consisting of concentrate feed and wheat). In total, information with respect to feed was (partly) missing for 17 broiler farms including 104 flock observations. Consequently, these observations were not taken into account in subsequent analyses. Within the data from the remaining 22 broiler farms, information about the mean weight at slaughter was missing for the second flock of farm 3 and mortality was missing for the seventh flock of farm 16. Hence, these observations were also not taken into account in subsequent analyses. The large number of missing data is explained by the fact that the design and collection of the data was not specifically designed for the aim of this study.

The data was provided and strictly screened by project partners. Additional screening resulted in 18 potential outliers (i.e. potential experimental errors) since these values deviated significantly from other parameters both within and between farms. The project partners responsible for collecting the data were contacted. Additional checks were performed based on the correctness of the parameters. For example, the amount of feed was checked by using the feed conversion rate. Afterwards, 10 outliers were observed and removed from the data. Details regarding the screening of the (potential) outliers are shown in the Appendix (see Table A.4.1). After removing the flock observations with missing data and outliers, a dataset with 134 flock observations from 22 Belgian broiler farms remained.

4.2.2. Technical farm performance

A widely used concept in economics is efficiency, which consists of technical and allocative efficiency. Technical efficiency is the ability of a farmer to produce maximum output with a given level of minimum input. Allocative efficiency measures the ability of a farmer to use inputs in optimal proportions given certain input prices (Coelli *et al.*, 2005). The focus in this research is on measuring technical efficiency as indicator of technical farm performance. Hence, the terms technical efficiency and technical farm performance are used interchangeably in the remainder of this study. The literature distinguishes two main efficiency measurement methods to measure the efficiency of decision-making units (DMUs) under evaluation: one is the parametric Stochastic Frontier Analysis (SFA) and the other one is the non-parametric method Data Envelopment Analysis (DEA) (Coelli *et al.*, 2005). The strength of DEA versus SFA is that it does not require any assumptions about the functional form and the distribution of the inefficiency term. However, a limitation of the original DEA method is that it is a deterministic approach assuming that there are no random factors that affect the location of the frontier when assessing performance (Horta *et al.*, 2012). Hence, the DEA method is sensitive to potential outliers. Bootstrapping is applied to remove the (potential) sample bias. The present study used the method as outlined in Simar and Wilson (1998) for obtaining bias corrected efficiency scores, and confidence intervals.

The DEA method was introduced by Charnes *et al.* (1978) who built on the work of Farrell (1957). Given a number of DMUs, efficiency scores are measured for each DMU relative to an efficiency frontier which is a benchmark of best performing firms (Ray, 2004). Variable returns to scale is used since the size of the farms included in the sample differs. In addition, short-term effects are preferred rather than long-term effects. Input orientation is used since farmers are assumed to adjust their input use more easily compared to outputs. Input-oriented models are specifically used to test if a DMU under evaluation can reduce its inputs while keeping the outputs at their current levels (Banker et al. 1984). DMUs in the present study are the flock observations. The present study used the following input-oriented DEA model for DMU_p:

$$\min \theta$$

Subject to

$$\sum_{n=1}^{N} \lambda_n x_{jn} \leq \theta x_{jp} \qquad j = 1, \dots, m$$

$$\sum_{n=1}^{N} \lambda_n y_{kn} \geq y_{kp} \qquad k = 1, \dots, r$$

$$\sum_{n=1}^{N} \lambda_n = 1$$

$$\lambda_n \geq 0 \qquad n = 1, \dots, N$$

where θ represents the (input-oriented) efficiency score of the *DMU* under analysis; N represents the number of *DMUs* under evaluation; λs represent the dual variables that identify the benchmarks for inefficient units; x_{jn} is the amount of input j used by *DMU* n; x_{jp} is the jth input for *DMU p*; y_{kn} is the amount of output k provided by *DMU* n; y_{kp} is the kth output for *DMU p*.

Figure 4.1 shows a schematic representation of an input-oriented DEA model. The Figure illustrates an example of how a production frontier of efficient DMUs is established. DMU *A* – DMU *D* are on the production frontier, which indicates that their efficiency score equals one. The production frontier dominates DMU *E* and DMU *F*. The efficiency score of DMU *E* is calculated by dividing the distance from point E' to point O by the distance from point E to point zero.

In the present study, one frontier is estimated for all flock observations and the efficiency of all farms is compared relative to that frontier. The computations used the package *Benchmarking*, which runs under R.

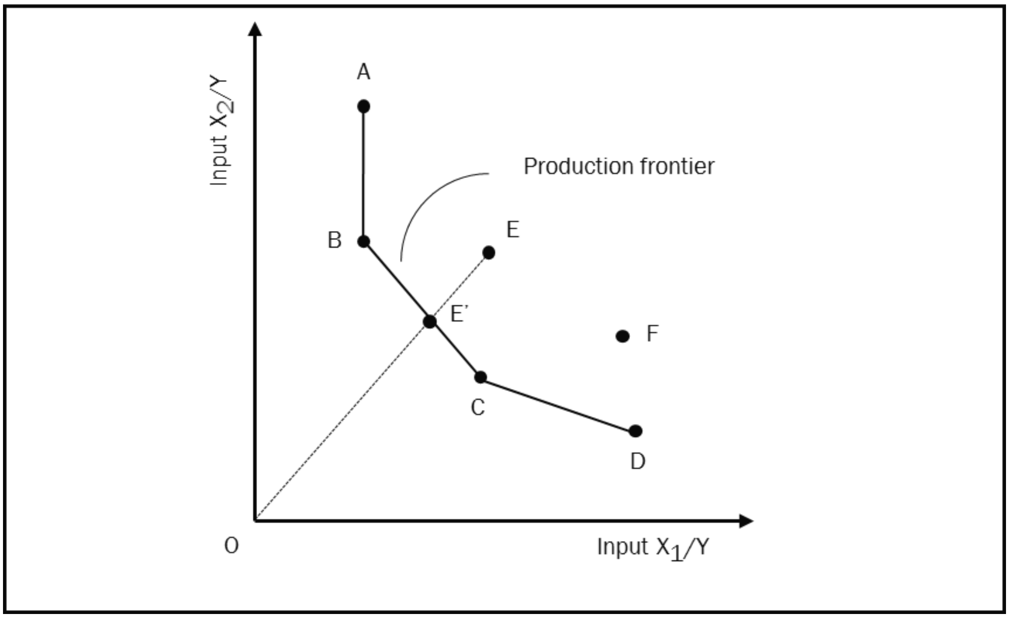

Figure 4.1. Schematic representation of an input-oriented DEA model

4.2.3. Quantification of AMU

AMU was quantified in a standardized manner by partners of the EFFORT project by using the treatment incidence (TI) as described by Persoons *et al.* (2012). The TI for broilers is defined as the number of chickens per 1,000 that are treated daily with one defined daily dose (DDD_{VET}). The DDD_{VET} is defined as the average maintenance dose per day and per kg chicken of a specific drug (Jensen *et al.*, 2004). The following formula was used to calculate AMU (see equation 4.1):

$$TI_{1,000} = \frac{\text{total amount of antimicrobial administered (mg)}}{DDD_{VET}\text{(mg/kg)} \times \text{number of days at risk} \times \text{kg chicken}} \times 1{,}000 \text{ animals at risk} \quad (4.1)$$

4.2.4. Cluster Analysis

The present study used cluster analysis to identify farms with similar technical farm performance and AMU. The farms are clustered based on the standardized values of both the average bias-corrected efficiency scores and the average treatment incidence of the farms. Milligan (1980) has shown that strong dependence of the *K*-means algorithm on initial clustering and suggest that good final cluster structures can be obtained by using Ward's hierarchical method (Ward, 1963) in order to provide the *K*-means algorithm with an initial number of clusters. The optimal number of clusters is therefore chosen based on the hierarchical Ward's minimum variance method, which minimizes the sum of squared distances between farms within a cluster and maximizes the square distance between the various clusters. Both the dendrogram and the agglomeration schedule from Ward's method and the level interpretability of the obtained solutions are used to establish the most meaningful number of clusters. In that decision process, the later criterion has been decisive in the present study. After selecting an appropriate number, a non-hierarchical K-means cluster method is applied to cluster the farms. K-means clustering minimizes the distance between the data and the corresponding cluster centroid. The squared Euclidean distance (i.e. the sum of the squared differences between the values of the clustering variables) is selected to measure the distance between the farms in the cluster analysis.

After the clustering, the groups of farms are compared by using the flock observations and looking at technical efficiency, AMU, the resource intensity of the two selected inputs, the number of antimicrobial treatments, the number of antimicrobial treatments related to different categories of clinical disorders, the type of active substance used, and the day of the first antimicrobial treatment. *Resource intensity* is a measure of the resources required for the provision of a kg of meat delivered to the slaughterhouse. The *clinical disorders* for which antimicrobials are mostly used include gut health problems, respiratory diseases and locomotion-related disorders (EMA and EFSA, 2017). Additional categories are first-week problems and other disorders. The present study used a colour system for ranking the *type of active substance*. The Belgian centre of expertise on Antimicrobial Consumption and Resistance in Animals introduced this system to determine the conditions of use for each active substance, based on their importance for animal and human health like classified by the World Health Organisation and the World Organisation for Animal Health. Yellow, orange and red are the colour codes used in the colour system. Yellow active substances can be used with no additional conditions (but laboratory testing is recommended). Orange active substances require at least a diagnosis based on laboratory testing. Use of red active substances is only allowed when diagnosis is based on laboratory testing and the pathogen is resistant to first, second or third-choice antimicrobials colour-coded yellow or orange.

To explain the differences between the farm clusters, a Shapiro-Wilk test was performed to test the normality of the data (i.e. the standardized residuals should be normally distributed). In addition, the Levene's test was carried out to test the homogeneity of variance. For the normally distributed data with equal variances for all groups of farms, a one-way ANOVA including the Tukey HSD post hoc test was applied. For the non-normally distributed data with equal variances, a Kruskal-Wallis test with Dunn's pairwise tests was used.

4.3. Results

4.3.1. Descriptive Statistics

One output and two inputs were selected to determine technical farm performance. Output (*Y*) corresponds to the total quantity of meat delivered to the slaughterhouse per flock, measured in kilograms. The total energy value of the total amount feed used per flock and the number of day-old chicks at set-up per flock are selected as inputs. These two inputs are considered as the main inputs in broiler production since feed costs and the costs for day-old chicks are the main production costs of broilers in euros per kg live weight in the European Union (van Horne, 2017). Regarding feed use, distinction is made between concentrate feed and wheat. The energy value for concentrate feed is considered to be 12.65 MJ (mega joules) per kilogram, and 12.47 MJ per kg for wheat (van Duinkerken and Spek, 2016). The total energy value of feed used (X_1) is calculated by multiplying the total kilograms concentrate feed used times the energy value of concentrate feed per kg plus the total kilograms wheat used times the energy value of wheat per kg. The second input selected consists of the number of day-old chicks used at set-up (X_2). *AMU* is quantified in a standardized manner using $TI_{1,000}$. When the $TI_{1,000}$ for overall antimicrobial consumption equals 300, it means that on average per day 300 broilers out of 1,000 animals were treated with one DDD_{VET}. A $TI_{1,000}$ of zero, indicates that no treatment was recorded for this flock.

Table 4.1 shows the descriptive statistics of the selected output, inputs, and AMU including the mean, the standard deviation, the minimum and maximum of all flock observations.

Table 4.1. Descriptive statistics of output Y, inputs X_1 and X_2, and AMU

	Unit	Mean	Standard Deviation	Min	Max
Y	kg	96,740	56,199	39,146	232,914
X_1	MJ	2,121,327	1,380,726	801,899	6,221,609
X_2	AU	40,467	23,588	17,317	100,796
AMU	TI_{1000}	145	110	0	557

Y = total kilograms (kg) meat delivered to slaughterhouse; X_1 = total energy value in mega joules (MJ) of the total amount of feed used; X_2 = total number of day-old chicks at start-up measured in animal units (AU); *AMU* = antimicrobial use expressed as treatment incidence (TI_{1000})

4.3.2. Technical farm performance and AMU

Results of the DEA are shown in Table 4.2. The first column of the table shows the farm ID followed by the number of flock observations per farm, which differs among the farms included in the sample. The subsequent columns of Table 4.2 show the average original efficiency scores, the average bias-corrected efficiency scores, the bias, and the confidence interval. The bootstrap DEA results show that the bias-corrected efficiency scores are within relatively narrow confidence intervals, i.e. the lower bound and the upper bounds are relatively close. Furthermore, the bias-corrected estimates are preferred to the original estimates, as described by Fried *et al.* (2008), since the estimated bias is much larger than the standard deviation (i.e. the square root of the variance like presented in Table 4.2). In the last column of the table, the average AMU is shown.

The average input-specific bias-corrected technical efficiency scores for farm 1 (see Table 4.2) equals 0.916 indicating that this farm is efficient for 91.6 percent and input use can be reduced on average with 8.4 percent to obtain the same level of output. The low margins and high volumes in broiler meat production force farmers to operate in an efficient way in order to survive, which explains the relatively high overall efficiency scores.

Table 4.2. The average input-specific technical efficiency scores (including the bias-correct efficiency scores, the bias, and the 95%-confidence interval) and AMU

Farm ID	Number of flocks	Efficiency scores	Bias-corrected efficiency scores	Bias	95% confidence interval		AMU
					Lower Limit	Upper limit	
1	6	0.925	0.916	0.009	0.903	0.924	114.39
2	7	0.913	0.900	0.013	0.886	0.912	185.65
3	3	0.968	0.932	0.037	0.883	0.966	71.54
4	6	0.934	0.926	0.008	0.916	0.932	116.25
5	6	0.892	0.880	0.012	0.869	0.890	133.59
6	7	0.968	0.945	0.024	0.915	0.966	29.43
7	3	0.909	0.893	0.016	0.877	0.906	223.35
8	2	0.977	0.968	0.009	0.956	0.976	59.58
9	6	0.957	0.942	0.015	0.929	0.955	133.77
10	7	0.987	0.972	0.015	0.957	0.985	178.88
11	6	0.947	0.934	0.013	0.916	0.945	318.24
12	8	0.916	0.908	0.008	0.899	0.915	203.84
13	6	0.899	0.892	0.006	0.883	0.898	150.37
14	7	0.959	0.950	0.009	0.939	0.958	324.86
15	8	0.993	0.967	0.027	0.938	0.991	117.72
16	3	0.948	0.935	0.013	0.920	0.947	168.07
17	8	0.962	0.936	0.025	0.895	0.960	78.67
18	7	0.854	0.843	0.011	0.827	0.852	16.74
19	6	0.948	0.932	0.016	0.913	0.946	168.29
20	8	0.937	0.928	0.010	0.915	0.936	124.18
21	7	0.913	0.905	0.009	0.894	0.912	88.76
22	7	0.918	0.909	0.009	0.898	0.916	169.55

4.3.3. Cluster analysis

Figure 4.2 shows the results of the non-hierarchical K-means cluster method. In total, three different clusters are distinguished. The distribution of the farms over the clusters is unbalanced. The three clusters include twelve, six and four broiler farms with 70, 38 and 26 flock observations respectively.

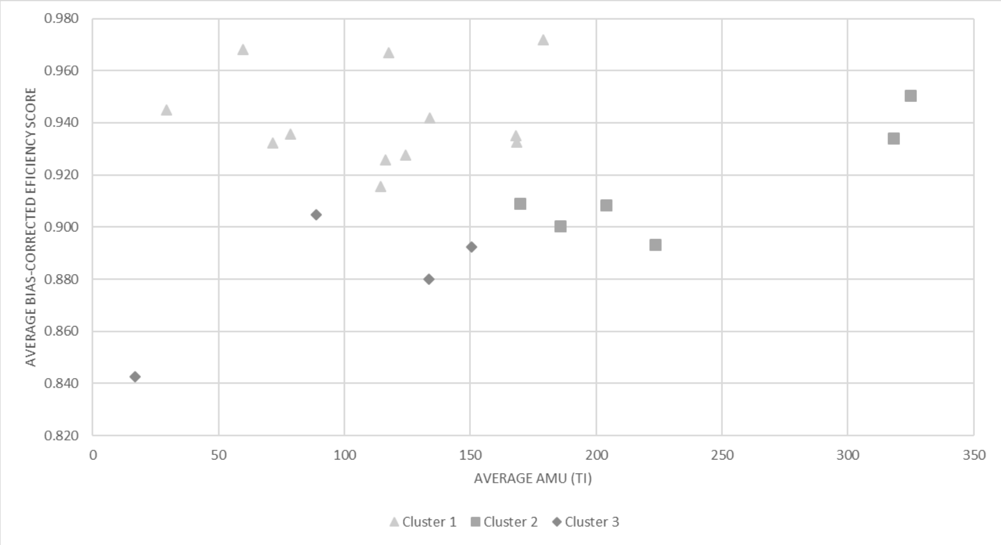

Figure 4.2. Results Hierarchical Cluster Analysis

Table 4.3 shows the mean and standard deviation of the selected variables in the three clusters and the comparison among the different variables between them. A Kruskal-Wallis test was conducted to compare the clusters with respect to all variables except for the resource intensity of input X_2 for which a Welch test with a Games-Howell post hoc test was conducted. The Kruskal-Wallis test indicated a significant difference in the mean ranks of at least one pair of clusters for the bias-corrected efficiency scores (p = 0.000). Dunn's pairwise comparison test indicate a significant difference in the mean ranks of cluster 1 and 2 (p = 0.003), cluster 1 and 3 (p = 0.000), and cluster 2 and 3 (p = 0.006). This indicated a significant higher technical farm performance of farms in cluster 1 compared to the farms in cluster 2 and 3. In addition, the farms in cluster 2 performed significantly better compared to the farms in cluster 3.

With respect to AMU, the Kruskal-Wallis test indicated that there was a significant difference in the mean ranks of at least one pair of clusters (p = 0.000). Dunn's pairwise comparison test indicate a significant difference in the mean ranks of cluster 1 and 2 (p = 0.000), and cluster 2 and 3 (p = 0.000). This indicated a significant higher AMU of farms in cluster 2 compared to the farms in cluster 1 and 3.

Table 4.3. Mean and standard deviation for the selected variables in four clusters and the comparison between them*

	Cluster 1 (n=70)		Cluster 2 (n=38)		Cluster 3 (n=26)	
	Mean	SD	Mean	Mean	Mean	SD
BCE	0.941[b,c]	0.033	0.918[a,c]	0.034	0.879[a,b]	0.040
AMU	115.098[b]	76.001	236.069[a,c]	132.402	93.936[b]	71.024
RI(x_1)	21.306[c]	2.686	20.573[c]	1.563	23.243[a,b]	2.474
RI(x_2)	0.413[b,c]	0.024	0.425[a]	0.024	0.431[a]	0.021
TRE	2.586[c]	1.198	2.632[c]	1.217	1.885[a,b]	0.816
GUT	1.414[c]	1.014	1.368[c]	0.913	0.577[a,b]	0.578
RES	0.029	0.168	0.079	0.359	0.077	0.272
LOC	0.057	0.234	0.026	0.162	0.038	0.196
FIR	0.829	0.613	0.921	0.539	0.692	0.618
OTH	0.229	0.487	0.237	0.490	0.192	0.491
COM	0.029[c]	0.168	0.000[c]	0.000	0.308[a,b]	0.618
YEL	0.229	0.423	0.079	0.273	0.077	0.272
ORA	2.214	1.075	2.447[c]	1.224	1.654[b]	0.745
RED	0.143	0.352	0.105	0.311	0.154	0.368
DT1	6.304	9.077	5.079	9.012	11.077	13.314

* Superscripts indicate significant difference ($P < 0.05$) compared with cluster 1 (a), cluster 2 (b) or cluster 3 (c); *BCE* = bias-corrected efficiency scores; AMU = antimicrobial use; *RI(X1)* = resource intensity of input x_1; *RI(X2)* = resource intensity of input x_2; *TR* = number of number of antimicrobial treatments; *GUT* = number of antimicrobial treatments related to gut health problems; *RES* = number of antimicrobial treatments related to respiratory problems; *LOC* = number of antimicrobial treatments related to locomotion problems; *FIR* = number of antimicrobial treatments related to first week problems; *OTH* = number of antimicrobial treatments related to other problems; *COM* = number of antimicrobial treatments related to combined problems; *YEL* = number of antimicrobial treatments with yellow active substances; *ORA* = number of antimicrobial treatments with orange active substances; *RED* = number of antimicrobial treatments with red active substances; *DT1* = day first antimicrobial treatment.

The Kruskal-Wallis test indicated that there was a significant difference in the mean ranks of at least one pair of clusters with respect to the resource intensity of input x_1 ($p = 0.000$). Dunn's pairwise comparison test indicate a significant difference in the mean ranks of cluster 1 and 3 ($p = 0.001$), and cluster 2 and 3 ($p = 0.000$). This indicates a significant higher resource intensity of input x_1 of the farms in cluster 3 compared to the farms in cluster 1 and 2.

The Welch test indicated that there was a significant difference in the mean difference of the resource intensity of input x_2 (*Welch's F* (2, 64.323) = 7.925, $p = 0.001$) between the clusters. Games-Howell post hoc comparisons showed a significant between cluster 1 and 2 ($p = 0.026$) and

4

cluster 1 and 3 (*p* = 0.001). This indicated a significant lower resource intensity of x_2 of the farms in cluster 1 compared to the farms in cluster 2 and 3.

With respect to the number of antimicrobial treatments, the Kruskal-Wallis test indicated a significant difference in the mean ranks of at least one pair of clusters (*p* = 0.022). Dunn's pairwise comparison test indicate a significant difference in the mean ranks of cluster 1 and 3 (*p* = 0.030), and cluster 2 and 3 (*p* = 0.044). This indicates that the number of antimicrobial treatments was significantly lower in the farms of cluster 3 compared to the farms in cluster 1 and 2.

In addition, the Kruskal-Wallis test indicated that there was a significant difference in the mean ranks of at least one pair of clusters for the number of antimicrobial treatments related to gut health problems (*p* = 0.000). Dunn's pairwise comparison test indicate a significant difference in the mean ranks of cluster 1 and 3 (*p* = 0.000), and cluster 2 and 3 (*p* = 0.001). This indicates that the number of antimicrobial treatments related to gut health problems was significantly lower at the farms of cluster 3 compared to the farms within cluster 1 and 2.

Regarding the number of antimicrobial treatments related to combined problems, the Kruskal-Wallis test indicated a significant difference in the mean ranks of at least one pair of the clusters (*p* = 0.000). Dunn's pairwise comparison test indicate a significant difference in the mean ranks of cluster 1 and 3 (*p* = 0.001), and cluster 2 and 3 (*p* = 0.000). This indicates that the number of antimicrobial treatments related to combined problems was significantly higher at the farms of cluster 3 compared to farms within cluster 1 and 2.

Finally, the Kruskal-Wallis test indicated a significant difference in the mean ranks of at least one pair of the clusters with respect to the number of antimicrobial treatments with orange active substances (*p* = 0.022). Dunn's pairwise comparison test indicate a significant difference in the mean ranks of cluster 2 and 3 (*p* = 0.022). This indicates that the number of antimicrobial treatments with orange active substances was significantly higher at the farms in cluster 2 compared to the farms in cluster 3.

4.4. Discussion and Conclusions

The aim of this study was to explore the relation between technical farm performance and AMU. A multidimensional performance indicator, that combined one output and two inputs, was used to assess the technical farm performance of 22 Belgian broiler farms and their corresponding AMU. DEA with bootstrapping was used to obtain the technical farm performance and a cluster analysis was used to compare clusters of farms with similar farm characteristics with respect to technical farm performance and AMU. In total, three clusters were distinguished in this study.

Results of the present study indicate that the technical farm performance of the farms in cluster 1 was significantly higher compared to the performance of the farms in cluster 2 and 3, while AMU of farms in cluster 1 was significantly lower compared to the farms in cluster 2. The farms in cluster 2 performed significantly less efficient compared to the farms in cluster 1, while their technical farm performance was significantly higher compared to the farms in cluster 3. AMU of the farms in cluster 2 was significantly higher compared to the farms in the other clusters. The farms in cluster 3 performed significantly less efficient compared to the performance of the farms in other clusters. Simultaneously, AMU was significantly lower at the farms in cluster 3 compared to the farms in cluster 2. The finding that farms can have low AMU and high technical farm performance are in line with the results of other studies, e.g. Collineau *et al.* (2017).

Within the present study, the clusters were also compared according to other variables related to technical farm performance and AMU. Significant differences between the clusters were found with respect to technical farm performance, AMU, resource intensity of feed, resource intensity of the number of day-old chicks at set-up, the number of antimicrobial treatments, the number of antimicrobial treatments related to either gut health or combined problems, and the number of antimicrobial treatments with orange active substances.

The results with respect to the resource intensity of feed indicated that the farms in cluster 3 significantly used more feed compared to the farms in the clusters 1 and 2. This might be an explanation for the significant lower technical farm performance of the farms in cluster 3 compared to the farms in cluster 1 and 2. In addition, the results with respect to the resource intensity of the number of day-old chicks at set-up indicated that the resource intensity with respect to this input was significantly lower for the farms in cluster 1 compared to the farms in cluster 2 and 3. This might indicate lower mortality rates and higher average daily growth for the farms in cluster 1 since these farms need less day-old chicks at set-up to obtain higher output. In addition, the results showed that the farms in cluster 3 used significantly less antimicrobial treatments as well as less antimicrobial treatments related to gut health problems compared to the farms in cluster 1 and 2. In addition, the results showed that the farms in cluster 3 used significantly more antimicrobial treatments related to combined problems compared to the other clusters. Finally, the number of antimicrobial treatments with orange active substances was significantly higher at the farms in cluster 2 compared to the farms in cluster 3.

The information with respect to the differences and similarities between the farms can be used in new policies to reduce AMU. For example, farms with similar characteristics as the farms in cluster 1 and 2 should focus on addressing gut health problems. Effective approaches regarding gut health problems might reduce the need for AMU. At the same time, the focus for farms in cluster 3 should be addressing combined problems in order to improve technical farm performance and reduce AMU. Hence, the results of the present study show that the farm conditions differ among the farms and different approaches are therefore needed to further reduce AMU.

Further research is need to validate the findings of this study in larger and more representative samples, as well as among broiler farms and other species in other countries. Future research should also take account for other inputs, like animal welfare and environmental issues, when estimating technical farm performance.

Acknowledgements

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Appendix

Table A.4.1. Overview of the (potential) outliers

Farm ID	Flock	Parameter	Explanation
3	4	FCR	The value was considered to be incorrected and therefore removed
4	4	FCR	The value was considered to be incorrected and therefore removed
4	6	MR	Not enough evidence to assume that the observation was incorrect
7	1, 2, 4–7	FCR	All values were checked by the veterinarian; the values of the first two flocks were correct, the values of the last four flocks were incorrected and therefore removed
11	6	MR	Not enough evidence to assume that the observation was incorrect
14	3	MR	Not enough evidence to assume that the observations were incorrect
15	6	FCR	The value was checked by the veterinarian; and appeared to be correct
16	1, 3, 5 and 6	FCR	All values were checked by the veterinarian; the value of the first flock was corrected, the values of the other flocks were incorrected and therefore removed
17	1	ADG	The value was checked by the veterinarian and corrected afterwards
19	5	MR	The veterinarian checked the value; and found out that there were problems in the climate control within the stable. Consequently, all technical performance indicators of this flock were considered as outlier and removed.

Chapter 5

The Impact on Technical and Economic Performance of Veterinary Interventions Aimed at Reducing Antimicrobial Use on Belgian Broiler Farms

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Abstract

Antimicrobial resistance is a global threat for both human and animal health. One of the main drivers of antimicrobial resistance is inappropriate antimicrobial use in livestock production. The aim of this study was to examine the technical and economic impact of tailor-made interventions, aimed at reducing antimicrobial use in broiler production. Historical (i.e. before intervention) and observational (i.e. after intervention) data was collected at 20 Belgian broiler farms. Results indicate that average daily growth and mortality generally increased after intervention, while feed conversion and antimicrobial use decreased. Economic performance after intervention was generally higher than before intervention. Sensitivity analyses on price changes confirm the robustness of this finding.

Key words: Veterinary antimicrobial use; Broiler Production; On-farm interventions.

5.1. Introduction

The introduction of antimicrobials in the second half of the 20th century has made a significant contribution to animal health and welfare as well as production efficiency (Odonkor and Addo, 2011; Speksnijder *et al.*, 2015c). Within the livestock production sector, pig and broiler production are top sectors using antimicrobials (Filippitzi *et al.*, 2014; van Boeckel *et al.*, 2015). Besides therapeutic treatments, antimicrobial agents are used for prophylactic purposes (i.e. disease prevention), metaphylactic purposes (i.e. group treatment when one or more animals of a flock or herd show disease symptoms) and growth promotion (McEwen and Fedorka-Cray, 2002). An important negative consequence of AMU is the potential risk for public health as it contributes to the selection and spread of antimicrobial resistance (AMR), especially when antimicrobials are used inappropriately (e.g. excessive use or under dosing of antimicrobials). Hence, there is societal and political pressure to reduce AMU. However, reducing AMU is not straightforward due to the high efficacy of antimicrobials and their relatively low cost (Lhermie *et al.*, 2017). Generally, there is agreement among policy makers and scientists that the use of antimicrobial growth promoters is not necessary since proven management alternatives are available which yield similar economic results (Aarestrup *et al.*, 2010; Maron *et al.*, 2013). Prophylactic use is also considered as overuse since application occurs even when there are no symptoms of disease. However, for metaphylactic and therapeutic use, it is less clear whether the use is justified.

Veterinarians can play an important role in reducing AMU by farmers (Currie *et al.*, 2018; Speksnijder *et al.*, 2015b). Tackling farm specific problems through tailor-made interventions might therefore be an important tool in reducing (the need for) AMU. Studies in pig production have shown that AMU can be reduced without jeopardising technical performance (e.g. Postma *et al.*, 2017). However, the farmers' main objection to implement new strategies for further reducing AMU appeared to be mainly financial (Visschers *et al.*, 2015). Hence, there is a need investigating the economic impact of reducing AMU. Existing studies on the impact of AMU on economic performance have focused on substituting improved management practices, particularly biosecurity measures, for AMU (Postma *et al.*, 2017; Rojo-Gimeno *et al.*, 2016). The possibilities of reducing AMU in broiler production through the application of tailor-made interventions have not been investigated so far. In addition, existing studies did not yet examine the impact of such interventions on technical and economic performance. In the light of the foregoing, the aim of this study was to examine the impact of tailor-made interventions in broiler production, aimed at reducing AMU, on technical and economic performance.

5.2. Materials and Methods

5.2.1. Data

The data used in this study is collected at 20 Belgian broiler farms within the framework of the European "Ecology from farm to fork of microbial drug resistance and transmission" (EFFORT) project. The broiler farms in this study are conventional farms with an intended slaughter age lower than 60 days and a growth rate higher than 55 grams per day. Farms generally have multiple stables, where each stable houses between 10,000 and 40,000 birds and the stocking density is 10 birds or more per square meter. Farmers' participation in the survey used in this study was voluntary. Based on the first farm visit and historical production data of each farm, the type of interventions were defined in a farm-specific action plan.

For each participating farm, historical data (i.e. before intervention) and observational data (i.e. after intervention) were collected on flock basis. Data was collected with respect to technical performance, such as average daily growth (ADG), feed conversion (FCR), mortality (MR) and AMU. Data on AMU was measured as treatment incidence (TI) as described by Persoons *et al.* (2012). The TI for broilers is defined as the number of broilers that are treated daily with one defined daily dose (DDD_{VET}) (see equation 5.1). The DDD_{VET} is defined as the average maintenance dose per day and per kg chicken of a specific drug (Jensen *et al.*, 2004).

$$TI = \frac{\text{total amount of antimicrobial administered (mg)}}{DDD_{VET}(\text{mg/kg}) \times \text{number of days at risk} \times \text{kg chicken}} \times 1{,}000 \text{ animals at risk} \qquad (5.1)$$

The number of flocks in both the historical and the observational data differs per farm. Historical data for 136 flocks was available (i.e. an average of 6.8 flock observations per farm) and observational data for 206 flocks (i.e. an average of 10.3 flock observations per farm).

Partners from the EFFORT project screened the data strictly. However, additional screening of technical performance indicated some large deviations within farms (e.g. a FCR higher than 2 or an ADG higher than 80 grams per day). These deviations were considered potential outliers (i.e. potential experimental errors). In total, 36 observations with potential outliers and missing data were observed. Thereafter, the project partner that collected the data checked the potential outliers by recalculating the performance indicators based on additional data that was not incorporated in this study. Finally, thirteen potential outliers appeared to be correct, twelve potential outliers were corrected and eleven observations with outliers (nine) or missing data (two) were removed. Details with respect to the screening of the data can be found in the Appendix (see Table A.5.1).

The historical and observational data from the intervention farms were complemented with the same information from 13 non-intervention Belgian broiler farms. These farms are semi-control farms since no specific action plan was developed nor implemented. However, regular veterinary practices have taken place at these farms. The data of these farms will therefore be used to compare the results of the intervention farms with the results of non-intervention farms.

5.2.2. Definition of intervention

Following definitions on intervention in human medicine by Davey *et al.* (2017), interventions were defined as any act, fact, or measure on where and why antimicrobial agents are used with the particular aim to reduce (the need for) AMU. Interventions in the present study can focus on the *farmer*, *farm and animal*. Interventions regarding the farmer are also known as persuasive interventions, which are targeted actions against specific AMU, the review of treatments and rules to omit preventive treatments and to limit to curative treatments. These interventions mainly aim at changing the attitude of farmers, and convincing farmers to reduce AMU. Interventions aimed at the farm are mainly aimed at the farm management while interventions aimed at the animals are mainly aimed at disease management (i.e. susceptibility of animals to diseases). Both interventions related to the farm and the animals are also known as structural interventions. The type and number of interventions depend on the tailor-made action plan that was established according to the specific problems on the farm, and can therefore vary between farms.

5.2.3. Statistical tests

The non-parametric Wilcoxon rank-sum test (also known as the Mann Whitney U test) is used to compare whether two independent samples (i.e. historical and observational) of a dependent variable (i.e. either ADG, FCR, MR, AMU, or gross margin) are from populations with the same distribution (Mann and Whitney, 1947; Wilcoxon, 1945). The unbalanced designs and small sample size in the present study are likely to violate the assumptions of the independent samples T-Test (Altman and Bland, 1995). The Wilcoxon rank-sum tests are carried out in Stata, which provides the z statistic and corresponding p-value. In addition, an estimate of the probability that a random draw from the historical data is larger than a random draw from the intervention data is estimated per farm for each variable. This probability is calculated by dividing the Mann Whitney *U* statistic by a multiplication of both sample sizes.

Effects of intervention might only be visible after a certain lapse of time. The presence of such a lag period was tested by removing the observational data of the technical performance variables one by one (i.e. the first flock from the observational data was removed first; next the second flock was removed and so on). Results of the Wilcoxon rank-sum tests after removing flock observations from the observational data are presented in the Appendix (see Table A.5.2–A.5.5). Each Table shows the results of a separate dependent variable with respect to technical farm performance. The results do not provide clear evidence of a lag period and all observational data was therefore included in the subsequent analyses.

5.2.4. Economic impact

The economic impact of on-farm intervention is estimated in two different ways. First, by calculating the economic value (EV) of changes in technical performance, and second by assessing the impact on the gross margin.

Economic value of changes in technical performance

The EV of the change in single technical performance parameters (including ADG, FCR and MR) is calculated using the historical and the observational data. The EV of the change in ADG (EV_{ADG}) is estimated in two ways. The first way assumes that the cycle duration is constant and computes the change in slaughter weight following a change in ADG (see equation 5.2).

$$EV_{ADG} = \Delta ADG \times CD \times \left(\left(PP - (FCR \times FP)\right) \times 10{,}000\ DO\right) \tag{5.2}$$

where ΔADG is the change in average daily growth when comparing average historical data and the intervention flock under review;

CD is the cycle duration, which is an average of the observational data;

PP is the producer price per kilogram meat;

FCR is the FCR of the intervention flock under review;

FP is the feed price per kilogram feed;

DO is the number of day-old chicks at set-up.

Within this equation, the change in ADG (compared with the historical average) is multiplied with the cycle duration, in order to calculate the total change in slaughter weight. An increase (decrease) in weight results in a higher (lower) revenue. However, there is also an effect on the feed costs, since a change in feed intake compensates a change in slaughter weight. The change in feed consumption is estimated by multiplying the change in slaughter weight with the FCR. This is multiplied with the feed price to express the change in feed consumption, resulting in the EV of a change in ADG per broiler. For comparison reasons, this is multiplied by 10,000 animals at set-up.

The second way for computing the EV of a change in technical performance assumes a constant slaughter weight while the cycle duration changes with the change in ADG (Gocsik *et al.*, 2013). In that case, the assumption of constant slaughter weight holds (see equation 5.3).

$$EV_{ADG} = \frac{\left(\frac{365}{\left(\frac{SL - ST}{ADG_{t_i}}\right) + EP} - \frac{365}{\left(\frac{SL - ST}{ADG_{t_0}}\right) + EP}\right) \times (RV - (DP + ((SL - ST) \times FCR \times FP) + DC)) \times 10{,}000\ DO}{\frac{365}{\left(\frac{SL - ST}{ADG_{t_0}}\right) + EP}} \qquad (5.3)$$

where *SL* is the slaughter weight;

ST is the weight at set-up;

ADG_{t_i} is the ADG of the intervention flock under review;

EP is the empty period;

ADG_{t_0} is the average ADG of the historical data;

RV is the revenue per broiler;

DP is the day-old chick price;

DC is the costs of delivery.

Dividing the overall growth by the ADG provides the duration of the production cycle. The total number of days required for one flock equals the cycle duration plus 14 days, which equals the empty period of the stable for cleaning and disinfection. Dividing 365 days by the total number of days required for one flock provides the number of flocks produced per year. The number of flocks per year is estimated with the ADG of the intervention flock (ADG_{t_i}), and the historical ADG (ADG_{t_0}). The difference between the two is multiplied by the gross revenue per animal (i.e. slaughter weight multiplied by the producer price), which is corrected for the direct variable costs per broiler (i.e. price of a day-old chick, feed costs, and costs of delivery). The gross margin is multiplied by 10,000 animals at set-up. The outcome is divided by the average number of production cycles per year to make the estimated variables comparable across farms.

Equation 5.4 shows the calculation of the EV of a change in FCR (EV_{FCR}).

$$EV_{FCR} = \Delta FCR \times (SL - SW) \times FP \times 10{,}000\ DO \qquad (5.4)$$

where ΔFCR is the change in feed conversion rate when comparing average historical data and the intervention flock under review;

The first step in computing EV_{FCR} is multiplying the change in the FCR by the weight gain (slaughter weight minus starting weight). A lower (higher) FCR indicates that less (more) feed is required. The change in required feed is finally multiplied by both the feed price and 10,000 animals at set-up.

The EV of a change in MR (EV_{MR}) is calculated per flock, using equation 5.5.

$$EV_{MR} = \Delta MR \text{ x } 10{,}000 \text{ DO x } (DP + \left(\frac{(PP \times SL) - DP}{2}\right) - DC) \quad (5.5)$$

where ΔMR is the change in mortality when comparing average historical data and the intervention flock under review.

Mortality is assumed to occur halfway the production period and therefore the lost revenue is divided by 2. A side effect of mortality are the costs of delivery that can be subtracted. Fixed costs per broiler may also change because of a change in mortality. However, these potential cost changes are not taken into account in the present study.

Gross margin analysis

The second step in analysing the economic impact of tailor-made interventions is gross margin analysis, which measures the difference between the revenue and the variable costs of the farm. The model described by Gocsik, et al. (2013) was adapted to calculate the economic impact of intervention on the gross margin. Details about the calculations regarding the gross margins can be found in the Appendix (Table A.6). Subsequently, the average gross margin obtained from historical data was compared with the average gross margin obtained from the observational data. The model distinguishes technical inputs and economic inputs.

Table 5.1 presents the technical inputs. The high standard deviation for the number of broilers slaughtered and number of chicks at set-up is caused by the high variation in the size of the farms included.

Table 5.1. Descriptive statistics technical inputs (average and standard deviation in parentheses)

Technical input variable	Historical	Observational	Unit
ADG	62.605 (4.010)	64.928 (3.223)	Grams
AMU	152.273 (121.900)	126.531 (93.161)	TI_{1000}
Cycle duration	41.815 (1.484)	41.833 (1.214)	Days
FCR	1.583 (0.059)	1.579 (0.052)	Feed/meat ratio
Mean weight	2.406 (0.146)	2.489 (0.130)	Kilograms
MR	2.5431 (1.199)	2.788 (1.048)	Percentage
Number of broilers slaughtered	43,301 (22,301)	42,055 (21,571)	Animals
Number of chicks at set-up	44,478 (22,967)	43,236 (22,146)	Animals

The main drivers of farm income are selected as the economic inputs. Farm income is determined by revenues and costs. Revenues are predominantly driven by the producer price and the slaughter weight. The main cost drivers are feed costs and purchase of day-old chicks (Castellini *et al.*, 2012; Mollenhorst *et al.*, 2006).

Table 5.2 presents the economic inputs used to calculate both returns and variable costs. The economic input data were derived from KWIN (Blanken *et al.*, 2016) and pertain to broiler production in The Netherlands. However, the data may very well reflect the situation in Belgium as broiler production takes place in similar production systems and under similar market conditions.

Table 5.2. Economic inputs

Economic input variable		Unit
Producer price	0.835	€/kg
Feed price	0.315	€/kg
Day-old chick price	0.335	€/animal
Total other variable costs	0.185	€/animal

Source: KWIN (Blanken *et al.*, 2016).

Sensitivity analysis

Prices in broiler production are characterized by high volatility. Therefore, a sensitivity analysis was conducted to assess the effect of ±5% and ±10% changes in producer price, feed price and day-old chick price, on the EV of the changes in technical performance and gross margins. Since the economic impact is standardized to 10,000 animals at set-up, the effect of changes in day-old chick price on the gross margin cannot assessed.

5.3. Results

5.3.1. On-farm interventions

During the intervention period, 119 interventions were carried out. An overview of the interventions is presented in the Appendix (see Table A.5.7). About 51.26% of the interventions undertaken targeted the animals (i.e. disease management), 19.33% of the interventions targeted the farmer, and 29.41% targeted the farm (i.e. farm management). Interventions are mainly addressing coccidiosis, enteritis, feed, and training of the farmer. Costs of applying the interventions were not included in the present study. However, the change in gross margin when comparing the historical data and the observational data gives an indication of the maximum price a rational farmer is willing to pay for the intervention(s).

5.3.2. Comparing historical and observational data

Table 5.3 shows the z statistic and p-value resulting from the Wilcoxon rank-sum test. The results indicate a significant difference between the historical and the observational data on ten different farms with respect to ADG. In addition, significant differences are found on seven farms with respect to the FCR, and a significant difference for MR was found on eight farms. For AMU, a significant difference was found on six farms, while a significant difference in gross margin was found on nine farms.

Table 5.3. Results of the Wilcoxon test (z-statistic and p-value in parentheses)

Farm ID	ADG	FCR	MR	AMU	Gross Margin
1	-2.364 (0.018)**	-0.798 (0.425)	-1.725 (0.085)*	1.597 (0.110)	-1.026 (0.305)
2	-2.627 (0.009)***	-0.999 (0.318)	-0.946 (0.344)	0.735 (0.462)	1.155 (0.248)
3	1.161 (0.246)	-0.898 (0.369)	-0.844 (0.399)	-0.954 (0.340)	1.265 (0.206)
4	-0.707 (0.480)	0.944 (0.345)	0.826 (0.409)	1.768 (0.077)*	-0.825 (0.409)
5	-1.593 (0.111)	-0.408 (0.683)	-1.952 (0.051)*	-1.676 (0.094)*	-1.857 (0.063)*
6	-2.636 (0.008)***	0.375 (0.708)	-2.676 (0.007)***	3.372 (0.001)***	-0.187 (0.851)
7	-0.050 (0.960)	-1.608 (0.108)	-2.067 (0.039)**	-0.201 (0.841)	1.206 (0.228)
8	0.317 (0.751)	2.258 (0.024)**	-0.705 (0.481)	-1.586 (0.113)	-1.657 (0.098)*
9	-3.465 (0.001)***	1.771 (0.077)*	-0.627 (0.531)	-0.037 (0.971)	-1.769 (0.077)*
10	-2.406 (0.016)**	1.405 (0.160)	-0.301 (0.764)	0.735 (0.462)	-3.274 (0.001)***
11	-0.053 (0.958)	1.695 (0.090)*	-2.172 (0.030)**	3.334 (0.001)***	1.323 (0.186)
12	0.525 (0.600)	0.315 (0.753)	1.155 (0.248)	1.470 (0.142)	-0.630 (0.529)
13	-2.172 (0.030)**	-0.832 (0.405)	-1.768 (0.077)*	0.794 (0.427)	-1.234 (0.217)
14	-0.945 (0.345)	0.841 (0.401)	1.261 (0.207)	0.105 (0.916)	-1.785 (0.074)*
15	-0.714 (0.475)	-1.367 (0.172)	-2.286 (0.022)**	-1.857 (0.063)*	1.857 (0.063)*
16	-0.265 (0.791)	-1.403 (0.161)	-1.579 (0.114)	-0.040 (0.968)	1.754 (0.079)*
17	1.775 (0.076)*	2.470 (0.014)**	-0.425 (0.671)	0.772 (0.440)	-2.392 (0.017)**
18	-1.960 (0.050)*	1.958 (0.050)*	1.429 (0.153)	1.852 (0.064)*	-1.217 (0.224)
19	-2.556 (0.011)**	2.018 (0.044)**	-1.006 (0.314)	-1.278 (0.201)	-1.095 (0.273)
20	-3.130 (0.002)***	-3.258 (0.001)***	-2.432 (0.015)**	0.463 (0.643)	3.240 (0.001)***

* indicate significance level at 0.1; ** indicate significance level at 0.05; *** indicate significance at 0.01

Table 5.4 shows the probability that a random draw from the historical data of the selected dependent variable is larger than the observational data. For example, the probability scores of 1.00 indicates that a random draw from the historical data with respect AMU is always larger compared to a random draw from the observational data.

Table 5.4. Probability that the random draw of the variable of the historical data is larger than the a random draw from the variable of the observational data

Farm ID	ADG	FCR	MR	AMU	Gross Margin
1	0.122*	0.333	0.224*	0.755	0.286
2	0.109*	0.352	0.359	0.609	0.672
3	0.683	0.358	0.367	0.354	0.700
4	0.389	0.648	0.630	0.778*	0.370
5	0.273	0.442	0.221*	0.260*	0.234*
6	0.111*	0.556	0.104*	1.000*	0.472
7	0.492	0.258	0.189*	0.470	0.682
8	0.543	0.805*	0.405	0.286	0.276*
9	0.010*	0.750*	0.411	0.495	0.250*
10	0.179*	0.688	0.460	0.598	0.063*
11	0.492	0.754*	0.175*	1.000*	0.698
12	0.578	0.547	0.672	0.719	0.406
13	0.175*	0.333	0.222*	0.619	0.278
14	0.359	0.625	0.688	0.516	0.234*
15	0.381	0.274	0.119*	0.190*	0.810*
16	0.462	0.295	0.269	0.495	0.756*
17	0.740*	0.833*	0.443	0.604	0.177*
18	0.206*	0.794*	0.714	0.778*	0.317
19	0.033*	0.867*	0.317	0.267	0.300
20	0.018*	0.000*	0.125*	0.571	1.000*

* indicate significance level at either 0.1, 0.05 or 0.01

5.3.3. Economic value of changes in technical performance

Table 5.5 shows the results of the EV of changes in technical performance. For each farm, the EV is calculated by comparing the average technical performance based on the average historical data with the technical performance for all observational flocks separately. Results presented in Table 5.5 are the average EV per farm for each technical performance indicator. In addition, an overall average for all farms is indicated. The standard deviations are shown in parentheses. The results show that the EV of the change in ADG (for both calculations) and FCR were generally positive, while the change in MR was generally negative. The EV when assuming a constant cycle duration is structurally higher compared to the EV when assuming a constant slaughter weight. The standard deviations are high relative to the mean value, which indicates high variability among the EVs. The equations used to calculate the EV of the change in technical performance are interlinked (i.e. the equation of one technical performance parameter also depends on one or more other technical performance parameters). Hence, the EV of the changes in technical performance have to be assessed individually and adding the EV of the different performance indicators would provide an overestimation of the effect.

Table 5.5. Results economic value (EV) of changes in technical performance (standardized to 10,000 animals at set-up) shown as average per farm with standard deviation in parentheses

Farm ID	EV_{ADG} constant cycle duration (€)	EV_{ADG} constant slaughter weight (€)	EV_{FCR} (€)	EV_{MR} (€)
1	676 (254)	283 (124)	- 379 (244)	- 90 (128)
2	623 (399)	257 (164)	- 222 (337)	- 36 (90)
3	- 325 (363)	- 115 (123)	- 71 (144)	- 53 (105)
4	273 (443)	129 (200)	129 (282)	80 (65)
5	395 (504)	170 (206)	- 27 (294)	- 57 (45)
6	468 (423)	193 (189)	82 (724)	- 100 (93)
7	32 (501)	31 (198)	- 734 (634)	- 77 (73)
8	- 28 (428)	- 7 (165)	315 (175)	- 31 (85)
9	919 (280)	382 (136)	341 (313)	- 58 (162)
10	268 (201)	108 (83)	117 (213)	- 9 (85)
11	19 (233)	11 (97)	455 (211)	- 92 (40)
12	- 85 (361)	- 24 (125)	79 (335)	145 (107)
13	428 (335)	179 (142)	- 49 (330)	- 49 (62)
14	192 (389)	75 (140)	114 (258)	82 (95)
15	128 (268)	49 (97)	- 123 (129)	- 133 (87)
16	59 (452)	39 (194)	- 228 (411)	- 146 (230)
17	- 173 (285)	- 65 (105)	331 (290)	28 (66)
18	405 (442)	174 (182)	481 (257)	101 (67)
19	1,554 (926)	703 (472)	490 (214)	- 86 (154)
20	891 (216)	394 (110)	- 699 (249)	- 144 (126)
Average (Std. deviation)	301 (554)	132 (235)	38 (467)	- 37 (130)

5.3.4. Gross margin analysis

Within the gross margin analysis, the difference between the average gross margin based on the historical data and the average gross margin based on the observational data was calculated per farm. Table 5.6 shows the average of these differences in gross margin per farm, both in absolute and relative terms. In addition, the change in AMU (both in absolute and relative terms) is shown for each farm. Although the results show different combinations regarding the change in gross margin and AMU, the results generally indicate that a decrease in AMU does not have negative consequences for the economic performance.

Table 5.6. Change in gross margin and AMU when comparing the historical data and the observational data

Farm ID	Δ Gross Margin		Δ AMU	
	(€)	(%)	(TI_{1000})	(%)
1	359	32	-41	-20
2	-394	-26	-60	-36
3	-295	-18	39	19
4	294	23	-58	-41
5	545	24	45	99
6	-42	-2	-307	-362
7	-413	-25	-1	-1
8	830	42	53	57
9	648	64	31	32
10	639	41	-2	-1
11	-299	-24	-230	-57
12	243	20	-57	-60
13	408	23	-34	-26
14	783	56	-5	-4
15	-399	-28	13	17
16	-569	-25	7	5
17	547	78	-39	-18
18	580	43	-36	-15
19	490	46	67	34
20	-1,149	-67	-53	-27
Average (Std. deviation)	140 (546)	22	-33 (90)	-20

Table 5.7 shows the results of the change in gross margin and AMU for the semi-control farms (both in absolute and relative terms). When comparing the results of the intervention farms and the semi-control farms, some differences can be observed. For the semi-control farms, the gross margin generally decreased while AMU increased. For only farm (i.e. farm 13), a decrease in AMU coincided with an increase in the gross margin.

Table 5.7. Results of the change in gross margin and AMU when comparing the historical data and the observational data of the (non-intervention) semi-control farms

Farm ID	Δ Gross margin		Δ AMU	
	(€)	(%)	(TI_{1000})	(%)
1	-452	-18	-5	-4
2	223	18	12	7
3	-333	-11	114	359
4	-1,195	-47	-39	-51
5	-768	-34	21	9
6	-651	-23	3	3
7	-420	-16	-12	-8
8	-576	-28	51	173
9	790	48	12	11
10	-1,546	-86	135	208
11	-1,264	-44	3	2
12	-158	-9	-36	-20
13	804	79	-66	-21
Average (Std. deviation)	-427 (721)	-13 (42)	15 (57)	51 (120)

5.3.5. Sensitivity analyses

Table 5.8 shows the results of the sensitivity analyses for both the EV of the change in technical performance and the gross margin. The numbers shown in the Table are an average for all farms in the sample. The average EV of a change in a technical performance parameter and the average gross margin is only shown when either the EV or the gross margin changes due to a price change. A change in the producer price affects the EV_{MR}, both calculations of the EV_{ADG} and the gross margin. The EV_{MR} has a small negative relationship with the producer price, while both estimations of the EV_{ADG} have a strong positive relationship with the producer price as well as the gross margin.

A change in the feed price influences the EV_{FCR}, both calculations of the EV_{ADG} and the gross margin. The EV_{FCR} has a positive relation with the feed price. There is a negative relationship between both estimations of the EV_{ADG} and the feed price. If the feed price increases, the gross profit margin per broiler decreases, and consequently the EV_{ADG} decreases. Hence, the gross margin also has a negative relationship with the feed price.

Table 5.8. Results sensitivity analysis on the economic value of changes in technical performance and the gross margin of the intervention farms (indices is shown in parentheses)

Price	Performance parameter	10% price decrease	5% price decrease	Baseline	5% price increase	10% price increase
Producer price	EV ADG constant cycle duration	253 (75)	295 (88)	336 (100)	377 (112)	419 (125)
	EV ADG constant weight	86 (58)	118 (79)	149 (100)	180 (121)	211 (142)
	EV MR	-33 (91)	-35 (96)	-36 (100)	-38 (104)	-39 (109)
	Δ Gross Margin	80 (57)	110 (78)	140 (100)	171 (122)	201 (143)
Feed price	EV FCR	18 (90)	19 (95)	20 (100)	21 (105)	22 (110)
	EV ADG constant cycle duration	385 (115)	361 (107)	336 (100)	312 (93)	287 (85)
	EV ADG constant weight	185 (124)	167 (112)	149 (100)	131 (88)	112 (76)
	Δ Gross Margin	187 (133)	164 (117)	140 (100)	117 (83)	94 (67)
Day-old chick price	EV ADG constant weight	159 (107)	154 (103)	149 (100)	144 (97)	139 (93)
	EV MR	-36 (99)	-36 (99)	-36 (100)	-36 (101)	-37 (101)

The price of a day-old chick affects both the EV_{MR} and the $EV_{ADG\ constant\ weight}$. The effect of a change in day-old chick price on the EV_{MR} is limited. There is a negative relationship between the $EV_{ADG\ constant\ weight}$ and the price of a day-old chick, since an increase in day-old chick price decreases the gross profit margin. Since, the gross margin is standardized for a default farm with 10,000 animals at set-up, no effect of changes in day-old chick price are observed.

The results of the sensitivity analyses indicate that the difference in the gross margin before and after intervention, both expressed per 10,000 animals at set-up, is always positive (even when the producer price drops with 10 percent or when the feed price increases with 10 percent). Hence, a rational farmer will apply the intervention as long as the economic value of the intervention is greater than the costs of applying the intervention.

5.4. Discussion and conclusions

The aim of this study was to analyse the effects of tailor-made interventions, aimed at reducing (the need for) AMU, on technical and economic farm performance on Belgian broiler farms. Results of this study indicate that ADG generally increased after intervention. Rojo-Gimeno et al. (2016) found similar results in a study regarding the effects of interventions in farrow-to-finish pig farms in Flanders (i.e. northern region in Belgium). FCR generally decreased after intervention on the Belgian broiler farms. Postma *et al.* (2017) found similar results in Flemish pig production. Generally, mortality increased after intervention in the present study, which contrasts the results of Rojo-Gimeno *et al.* (2016) and Postma *et al.* (2017) with respect to farrow-to-finish pig farms in Belgium. A possible explanation for the increase in mortality is that the persuasive interventions applied in the present study partly aim to develop rules to omit preventive treatments and limit to curative treatments. Interventions might result in increased mortality when the application was incorrect or when the effect was insufficient. AMU generally decreased on the farms in the sample. This result is in line with the results of Rojo-Gimeno *et al.* (2016) and Postma *et al.* (2017) with respect to farrow-to-finish pig farms in Belgium. Postma *et al.* (2017) even found a reduction in AMU of more than 50 percent.

Sensitivity analysis has shown that the results with respect to economic farm performance are robust. Results from semi-control farms indicates that gross margins generally decreased while AMU generally increased over the same period. This outcome strengthens the finding that interventions can have a positive impact on AMU, technical performance and economic performance. However, in this study it is not possible to provide a proof for causality of relations between intervention and impacts on farm performance and AMU. In addition, application costs of intervention as well as the changing health care costs resulting from the observed change in AMU were not taking into account in this study since data regarding these costs were missing. Future research should therefore focus on testing the causality of relations between intervention and AMU. In addition, costs of applying both intervention and AMU have to be incorporated in future studies.

Although the present study focused on Belgian broiler farms, the findings are relevant for countries that face similar concerns with respect to reducing AMU (e.g. other European countries) and develop their production in a similar direction as Belgium (e.g. The Netherlands, France and the United Kingdom). However, participation in the survey used in the present study was voluntary and therefore it is likely that participating farmers were more intrinsically motivated to reduce AMU. In that respect, effects of intervention might be different when interventions are mandatory.

To conclude, results of the present study have shown that intervention can result in reduced AMU. In addition, the results show that a decrease in AMU does not necessarily have negative consequences for the technical and economic farm performance.

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Appendix

Table A.5.1. Overview of the missing data and (potential) outliers

Farm ID	Flock	Type of data	Parameter	Explanation
1	1, 2, 4–7	Historical	FCR	All values were checked by the veterinarian; the values of the first two flocks were correct, the values of the last four flocks were incorrected and therefore removed
3	10	Observational	ADG, FCR, and MR	Missing data; data could not be obtained
6	8–12	Observational	ADG	All values were checked by the veterinarian; and replaced by the correct data
7	2,4	Historical	FCR	Not enough evidence to assume that the observations were incorrect
7	10, 11	Observational	ADG	All values were checked by the veterinarian; and replaced by the correct data
8	1	Historical	ADG	The value was checked by the veterinarian and corrected afterwards
9	13–16	Observational	FCR	All values were checked by the veterinarian; and replaced by the correct data
11	3 – 5	Historical	MR	Not enough evidence to assume that the observations were incorrect
12	6	Historical	FCR	The value was checked by the veterinarian; and appeared to be correct
12	5	Observational	FCR	The value was checked by the veterinarian; and appeared to be correct
13	1, 3, 5 and 6	Historical	FCR	All values were checked by the veterinarian; the value of the first flock was corrected, the values of the other flocks were incorrected and therefore removed
13	3	Historical	MR	Not enough evidence to assume that the observation was incorrect
13	7	Historical	MR	Missing observation; data could not be obtained
14	1	Historical	ADG	The value was checked by the veterinarian and corrected afterwards
16	5	Historical	MR	Not enough evidence to assume that the observation was incorrect
16	5	Historical	MR	The veterinarian checked the value; in this flock, there were problems in the climate control within the stable. Consequently, all technical performance indicators of this flock were considered as outlier and removed.
19	3	Observational	ADG	The value was checked by the veterinarian; and appeared to be correct

Table A.5.2. Results Wilcoxon rank-sum test (z-statistic and p-value) regarding average daily growth after excluding intervention flocks one by one

Farm	All	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10	-11	-12	-13	-14	-15
1	-2.364 (0.018)**	-2.429 (0.015)**	-2.192 (0.028)**	-2.268 (0.023)**	-1.937 (0.053)*	-1.464 (0.143)	-1.091 (0.275)	NA	NA	NA	NA	NA	NA	NA	NA	NA
2	-2.627 (0.009)***	-2.432 (0.015)**	-2.197 (0.028)**	-2.052 (0.040)**	-1.701 (0.089)*	-1.228 (0.220)	-1.833 (0.067)*	-1.167 (0.243)	NA	NA	NA	NA	NA	NA	NA	NA
3	1.161 (0.246)	1.190 (0.234)	1.226 (0.220)	1.001 (0.317)	0.733 (0.464)	0.732 (0.464)	0.915 (0.360)	0.943 (0.346)	0.984 (0.325)	0.450 (0.653)	0.450 (0.653)	0.000 (1.000)	0.297 (0.766)	NA	NA	NA
4	-0.707 (0.480)	-0.387 (0.699)	-0.714 (0.475)	-0.801 (0.423)	-0.730 (0.465)	-0.853 (0.394)	-0.258 (0.796)	-0.667 (0.505)	-1.000 (0.317)	NA	NA	NA	NA	NA	NA	NA
5	-1.593 (0.111)	-1.473 (0.141)	-1.226 (0.220)	-1.051 (0.293)	-0.840 (0.401)	-0.579 (0.562)	-1.075 (0.283)	-0.774 (0.439)	-0.353 (0.724)	0.612 (0.541)	-0.697 (0.486)	NA	NA	NA	NA	NA
6	-2.636 (0.008)***	-2.528 (0.012)**	-2.841 (0.005)***	-2.735 (0.006)***	-2.611 (0.009)***	-2.463 (0.014)**	-2.934 (0.003)***	-2.803 (0.005)***	-2.640 (0.008)***	-2.427 (0.015)**	-2.131 (0.033)**	-1.655 (0.098)*	NA	NA	NA	NA
7	-0.050 (0.960)	0.272 (0.786)	0.296 (0.767)	0.325 (0.746)	0.072 (0.943)	0.081 (0.936)	0.646 (0.518)	1.407 (0.159)	0.923 (0.356)	0.342 (0.733)	0.000 (1.000)	NA	NA	NA	NA	NA
8	0.317 (0.751)	0.298 (0.765)	0.119 (0.905)	0.085 (0.933)	0.317 (0.751)	0.293 (0.770)	-0.053 (0.958)	-0.347 (0.729)	-0.447 (0.655)	-0.857 (0.391)	-1.056 (0.291)	-1.134 (0.257)	-0.570 (0.569)	0.293 (0.770)	0.218 (0.827)	NA
9	-3.465 (0.001)***	-3.425 (0.001)***	-3.382 (0.001)***	-3.333 (0.001)***	-3.278 (0.001)***	-3.216 (0.001)***	-3.145 (0.002)***	-3.064 (0.002)***	-3.098 (0.002)***	-3.000 (0.003)***	-2.882 (0.004)***	-2.739 (0.006)***	-2.558 (0.011)**	-2.324 (0.020)**	-2.000 (0.046)**	-1.500 (0.134)
10	-2.406 (0.016)**	-2.362 (0.018)**	-2.239 (0.025)**	-2.101 (0.036)**	-1.945 (0.052)*	-2.039 (0.042)**	-1.854 (0.064)*	-2.170 (0.030)**	-2.083 (0.037)**	-1.853 (0.064)*	-1.714 (0.087)*	-1.380 (0.168)	-1.134 (0.257)	-0.570 (0.569)	-1.171 (0.242)	-1.528 (0.127)
11	-0.053 (0.958)	-0.231 (0.817)	0.064 (0.949)	-0.143 (0.886)	-0.568 (0.570)	-0.756 (0.450)	-0.114 (0.909)	0.293 (0.770)	0.218 (0.827)	NA	NA	NA	NA	NA	NA	NA
12	0.525 (0.600)	0.231 (0.817)	0.000 (1.000)	-0.146 (0.884)	0.170 (0.865)	0.408 (0.683)	0.783 (0.433)	0.775 (0.439)	NA	NA	NA	NA	NA	NA	NA	NA
13	-2.172 (0.030)**	-2.085 (0.037)**	-1.855 (0.064)*	-2.003 (0.045)**	-2.196 (0.028)**	-1.894 (0.058)*	-1.486 (0.137)	-2.058 (0.040)**	-1.537 (0.124)	NA	NA	NA	NA	NA	NA	NA
14	-0.945 (0.345)	-0.810 (0.418)	-1.033 (0.302)	-1.317 (0.188)	-1.189 (0.235)	-1.021 (0.307)	-2.089 (0.037)**	-1.549 (0.121)	NA	NA	NA	NA	NA	NA	NA	NA
15	-0.714 (0.475)	-1.056 (0.291)	-0.756 (0.450)	-0.114 (0.909)	0.000 (1.000)	0.218 (0.827)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
16	-0.265 (0.791)	-0.094 (0.925)	0.101 (0.919)	-0.109 (0.913)	-0.357 (0.721)	-0.653 (0.514)	-1.014 (0.311)	-0.815 (0.415)	-0.561 (0.575)	-0.220 (0.826)	-0.809 (0.419)	-1.776 (0.076)*	-1.103 (0.270)	NA	NA	NA
17	1.775 (0.076)*	1.900 (0.057)*	2.134 (0.033)**	2.407 (0.016)**	2.207 (0.027)**	2.085 (0.037)**	1.939 (0.053)*	1.759 (0.079)*	1.531 (0.126)	1.228 (0.220)	0.786 (0.432)	0.000 (1.000)	NA	NA	NA	NA
18	-1.960 (0.050)*	-2.548 (0.011)**	-2.622 (0.009)*	-2.575 (0.010)**	-2.359 (0.018)**	-2.273 (0.023)**	-1.943 (0.052)*	-1.470 (0.142)	-1.098 (0.272)	NA	NA	NA	NA	NA	NA	NA
19	-2.556 (0.011)**	-2.402 (0.016)**	-2.449 (0.014)**	-2.236 (0.025)**	-1.936 (0.053)*	-1.464 (0.143)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
20	-3.130 (0.002)***	-3.009 (0.003)***	-2.865 (0.004)***	-2.689 (0.007)***	-2.468 (0.014)**	-2.178 (0.029)**	-1.771 (0.077)*	-1.546 (0.122)	NA	NA	NA	NA	NA	NA	NA	NA

* indicate significance level at 0.1, ** indicate significance level at 0.05 and *** indicate significance at 0.01

5

Table A.5.3. Results Wilcoxon rank-sum test (z-statistic and p-value) regarding feed conversion after excluding intervention flocks one by one

Farm	All	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10	-11	-12	-13	-14	-15
1	-0.798 (0.425)	-0.775 (0.439)	-0.745 (0.456)	-0.707 (0.480)	-0.655 (0.513)	-0.577 (0.564)	-0.447 (0.655)	NA	NA	NA	NA	NA	NA	NA	NA	NA
2	-0.999 (0.318)	-0.985 (0.324)	-0.970 (0.332)	-0.954 (0.340)	-0.426 (0.670)	-0.103 (0.918)	0.394 (0.694)	0.000 (1.000)	NA	NA	NA	NA	NA	NA	NA	NA
3	-0.898 (0.369)	-0.795 (0.427)	-0.736 (0.462)	-0.734 (0.463)	-0.733 (0.464)	-0.732 (0.464)	-0.549 (0.583)	-0.524 (0.600)	-0.246 (0.806)	0.150 (0.881)	0.150 (0.881)	0.782 (0.434)	1.485 (0.138)	NA	NA	NA
4	0.944 (0.345)	1.034 (0.301)	0.715 (0.474)	0.642 (0.521)	1.098 (0.272)	0.855 (0.392)	0.519 (0.604)	0.335 (0.737)	1.514 (0.130)	NA	NA	NA	NA	NA	NA	NA
5	-0.408 (0.683)	-0.293 (0.770)	-0.053 (0.958)	0.231 (0.817)	0.575 (0.565)	1.000 (0.317)	0.893 (0.372)	0.756 (0.450)	0.570 (0.569)	-0.293 (0.770)	1.091 (0.275)	NA	NA	NA	NA	NA
6	0.375 (0.708)	0.201 (0.841)	0.434 (0.664)	0.826 (0.409)	0.775 (0.438)	0.429 (0.668)	0.962 (0.336)	0.548 (0.584)	0.000 (1.000)	-0.258 (0.796)	-1.333 (0.182)	-1.500 (0.134)	NA	NA	NA	NA
7	-1.608 (0.108)	-1.519 (0.129)	-1.414 (0.157)	-1.291 (0.197)	-1.000 (0.317)	-0.641 (0.522)	-0.913 (0.361)	-0.426 (0.670)	-0.516 (0.606)	-1.000 (0.317)	-1.000 (0.317)	NA	NA	NA	NA	NA
8	2.258 (0.024)**	2.128 (0.033)**	2.062 (0.039)**	1.903 (0.057)*	1.723 (0.085)*	1.612 (0.107)	1.536 (0.125)	1.389 (0.165)	1.214 (0.225)	0.857 (0.391)	1.056 (0.291)	0.567 (0.571)	0.570 (0.569)	0.293 (0.770)	-0.218 (0.827)	NA
9	1.771 (0.077)*	1.636 (0.102)	1.486 (0.137)	1.317 (0.188)	1.125 (0.261)	1.308 (0.191)	1.086 (0.277)	0.826 (0.409)	0.518 (0.605)	0.143 (0.886)	-0.321 (0.748)	-0.367 (0.714)	-0.215 (0.830)	0.000 (1.000)	0.671 (0.502)	-0.505 (0.614)
10	1.405 (0.160)	1.377 (0.169)	1.346 (0.179)	1.309 (0.191)	1.354 (0.176)	1.315 (0.189)	1.759 (0.079)*	1.749 (0.080)*	1.507 (0.132)	1.473 (0.141)	2.149 (0.032)**	2.200 (0.028)**	2.084 (0.037)**	2.172 (0.030)**	2.058 (0.040)**	1.537 (0.124)
11	1.695 (0.090)*	1.448 (0.148)	1.535 (0.125)	1.216 (0.224)	1.218 (0.223)	2.079 (0.038)**	1.709 (0.087)*	1.171 (0.242)	1.528 (0.127)	NA	NA	NA	NA	NA	NA	NA
12	0.315 (0.753)	0.695 (0.487)	1.034 (0.301)	1.319 (0.187)	1.361 (0.174)	0.818 (0.413)	0.262 (0.793)	1.167 (0.243)	NA	NA	NA	NA	NA	NA	NA	NA
13	-0.832 (0.405)	-0.816 (0.414)	-0.798 (0.425)	-0.775 (0.439)	-0.745 (0.456)	-0.707 (0.480)	-0.655 (0.513)	-0.577 (0.564)	-0.447 (0.655)	NA	NA	NA	NA	NA	NA	NA
14	0.841 (0.401)	0.579 (0.563)	1.034 (0.301)	1.319 (0.187)	1.701 (0.089)*	1.228 (0.220)	2.095 (0.036)**	1.556 (0.120)	NA	NA	NA	NA	NA	NA	NA	NA
15	-1.367 (0.172)	-1.063 (0.288)	-1.144 (0.253)	-1.038 (0.299)	-0.596 (0.552)	-1.098 (0.272)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
16	-1.403 (0.161)	-1.499 (0.134)	-1.407 (0.159)	-1.302 (0.193)	-1.061 (0.289)	-0.904 (0.366)	-0.857 (0.391)	-0.480 (0.631)	0.000 (1.000)	0.426 (0.670)	1.291 (0.197)	2.000 (0.046)**	1.500 (0.134)	NA	NA	NA
17	2.470 (0.014)**	2.561 (0.010)**	3.111 (0.002)***	3.081 (0.002)***	2.943 (0.003)***	2.893 (0.004)***	2.840 (0.005)***	2.781 (0.005)***	2.717 (0.007)***	2.449 (0.014)**	2.089 (0.037)**	1.549 (0.121)	NA	NA	NA	NA
18	1.958 (0.050)*	1.852 (0.064)*	1.853 (0.064)*	2.000 (0.046)**	1.868 (0.062)*	1.890 (0.059)*	1.709 (0.087)*	1.464 (0.143)	1.091 (0.275)	NA	NA	NA	NA	NA	NA	NA
19	2.018 (0.044)**	1.997 (0.046)**	1.729 (0.084)	1.358 (0.175)	0.789 (0.430)	1.508 (0.132)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
20	-3.258 (0.001)***	-3.148 (0.002)***	-3.021 (0.003)***	-2.867 (0.004)***	-2.676 (0.007)***	-2.430 (0.015)**	-2.093 (0.036)**	-1.575 (0.115)	NA	NA	NA	NA	NA	NA	NA	NA

* indicate significance level at 0.1, ** indicate significance level at 0.05 and *** indicate significance at 0.01

Table A.5.4. Results Wilcoxon rank-sum test (z-statistic and p-value) regarding mortality after excluding intervention flocks one by one

Farm	All	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10	-11	-12	-13	-14	-15
1	-1.725 (0.085)*	-1.571 (0.116)	-1.380 (0.168)	-1.512 (0.131)	-1.937 (0.053)*	-1.464 (0.143)	-1.091 (0.275)	NA	NA	NA	NA	NA	NA	NA	NA	NA
2	-0.946 (0.344)	-1.390 (0.165)	-1.422 (0.155)	-1.026 (0.305)	-1.361 (0.174)	-1.841 (0.066)*	-1.310 (0.190)	-0.389 (0.697)	NA	NA	NA	NA	NA	NA	NA	NA
3	-0.844 (0.399)	-0.737 (0.461)	-0.858 (0.391)	-0.601 (0.548)	-0.293 (0.769)	0.081 (0.935)	-0.366 (0.714)	-0.524 (0.600)	-0.738 (0.461)	-1.050 (0.294)	-1.050 (0.294)	-0.391 (0.696)	0.891 (0.373)	NA	NA	NA
4	0.826 (0.409)	0.775 (0.439)	0.714 (0.475)	0.641 (0.522)	0.913 (0.361)	0.853 (0.394)	0.775 (0.439)	0.667 (0.505)	0.500 (0.617)	NA	NA	NA	NA	NA	NA	NA
5	-1.952 (0.051)*	-1.958 (0.050)*	-2.072 (0.038)**	-2.092 (0.036)**	-2.120 (0.034)**	-2.158 (0.031)**	-2.212 (0.027)**	-2.294 (0.022)**	-2.430 (0.015)**	-2.093 (0.036)**	-1.575 (0.115)	NA	NA	NA	NA	NA
6	-2.676 (0.007)***	-2.571 (0.010)**	-2.611 (0.009)***	-2.536 (0.011)**	-2.520 (0.012)**	-2.503 (0.012)**	-2.402 (0.016)**	-2.373 (0.018)**	-2.345 (0.019)**	-2.066 (0.039)**	-1.667 (0.096)*	-1.000 (0.317)	NA	NA	NA	NA
7	-2.067 (0.039)**	-2.232 (0.026)**	-2.538 (0.011)**	-2.394 (0.017)**	-2.220 (0.026)**	-2.009 (0.045)**	-2.745 (0.006)***	-2.566 (0.010)**	-2.334 (0.020)**	-2.012 (0.044)**	-1.514 (0.130)	NA	NA	NA	NA	NA
8	-0.705 (0.481)	-0.485 (0.628)	-0.238 (0.812)	0.042 (0.966)	-0.181 (0.856)	-0.146 (0.884)	-0.424 (0.672)	-0.869 (0.385)	-0.512 (0.609)	-0.644 (0.520)	-0.651 (0.515)	-1.421 (0.155)	-1.481 (0.139)	-2.049 (0.040)**	-1.528 (0.127)	NA
9	-0.627 (0.531)	-0.428 (0.668)	-0.206 (0.837)	-0.263 (0.792)	-0.281 (0.779)	-0.302 (0.763)	-0.326 (0.745)	-0.354 (0.723)	-0.258 (0.796)	-0.286 (0.775)	-0.481 (0.630)	-0.732 (0.464)	-0.855 (0.392)	-0.259 (0.795)	0.671 (0.502)	0.505 (0.614)
10	-0.301 (0.764)	-0.212 (0.832)	-0.187 (0.852)	-0.277 (0.781)	-0.423 (0.673)	-0.770 (0.441)	-0.684 (0.494)	-0.900 (0.368)	-1.042 (0.297)	-0.959 (0.337)	-0.857 (0.391)	-0.731 (0.465)	-0.567 (0.571)	-0.342 (0.732)	0.000 (1.000)	0.655 (0.513)
11	-2.172 (0.030)**	-2.083 (0.037)**	-1.981 (0.048)**	-1.857 (0.063)*	-1.705 (0.088)*	-1.512 (0.131)	-1.254 (0.210)	-1.171 (0.242)	-1.091 (0.275)	NA	NA	NA	NA	NA	NA	NA
12	1.155 (0.248)	1.273 (0.203)	1.420 (0.156)	1.610 (0.107)	1.189 (0.235)	0.816 (0.414)	1.044 (0.296)	0.775 (0.439)	NA	NA	NA	NA	NA	NA	NA	NA
13	-1.768 (0.077)*	-1.549 (0.121)	-1.571 (0.116)	-1.441 (0.150)	-1.278 (0.201)	-1.279 (0.201)	-1.033 (0.302)	-1.000 (0.317)	-0.500 (0.617)	NA	NA	NA	NA	NA	NA	NA
14	1.261 (0.207)	0.927 (0.354)	1.422 (0.155)	1.026 (0.305)	0.851 (0.395)	0.612 (0.540)	0.261 (0.794)	1.162 (0.245)	NA	NA	NA	NA	NA	NA	NA	NA
15	-2.286 (0.022)**	-2.030 (0.042)**	-1.701 (0.089)*	-1.254 (0.210)	-2.049 (0.040)	-1.528 (0.127)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
16	-1.579 (0.114)	-1.499 (0.134)	-1.307 (0.191)	-1.193 (0.233)	-1.061 (0.289)	-1.549 (0.121)	-1.286 (0.199)	-0.961 (0.337)	-0.548 (0.584)	-0.213 (0.831)	-0.775 (0.439)	-1.667 (0.096)*	-1.000 (0.317)	NA	NA	NA
17	-0.425 (0.671)	-0.290 (0.772)	-0.045 (0.965)	0.145 (0.885)	0.368 (0.713)	0.231 (0.817)	0.516 (0.606)	0.146 (0.884)	0.170 (0.865)	0.612 (0.540)	-0.261 (0.794)	-1.162 (0.245)	NA	NA	NA	NA
18	1.429 (0.153)	1.389 (0.165)	1.086 (0.277)	1.000 (0.317)	1.218 (0.223)	0.945 (0.345)	0.342 (0.732)	0.293 (0.770)	-0.218 (0.827)	NA	NA	NA	NA	NA	NA	NA
19	-1.006 (0.314)	-0.629 (0.530)	-0.735 (0.462)	-1.640 (0.101)	-1.936 (0.053)*	-1.464 (0.143)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
20	-2.432 (0.015)**	-2.366 (0.018)**	-2.289 (0.022)**	-2.034 (0.042)**	-1.701 (0.089)*	-1.254 (0.210)	-1.464 (0.143)	-1.091 (0.275)	NA	NA	NA	NA	NA	NA	NA	NA

* indicate significance level at 0.1, ** indicate significance level at 0.05 and *** indicate significance at 0.01

5

Table A.5.5. Results Wilcoxon rank-sum test (z-statistic and p-value) regarding antimicrobial use after excluding intervention flocks one by one

Farm	All	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10	-11	-12	-13	-14	-15
1	1.597 (0.110)	1.429 (0.153)	1.218 (0.223)	0.945 (0.345)	0.570 (0.569)	0.878 (0.380)	-0.218 (0.827)	NA	NA	NA	NA	NA	NA	NA	NA	NA
2	0.735 (0.462)	0.579 (0.563)	0.645 (0.519)	0.732 (0.464)	0.849 (0.396)	0.816 (0.414)	1.044 (0.296)	0.775 (0.439)	NA	NA	NA	NA	NA	NA	NA	NA
3	-0.954 (0.340)	-1.174 (0.240)	-1.427 (0.154)	-1.236 (0.217)	-1.011 (0.312)	-0.742 (0.458)	-0.744 (0.457)	-0.561 (0.575)	-0.108 (0.914)	0.000 (1.000)	0.794 (0.427)	0.402 (0.688)	-0.297 (0.766)	NA	NA	NA
4	1.768 (0.077)*	1.936 (0.053)*	1.714 (0.087)*	1.601 (0.109)	1.461 (0.144)	1.279 (0.201)	1.549 (0.121)	1.000 (0.317)	0.000 (1.000)	NA	NA	NA	NA	NA	NA	NA
5	-1.676 (0.094)*	-1.758 (0.079)*	-1.536 (0.125)	-1.390 (0.165)	-1.727 (0.084)*	-1.574 (0.116)	-1.383 (0.167)	-1.894 (0.058)*	-1.715 (0.086)*	-1.470 (0.142)	-1.098 (0.272)	NA	NA	NA	NA	NA
6	3.372 (0.001)***	3.317 (0.001)***	3.254 (0.001)***	3.182 (0.002)***	3.098 (0.002)***	3.000 (0.003)***	2.882 (0.004)***	2.739 (0.006)***	2.558 (0.011)**	2.324 (0.020)**	2.000 (0.046)**	1.500 (0.134)	NA	NA	NA	NA
7	-0.201 (0.841)	-0.325 (0.745)	-0.589 (0.556)	-0.387 (0.699)	-0.429 (0.668)	-0.641 (0.522)	-0.365 (0.715)	-0.640 (0.522)	-0.775 (0.439)	-1.333 (0.182)	-1.000 (0.317)	NA	NA	NA	NA	NA
8	-1.586 (0.113)	-1.641 (0.101)	-1.545 (0.122)	-1.521 (0.128)	-1.585 (0.113)	-1.659 (0.097)*	-1.535 (0.125)	-1.389 (0.165)	-1.214 (0.225)	-1.286 (0.199)	-1.056 (0.291)	-1.134 (0.257)	-1.254 (0.210)	0.293 (0.770)	0.218 (0.827)	NA
9	-0.037 (0.971)	-0.039 (0.969)	0.206 (0.837)	0.219 (0.826)	0.328 (0.743)	0.654 (0.513)	0.597 (0.551)	0.531 (0.596)	0.582 (0.561)	0.787 (0.431)	0.722 (0.470)	0.640 (0.522)	0.535 (0.593)	-2.324 (0.020)**	-2.000 (0.046)	-1.500 (0.134)
10	0.735 (0.462)	0.811 (0.418)	1.119 (0.263)	1.308 (0.191)	1.183 (0.237)	1.042 (0.298)	0.878 (0.380)	1.323 (0.186)	1.157 (0.247)	1.342 (0.180)	1.143 (0.253)	0.893 (0.372)	0.378 (0.706)	-0.570 (0.569)	-1.171 (0.242)	-1.528 (0.127)
11	3.334 (0.001)***	3.240 (0.001)***	3.130 (0.002)***	3.000 (0.003)***	2.842 (0.005)***	2.646 (0.008)***	2.393 (0.017)**	2.049 (0.040)**	1.528 (0.127)	NA	NA	NA	NA	NA	NA	NA
12	1.470 (0.142)	1.157 (0.247)	1.678 (0.093)	1.610 (0.107)	1.359 (0.174)	1.225 (0.221)	1.567 (0.117)	1.162 (0.245)	NA	NA	NA	NA	NA	NA	NA	NA
13	0.794 (0.427)	1.157 (0.247)	1.086 (0.277)	1.571 (0.116)	2.030 (0.042)**	2.646 (0.008)*	2.393 (0.017)**	2.049 (0.040)**	1.528 (0.127)	NA	NA	NA	NA	NA	NA	NA
14	0.105 (0.916)	0.116 (0.908)	0.129 (0.897)	0.146 (0.884)	0.170 (0.865)	0.204 (0.838)	0.261 (0.794)	0.000 (1.000)	NA	NA	NA	NA	NA	NA	NA	NA
15	-1.857 (0.063)*	-2.030 (0.042)**	-1.890 (0.059)*	-1.709 (0.087)*	-1.464 (0.143)	-1.091 (0.275)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
16	-0.040 (0.968)	0.254 (0.800)	-0.045 (0.964)	0.098 (0.922)	0.265 (0.791)	-0.116 (0.908)	0.319 (0.749)	0.857 (0.391)	1.543 (0.123)	1.323 (0.186)	0.798 (0.425)	0.000 (1.000)	-1.528 (0.127)	NA	NA	NA
17	0.772 (0.440)	0.578 (0.563)	0.533 (0.594)	0.866 (0.387)	0.630 (0.529)	0.579 (0.563)	1.162 (0.245)	0.878 (0.380)	0.849 (0.396)	0.612 (0.540)	0.522 (0.602)	0.387 (0.699)	NA	NA	NA	NA
18	1.852 (0.064)*	1.620 (0.105)	1.342 (0.180)	1.000 (0.317)	0.568 (0.570)	1.134 (0.257)	0.570 (0.569)	1.171 (0.242)	0.218 (0.827)	NA	NA	NA	NA	NA	NA	NA
19	-1.278 (0.201)	-0.940 (0.347)	-0.490 (0.624)	-0.745 (0.456)	-0.387 (0.699)	-0.293 (0.770)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
20	0.463 (0.643)	0.447 (0.655)	0.286 (0.775)	0.568 (0.570)	0.945 (0.345)	1.026 (0.305)	1.171 (0.242)	0.218 (0.827)	NA	NA	NA	NA	NA	NA	NA	NA

* indicate significance level at 0.1, ** indicate significance level at 0.05 and *** indicate significance at 0.01

Table A.5.6. Overview used equations in the gross margin analysis

Description	Equation
Total feed used by delivered animals (kg)	$\left(\frac{\text{cycle duration} \times \text{FCR} \times \text{ADG}}{1{,}000}\right) \times$ number of animals slaughtered
Total revenue	Mean weight × number of animals slaughtered × producer price
Total feed costs	(Total feed used by delivered animals × feed price per kg) + $\frac{\left(\frac{\text{cycle duration} \times \text{FCR} \times \text{ADG}}{1{,}000}\right) \times (\text{number of animals slaughtered - number of animals at set-up})}{2} \times$ feed price per kg
Total costs day-old chicks	Number of day-old chicks at set-up x day-old chick price
Total feed profit	Total revenue – total feed costs – total costs day-old chicks
Total other variable costs	Number of day-old chicks at set-up x other variable costs per animal
Gross margin	Total revenue – total feed costs – total costs day-old chicks – total other variable costs
Gross margin per 10,000 animals at set-up	$\frac{\text{Gross margin}}{\text{number of day-old chicks at set-up}} \times$ 10,000 animals at set-up

5

Table A.5.7. Overview of interventions

Problem	Number of actions	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Animals	**61**																				
Coccidiosis	**36**																				
Burning floor	2		1																	1	
Cleaning with soda	2													1							1
Improve diagnostics - systematic OPG's	8					1	1			1	1	1					1	1		1	
Optimise Anticoccidial rotation program	11	1				1	1	1		1	1	1	1	1			1			1	
Phytoproducts	3		1											1		1					
Systematic coccidiosis scoring	5							1					1		1		1	1			
Vaccination coccidiosis	5		1	1					1									1			1
Enteritis	**16**																				
Improved diagnostics, lesions scoring by Vet	7			1	1			1	1	1					1	1					
Phytoproducts	4	1												1				1	1		
Probiotics	5			1	1					1									1		1
Immunity	***7***																				
Improve vaccination protocol	2											1								1	
New vaccination schedule based on serology	5		1				1							1	1	1					
Respiratory problems	***2***																				
Improved diagnostics: serology/PCR	1							1													
Weekly disinfection with Halamid spray	1							1													
Farmer	**23**																				
Monitoring	**9**																				
Close follow up first week D0-D1-D7	9			1	1				1	1			1		1	1	1	1			
Training farmer	**14**																				
Education with "Poultry-Signals"	6		1	1					1	1		1						1			
Measure weight, climate D1	7			1	1			1	1				1		1	1					
Optimize chick feeding	1																				1

Table A.5.7. Overview of interventions (continued)

Problem	Number of actions	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Farm	**35**																				
Climate	**4**																				
Audit by specialist & new schedules	4		1							1			1					1			
Feed	**16**																				
Feed additives - prebiotic, probiotic, acids	10		1			1	1	1		1					1	1		1	1		1
New feed mill	6		1												1	1		1	1		1
Hygiene	**2**																				
Cleaning by specialised company	1														1						
Separation clean & dirty area	1														1						
Litter	**2**																				
Change to peat	2		1												1						
Stocking density	**2**																				
Lower stocking density	2	1	1																		
Veterinarian	**2**																				
New vet	2											1			1						
Water quality	**7**																				
Disinfection water	5							1		1			1		1					1	
Regular water analysis	1			1																	
Separate medication reservoirs	1			1																	

5

Chapter 6

General Discussion

6.1. Introduction

The introduction of antimicrobials in veterinary medicine changed the options for the treatment of livestock diseases drastically. Antimicrobial use (AMU) in livestock production significantly improved animal health and productivity (Odonkor and Addo, 2011). A major drawback of AMU is the development and spread of antimicrobial resistance (AMR), which jeopardizes the treatment of ordinary diseases in both humans and animals. Stimulating prudent AMU in veterinary medicine is therefore one of the main EU policy areas to tackle AMR (European Commission, 2015). Prudent use should result in more rational and targeted use, and therefore increase the therapeutic effect of antimicrobial agents and reduce the development and spread of AMR. The final outcome of prudent use should be an overall reduction of AMU, predominantly by limiting AMU only to those situations where they are inevitable (European Commission, 2015). However, effects of reducing AMU on farm performance are generally unknown. Yet there are major gaps in knowledge, data and information regarding the strategies for, as well as the farm-economic impact of, reducing veterinary AMU. These gaps hampered decision-making on international and national policies as well as in setting private standards for reducing veterinary AMU (Rushton *et al.*, 2014).

The overall objective of this dissertation was to assess the scope for, and the farm-economic impact of reducing AMU in livestock production. This objective was split into four sub-objectives, addressed in each of the research Chapters 2-5. *Chapter 2* develops a conceptual framework that covers an integrated assessment of potential measures and strategies within the supply chain to reduce both (the need for) AMU and the prevalence of (pathogenic) microorganisms, to decrease the risks of human exposure to AMR. *Chapter 3* presents a theoretical framework that derives the economic value of veterinary AMU and determines the factors affecting the economic value. *Chapter 4* assessed the relation between farm performance and AMU, and examined differences between farm clusters with similar characteristics regarding AMU and farm performance. *Chapter 5* provides an assessment of the impact of interventions, aimed at reducing AMU, on farm performance.

This concluding chapter synthesises the results of the different chapters, elaborates on the implications for farmers, policy makers and other stakeholders, reflects on the theory, data and methods, outlines directions for future research, and ends with the main conclusions of this dissertation.

6.2. Synthesis

6.2.1. Scope for reducing AMU

This dissertation distinguishes three categories of strategies to reduce AMU in livestock production. The first category focusses on strategies that specifically target the farmer. The other categories focus on strategies that target the farm and the animals.

Strategies focussed on the farmer

Chapter 2 conceptually showed the on-farm decision-making context in which the farmer is the main decision-maker with respect to the use of antimicrobial agents. The results of Chapter 3 showed that, besides the prices of inputs and output, farmers' risk attitude and the variance of profit are main determinants for the economic value of AMU. Risk attitudes can be deeply rooted, and determine the subjective perception and valuation of objective information. In that respect, the farmers' risk attitude affects the (perceived) variance of profit, which is determined by the farmers' subjective probabilities and impacts that a farmer assigns to uncertain events (including the effects of AMU and disease outbreaks). Strategies focused on the farmer should specifically aim for the farmers' perceptions of the probabilities and impacts assigned by the farmer to uncertain events. If uninformed risk averse farmers assign high probabilities to the most negative consequences of a disease outbreak, there will be an overestimation of the real economic value of AMU resulting in antimicrobial overuse. This overestimation of the real economic value of AMU might be a theoretical explanation for farms with both high technical farm performance and AMU (like observed in Chapter 4). Conversely, assigning low probabilities can result in an underestimation of the real economic value of AMU causing antimicrobial underuse. However, underuse is likely to be corrected by the farmer since it directly affects the technical farm performance. Conversely, overuse is less likely to be observed (and corrected) by the farmer. In that respect, educating and training farmers can help farmers in assigning probabilities and impacts to uncertain events, including the effects of both AMU and disease outbreaks. The subjective expected utility (SEU) theory, introduced Von Neumann and Morgenstern (1953), can be used as a basis for understanding the probabilities and impacts that farmers assign to uncertain events.

Relatively few studies have investigated the perception of farmers regarding AMU. Visschers *et al.* (2015) conducted a survey among pig farms in Belgium, France, Germany, Sweden and Switzerland. Farmers were significantly more worried about financial issues compared to AMR, and believed that a loss in revenues for slaughter pigs treated with a large amount of AMU would have the most impact on reduced AMU in their country (Visschers *et al.*, 2015). Hence, the findings of Visschers *et al.* (2015) might indicate that farmers overestimate the real economic value of AMU which shows the importance of addressing the farmer when reducing AMU in livestock production.

Strategies focussed on the farm and the animals

According to Chapter 2, the decision to use antimicrobial agents is determined by the entire complexity and variety of decisions with respect to the farm and the animals. Decisions with respect to the farm include decisions regarding the farm layout and farm management, while decisions with respect to the animal relate to decisions regarding the animal characteristics and disease management. Chapter 2 distinguished strategic, tactical and operational decisions. The combination of these decisions regarding the farm and the animals, as discussed in Chapter 2, determine both the position on the production function and the damage abatement function (and consequently determine input use including AMU). Chapter 3 provided a theoretical underpinning that improving the production system enables substitution of AMU for non-antimicrobial alternatives and could help reducing AMU without negative consequences for technical farm performance. These non-antimicrobial alternatives can be both related to the farm (e.g. improving biosecurity) and the animals (e.g. implementing preventive measures including vaccination). Farms with low technical farm performance might need to focus on the farm and animals to increase their performance (Chapter 2-4). Results of Chapter 5 indicate that combinations of interventions with respect to the farmer, the farm and the animals can reduce AMU without necessarily having negative consequences for the technical farm performance. Rojo-Gimeno *et al.* (2016) and Postma *et al.* (2017) found similar results in Belgian pig production, and showed that reducing AMU is possible without jeopardizing technical farm performance mainly by improving biosecurity.

6.2.2. Impact of reducing AMU

The conceptual framework in Chapter 2 suggested that all strategies aimed at reducing the need for AMU, have both short-term and long-term effects, and are therefore likely to affect the technical and economic farm performance. In addition, the framework presented in Chapter 3 provides a theoretical underpinning for the observation that production system improvements can reduce AMU without negative consequences for technical farm performance. The impact of combined interventions, targeting measures focussed on the farmer, the farm and the animals, on both farm performance and AMU was assessed in Chapter 5 by comparing data from Belgian broiler farms before and after intervention. The results of Chapter 5 indicated that a reduction in AMU does not necessarily impair technical farm performance. More specifically, the results of Chapter 5 indicate that average daily gain generally increased after intervention. Rojo-Gimeno *et al.* (2016) found similar results in a study regarding the effects of interventions in farrow-to-finish pig farms. Feed conversion has generally decreased after intervention. Postma *et al.* (2017) found similar results in Belgian pig production. Generally, mortality has increased after intervention, contrary to the results of Rojo-Gimeno *et al.* (2016) and Postma *et al.* (2017). AMU has generally decreased. This result is in line with the results of Rojo-Gimeno *et al.* (2016) and Postma et al. (2017), and shows that combined measures targeting the farmer, the farm and the animals can reduce AMU as stated in Chapter 2 and 3. Technical performance was also converted into economic performance in Chapter 5. Results indicate that the economic performance generally improved after intervention. However, these results have to be interpreted with care since the costs of implementing interventions were unknown as well as the cost savings of reduced AMU.

6.3. Implications

6.3.1. Business implications

Farms have unique combinations of technical farm performance and AMU (see Chapter 4). The need for AMU in the cluster of farms that combine high technical farm performance and low AMU appears to be relatively low. Proper monitoring and regular contact with the veterinarian can help maintaining the high technical farm performance while keeping AMU low.

High levels of AMU can indicate that the farmer overestimates the real economic value of AMU. If so, proper coordination between the farmer and the veterinarian can be crucial for reducing AMU. The importance of the relation between the farmer and the veterinarian was also recently addressed by Currie *et al.* (2018), who conducted a Delphi study to identify veterinary behaviours which UK-based experts believe to contribute to AMR and antimicrobial stewardship. Their findings indicated that interactions between the farmer and the veterinarian are a major influencing factor. Veterinarians can help farmers to avoid making overestimations of the real economic value. As shown in Chapter 5, strategies targeting the farmer may entail both training and monitoring to make better estimations of the probabilities and impacts of uncertain events (including the impact of AMU and potential disease outbreaks). Interventions targeting the farm and the animals are needed when the high level of AMU compensates for poor (hygienic) farm conditions. Examples of such interventions can be improved biosecurity (i.e. focused on the farm) or vaccination (i.e. focused on the animals). Results of Chapter 5 indicate that combined interventions targeting the farmer, the farm and the animals can reduce AMU without necessarily having negative consequences for technical farm performance. Hence, interventions can be a main tool for farmers to reduce their AMU.

Chapter 4 also observed farms that combine low technical farm performance and low AMU. If insufficient farm conditions result in low performance, interventions targeting the farm and the animals might improve the technical farm performance. Depending on the type of interventions, the level of AMU might be kept low as well. On the one hand, the farmer can ensure that the animals become less susceptible to disorders, e.g. by improving biosecurity (i.e. targeting the farm) or through vaccination (i.e. targeting the animals). On the other hand, the farmer can ensure that the impact of a disorder becomes less significant through an early detection of clinical signs to enable quick counter-measures (including AMU and non-antimicrobial alternatives). The introduction of precision livestock farming offers a management tool that enables a farmer to monitor animals automatically by using sensors, cameras and microphones (Armstrong et al., 2014).

The category of farms that combines low technical farm performance and high AMU was not observed within Chapter 4. In practice, it would be difficult for this category of farms to survive, especially since these farms require improvements that appear to affect both the variable and the fixed costs. Results of Chapter 5 indicate that reducing AMU does not necessarily have negative consequences for technical farm performance. Interventions can therefore help reducing AMU but do not ensure improvements with respect to technical farm performance.

6.3.2. Policy implications

The theoretical model of Chapter 3 suggests that the price of antimicrobials is one of the main determinants of the economic value of AMU in the short-run. In that respect, increasing the price of AMU might reduce the economic value of AMU resulting in a reduction of AMU. However, the question is whether an increase in the price of antimicrobials alone is sufficient for reducing AMU. For example, Lhermie *et al.* (2018) showed that a price increase of antimicrobials lower than 5-fold was not sufficient to encourage the use of alternative non-antimicrobial treatments in dairy production given the relatively high costs of these alternatives. Price increases of such magnitude are therefore likely to significantly affect farmers' income. Vågsholm and Höjgård (2010) opted for a tax on AMU based on the expected costs of developing new antimicrobial substances to balance the incentives and externalities of AMU and development of new antimicrobial substances. However, the practical feasibility of implementing generic measures like a price increase or a tax on AMU is debatable especially when these measures are only implemented at national level. Farmers might decide to (illegally) buy antimicrobial agents abroad. Hence, the effect of generic measures on AMU like prices increases and taxes are expected to be small. In order to successfully reduce AMU, policy should focus on strategies that reduce AMU *but* do not impair farm performance.

Policy can contribute to reductions in AMU by enabling possibilities for farmers to use benchmarking to establish their relative performance with respect to technical farm performance and AMU against an appropriate standard. However, this requires precise monitoring of technical farm performance and AMU to establish these standards. In that respect, farmers can use benchmarking to determine strategies to reduce AMU without compromising farm performance.

Policy can also contribute to increasing awareness among farmers and veterinarians with respect to AMU and AMR. Increasing awareness is possible via official guidelines, and by improving education about the consequences of inappropriate prescribing behaviour. Previous studies have shown that veterinarians in the UK have a low uptake of AMU guidelines, limited awareness of their details and are prone to social norms and verbally agreed protocols in practice (Hughes *et al.*, 2012; Mateus *et al.*, 2014). However, there is a high level of awareness with respect to guidelines that are widely available in print or web-based (Currie *et al.*, 2018).

Results of this dissertation (Chapter 2, 3 and 5) have shown that farms need to adjust their farm and disease management in order to reduce AMU successfully. However, these adjustments often require investments. Policy can stimulate major investments directly or indirectly. *Direct stimulation* is possible by providing subsidies for livestock farmers, for example by linking Single Farm Payment within the EU Common Agricultural Policy (CAP) to meet particular targets with respect to reductions in AMU. *Indirect stimulation* is possible through the introduction of accelerated depreciation, which allows for greater deductions of an asset and is used to minimize taxable income in the early years of the investment's life in exchange for increased taxable income in future years. Accelerated depreciation can be a valuable tax incentive, which can encourage farmers to acquire new assets to improve their production system.

6.4. Reflections on Theories, Data and Methods

6.4.1. Theories

This dissertation developed two theoretical frameworks for assessing the scope for, and the farm-economic impact of reducing AMU in livestock production. The first framework was presented in Chapter 2 and covered an integrated assessment of potential measures and strategies within the supply chain to reduce both (the need for) AMU and the prevalence of (pathogenic) microorganisms, to decrease the risks of human exposure to AMR. The second framework in Chapter 3 presented a theoretical underpinning for deriving the economic value of veterinary AMU and for determining the factors affecting the economic value.

Chapter 2 discussed the on-farm and beyond-farm decision-making context and indicated that the farmer is the main decision-maker on-farm (also with respect to AMU). The decision to use antimicrobials is determined by the entire complexity and variety of decisions taken, which can strongly differ between farms. These decisions can be related either to the farm or to the animals. Scientific literature was used to compile a list of the main decisions that can be taken on-farm with respect to both the farm and the animals. The framework presented in Chapter 2 was validated by a panel of Dutch policy makers involved in livestock production by testing both the completeness and the practical usability of the framework during two workshops. The panel included policy makers from the Dutch Commodity Boards for Livestock, Meat and Eggs, the Dutch Ministry of Economic Affairs, the Dutch Animal Health Service, The Netherlands Food and Consumer Product Safety Authority, and the Dutch Agricultural and Horticultural Organisation (i.e. one policy maker from each organisation).

Although the framework presented in Chapter 2 emphasized the importance of the behaviour of individual farmers, future research has to apply theories that can explain the behaviour of farmers (e.g. the theory of planned behaviour). According to the theory of planned behaviour, attitude and behaviour, subjective norms, and perceived behavioural control, together shape the behavioural intentions and behaviours of an individual (Ajzen, 1991). A better understanding of the behaviour of farmers might provide potential explanations for excessive and inappropriate use of individual farmers.

The conceptual framework presented in Chapter 3 specifically builds on the concept of damage abatement inputs, introduced in the agricultural economics literature by Hall and Norgaard (1973) and Talpaz and Borosh (1974). In addition, assumptions were made with respect to both profit and utility maximization that originate from neoclassical economic theory. Hence, the conceptual framework presented in Chapter 3 is firmly rooted in the scientific literature.

6.4.2. Data

The data used in this dissertation was collected at Belgian broiler farms within the framework of the European “Ecology from farm to fork of microbial drug resistance and transmission” (EFFORT) project. The data used in this dissertation focused on the technical data (including average daily gain, feed conversion, mortality and AMU), collected by project partners from the EFFORT-project. Distinction was made between historical data (i.e. before intervention) and observational data (i.e. after intervention). AMU was quantified by project partners in a standardized manner by using treatment incidence (TI) as described by Persoons *et al.* (2012). The TI is expressed as the number of defined daily doses (DDD_{VET}) administered per 1000 animal-days at risk or the number of days per 1000 animal-days that the flock is receiving a dose of antimicrobials, reflecting the percentage of the lifetime a bird in certain flock is treated with antimicrobials.

The selected study design to collect the data had several limitations. First, farmers’ participation in the survey was voluntary. This created a potential sample bias since the sample only included farmers that were intrinsically motivated to reduce AMU. Second, the number of flock observations per farm was relatively small and the number of flock observations before and after intervention differed per farm as well as between farms. Third, multiple interventions were implemented simultaneously on the sample of farms. As a result, potential effects on technical and economic farm performance could not be related to a specific intervention. Fourth, the pre-intervention levels of both technical farm performance and AMU significantly differed among the farms. These differences ensured that the convenience of reducing AMU significantly differed between farms. Fifth, data about prices and production costs (including the costs of intervention and AMU) were lacking as well as data with respect to other important issues regarding livestock production (including animal health and welfare, and environmental issues). The final limitation was that farms naturally evolve, e.g. farmers gain knowledge and carry out changes with respect to both farm and disease management themselves. This created additional variation in the data that could not simply be attributed to the intervention. Hence, it could not be ruled out that similar reductions in AMU would have occurred without the interventions. Future data collection in the context of AMU and both technical and economic farm performance should account for these limitations.

6.4.3. Methods

The limitations in the data as outlined in the above had consequences for methods used in this dissertation. Chapter 3 employed concepts of the production function and the damage abatement function to determine the economic value of AMU. Hence, it would have been a logical next step to estimate the damage abatement function in the next chapter. However, data availability and quality did not allow for estimating the damage abatement function. The data that were initially available were discrete (e.g. the number of antimicrobial treatments) and therefore not suitable for estimating a damage abatement function. Later on, data with respect to the treatment incidence became available. However, the limited number of observations per farm and the low variation within the data did not allow for estimating a damage abatement function. Generally, it is assumed that the TI can be used as an input for estimating the damage abatement function. However, more flock observations per farm as well as more farms are needed to estimate the damage abatement function.

Given the available data, efficiency analysis was selected to determine technical farm performance. A non-parametric approach (i.e. Data Envelopment Analysis (DEA)) was selected instead of a parametric approach (e.g. Stochastic Frontier Analysis) since DEA does not require any assumptions about the functional form and inefficiency. Bootstrapping was used to correct for potential sample bias. A selection of inputs and output to be used in the DEA model of Chapter 4 was made based on the available data. Feed and number of day-old chicks were selected as inputs, while the number of kilograms meat delivered to the slaughterhouse was selected as output. The use of DEA implied that both the damage abatement effect of AMU and the impact of reducing AMU on the damage abatement effect remain unknown.

The differences in the pre-intervention levels of both technical farm performance and AMU implied that each farm had to be used as its own control. Hence, data before and after intervention were compared separately for each farm. The technical data was used to estimate the economic performance, expressed as the economic value of a change in technical performance as well as the gross margin. However, data with respect to the costs of both interventions and cost savings of reduced AMU were missing. The effect on economic performance is therefore not corrected for the costs of intervention and AMU (or for costs savings in case of reduced AMU). Results with respect to economic performance need therefore be interpreted with care. Prices and costs of Dutch broiler production were used since Belgian prices and costs were not collected within the project and were not available from the literature. However, the data may very well reflect the situation in Belgium as broiler production takes place in similar production systems and under similar market conditions. In addition, sensitivity analyses were performed to test the robustness of the results to price changes.

6.5. Implications for Future Research

Future research should specifically aim for analyses in which the costs of intervention as well as the cost savings of reduced AMU are explicitly taken into account to make better assessments of the impact of intervention on economic performance. In the survey among broiler farms used in this thesis, multiple interventions were implemented simultaneously on the sample of farms. As a result, potential effects on technical and economic farm performance cannot be traced back to a specific type of intervention. Future research should focus on identifying technical and economic effects of individual interventions. However, as shown in this dissertation, identifying the effects of individual interventions is not easy since successful strategies to reduce AMU consists of multiple measures that can be focussed on the farmer, the farm and the animals.

AMU and AMR are just a single category of interlinked issues that raise concerns regarding modern livestock production (McGlone, 2001; Tilman *et al.*, 2002). Examples of other issues are environmental impacts, and animal health and welfare. Hence, future research should consider the decrease in AMU in a broader context, including potential interactions with other dimensions of livestock production. An integrated approach as such adds to the complexity of the research, but simultaneously advances developments towards sustainable livestock production.

6.6. Main conclusions

From this dissertation, the following main conclusions are drawn:

- High technical farm performance and low AMU are not mutually exclusive in broiler production *(Chapter 3-5)*;
- Farms have unique combinations of technical farm performance and AMU, and therefore require farm-specific strategies to successfully reduce AMU *(Chapter 2-5);*
- Successful strategies for reducing AMU need to target combined interventions regarding the farmer, the farm and the animals *(Chapter 2, 3 and 5)*;
- Microeconomic theory postulates that the main determinants of the economic value of AMU are the prices of productive inputs, damage abatement inputs and outputs, the production technology, the damage abatement function, the risk attitude of the farmer and the variance of profit (*Chapter 3);*
- Risk averse farmers overestimate the real economic value of AMU (*Chapter 3)*;
- Production system improvements, targeting the farm and the animals, can improve the damage abatement effect of AMU and reduce the need for AMU (*Chapter 3 and 5)*;
- Broiler farms can improve their technical farm performance regardless the improvement possibilities regarding AMU (*Chapter 4)*.

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Summary

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Antimicrobial agents are used abundantly in livestock production to treat diseased animals. In that respect, antimicrobial use (AMU) provides an important basis for improving animal health and productivity. However, despite the benefits of veterinary AMU, inappropriate use invariably leads to the development and spread of antimicrobial resistance (AMR), which endangers both human and animal health. Various generic measures have already been taken to reduce AMU in livestock production including a European ban on the use of antimicrobial growth promoters. Although some countries already reduced AMU significantly (e.g. Denmark and The Netherlands), there is societal and political pressure to further reduce AMU. The overall objective of this dissertation was to assess the scope for, and the farm-economic impact of reducing AMU in livestock production. The dissertations' underlying assertion is that an assessment of these issues can help in understanding pathways for reducing veterinary AMU. To achieve the overall objective, four sub-objectives were defined which were addressed in Chapter 2-5.

Chapter 2 provides a conceptual framework that includes an integrated assessment of the measures and strategies that can be applied within the supply chain in order to reduce the risks of human exposure to AMR. The conceptual framework makes a distinction between the on-farm and the beyond-farm decision-making context. The on-farm decision-making context focuses on the strategies that can reduce (the need for) AMU. The farmer is the main decision-maker that takes various decisions with respect to the farm and the animals. The combination of decision determines the disease risk and therefore the need for AMU. In that respect, the main areas of attention when reducing AMU are the farmer, the farm and the animals. The beyond-farm decision-making focuses on the prevalence of (pathogenic) microorganisms. The various measures that can be taken beyond-farm are extensively discussed for each stage of the supply chain. In addition, the aspect of compliance is discussed. The conceptualization presented in Chapter 2 can be a qualitative basis for future bio-economic modelling and quantitative analyses. Specifically, such models and analyses need to include the potential risks and the potential benefits associated with AMU.

The focus in Chapter 3, 4 and 5 is on the farm level. Chapter 3 builds upon the on-farm decision-making context like outlined in Chapter 2 and provides a theoretical framework to assess the economic value of AMU. Within the framework, antimicrobial agents are considered damage

abatement inputs. These inputs do not directly increase productivity, like productive inputs, but are used to minimize the damage caused by livestock diseases. Three situations are distinguished: 1) a baseline model for a farm with a conventional production system; 2) an extension of the baseline model which includes the impact of production system improvements; and 3) a second extension of the baseline model that includes risk and risk attitude impacts. The baseline model shows that the economic value of AMU is affected in the short-run by the prices of both productive and damage abatement inputs. Production system improvements reduce the need for AMU and therefore affect the economic value of AMU. In addition, the framework indicates that both risk and risk attitude affect the level of AMU. Generally, the framework shows that the economic value is negatively affected by the price of productive inputs and damage abatement inputs, and positively affected by the output price, the input-output combination, the damage abatement effect, the level of risk aversion and the variance of profit. The framework provides a solid theoretical basis for understanding the behaviour of individual farmers regarding AMU and therefore for the development of effective policies aimed at reducing AMU in livestock production.

Results of Chapter 2 and 3 imply that there are differences in the individual behaviour of farmers regarding AMU. Hence, Chapter 4 empirically assessed the relation between AMU and technical farm performance in Belgian broiler farms. Cluster analysis was used to obtain clusters of farms with similar characteristics with respect to AMU and technical farm performance. Three farm clusters were obtained. Between the clusters, significant differences were found with respect to technical farm performance, AMU, resource intensity of feed, resource intensity of the number of day-old chicks at set-up, the number of antimicrobial treatments, the number of antimicrobial treatments related to either gut health or combined problems, and the number of antimicrobial treatments with orange active substances.

The next step was to examine the impact of interventions at Belgian broiler farms, aiming for reduced AMU, on farm performance in Chapter 5, including technical and economic impact. Results indicate that average daily growth and mortality generally increased after intervention, while feed conversion and AMU decreased. Technical performance transformed into economic performance, expressed as the economic value of the change in technical performance and gross

margins (i.e. revenue minus variable costs). The economic performance generally improved after intervention. However, these results need to be interpreted with care since both costs of intervention and the costs savings of reduced AMU are not taken into account. Sensitivity analyses on price changes confirm the robustness of this finding. Hence, the results suggest that intervention can contribute to a decrease in AMU and the decrease in AMU does not necessarily has negative consequences for technical farm performance.

Chapter 6 synthesised the results of the different chapters and discussed implications for future research. Overall, this dissertation underlined that there are possibilities for reducing AMU without necessarily having negative consequences with respect to technical farm performance. From this dissertation, the following main conclusions are drawn:

- High technical farm performance and low AMU are not mutually exclusive in broiler production *(Chapter 3-5)*;
- Farms have unique combinations of technical farm performance and AMU, and therefore require farm-specific strategies to successfully reduce AMU *(Chapter 2-5);*
- Successful strategies for reducing AMU need to target combined interventions regarding the farmer, the farm and the animals *(Chapter 2, 3 and 5)*;
- Microeconomic theory postulates that the main determinants of the economic value of AMU are the prices of productive inputs, damage abatement inputs and outputs, the production technology, the damage abatement function, the risk attitude of the farmer and the variance of profit (*Chapter 3);*
- Risk averse farmers overestimate the real economic value of AMU (*Chapter 3)*;
- Production system improvements, targeting the farm and the animals, can improve the damage abatement effect of AMU and reduce the need for AMU (*Chapter 3 and 5)*;
- Broiler farms can improve their technical farm performance regardless the improvement possibilities regarding AMU (*Chapter 4)*.

Samenvatting

Antimicrobiële middelen worden op grote schaal gebruikt in de veehouderij om zieke dieren te behandelen. In dat opzicht vormt antimicrobieel gebruik (AM-gebruik) een belangrijke basis voor (de verbetering van) diergezondheid en productiviteit. Ondanks de voordelen van veterinair AM-gebruik resulteert ongepast gebruik in de ontwikkeling en verspreiding van antimicrobiële resistentie (AMR), waardoor zowel de humane gezondheid als de diergezondheid in gevaar kan komen. Verschillende maatregelen zijn inmiddels genomen om het AM-gebruik in de veehouderij te reduceren waaronder een verbod op het gebruik van antimicrobiële groeibevorderaars. Ondanks dat een aantal landen het AM-gebruik aanzienlijk hebben verlaagd (bijvoorbeeld Denemarken en Nederland), is er een maatschappelijke en politieke druk om het AM-gebruik verder te reduceren. De algehele doelstelling van deze dissertatie was om de reikwijdte voor, en de bedrijfseconomische impact van het reduceren van het AM-gebruik in de veehouderij te onderzoeken. Om dit te bereiken, zijn vier subdoelstellingen geformuleerd die elk worden behandeld in de hoofdstukken 2-5.

Hoofdstuk 2 verstrekt een conceptueel raamwerk met daarin een geïntegreerd overzicht van de maatregelen en strategieën die kunnen worden toegepast in de keten om het risico op humane blootstelling aan AMR te reduceren. Het conceptuele raamwerk maakt onderscheid tussen de besluitvormingscontext op het bedrijf en de besluitvormingscontext na het bedrijf. De focus in de besluitvormingscontext op het bedrijf ligt bij de strategieën die (de noodzaak voor) AM-gebruik kunnen reduceren. De veehouder is de belangrijkste besluitvormer met betrekking tot het bedrijf en de dieren. De combinatie van beslissingen bepaalt het ziekterisico en daarmee de noodzaak voor AM-gebruik. In dat opzicht zijn de veehouder, het bedrijf en de dieren de belangrijkste aandachtsgebieden om het AM-gebruik terug te brengen. De besluitvormingscontext na het bedrijf richt zich op de prevalentie van (pathogene) micro-organismen. De verschillende maatregelen die na het bedrijf kunnen worden genomen zijn uitgebreid besproken voor de verschillende stadia in de keten. Daarnaast is het nalevingsaspect besproken. De conceptualisering zoals gepresenteerd in Hoofdstuk 2 kan een kwalitatieve basis voor toekomstige bio-economische modellering en kwantitatieve analyses zijn. Dergelijke modellen en analyses moeten specifiek de potentiele risico's en potentiele voordelen van geassocieerd AM-gebruik meenemen.

De focus in Hoofdstuk 3, 4, en 5 ligt op het bedrijfsniveau. Hoofdstuk 3 bouwt op de besluitvormingscontext op het bedrijf zoals beschreven in Hoofdstuk 2 en verstrekt een theoretisch raamwerk de economische waarde van AM-gebruik te bepalen. In het raamwerk worden antimicrobiële middelen gezien als damage abatement inputs. Deze inputs verhogen niet direct de productiviteit, zoals productive inputs, maar worden gebruikt om de schade die wordt veroorzaakt door dierziektes te reduceren. Drie situatie zijn onderscheiden: 1) een baselinemodel voor een bedrijf met een conventioneel productiesysteem; 2) een uitbreiding van het baselinemodel wat de impact van verbeteringen in het productiesysteem bevat; en 3) een tweede uitbreiding van het baselinemodel waar de impact van risico en risicohouding zijn meegenomen. Het baselinemodel laat zien dat de economische waarde van AM-gebruik op korte termijn wordt beïnvloed door de prijzen van zowel productive als damage abatement inputs. Verbeteringen in het productiesysteem kunnen de noodzaak voor AM-gebruik verminderen en daardoor de economische waarde van AM-gebruik. Daarnaast laat het raamwerk zien dat zowel risico als risicohouding het niveau van antimicrobieel gebruik beïnvloeden. Het raamwerk laat zien dat de economische waarde over het algemeen negatief wordt beïnvloed door de prijs van productive inputs en damage abatement inputs, en positief wordt beïnvloed door de outputprijs, input-output combinatie, het damage abatement effect, het niveau van risicoaversie en de variantie van winst. Het raamwerk biedt een solide theoretische basis om het gedrag van individuele veehouders met betrekking tot AM-gebruik te begrijpen en daarmee voor de ontwikkeling van effectief beleid gericht op het reduceren van AM-gebruik in de veehouderij.

De resultaten van Hoofdstuk 2 en 3 impliceren dat er verschillen zijn in het individuele gedrag van veehouders met betrekking tot AM-gebruik. Daarom wordt in Hoofdstuk 4 de relatie tussen AM-gebruik en technische bedrijfsprestatie bij Belgische vleeskuikenbedrijven getest. Cluster analyse is gebruikt om clusters van bedrijven te verkrijgen met vergelijkbare karakteristieken met betrekking tot AM-gebruik en technische bedrijfsprestatie. Drie clusters zijn verkregen. Tussen de bedrijfsclusters zijn significante verschillen gevonden met betrekking tot technische bedrijfsprestatie, AM-gebruik, resource-intensiteit van voer, resource-intensiteit van het aantal dieren bij opleg, het aantal antimicrobiële behandelingen, het aantal antimicrobiële behandeling gerelateerd aan darmgezondheidsproblemen of gecombineerde problemen, en het aantal antimicrobiële behandelingen oranje actieve stoffen. Deze verschillen moeten in oogschouw worden genomen in beleid gericht op het reduceren van AM-gebruik.

De volgende stap was het onderzoeken van de impact van interventies op Belgische vleeskuikenbedrijven, gericht op het reduceren van AM-gebruik, op de bedrijfsprestatie in Hoofdstuk 5, inclusief technische en economische impact. De resultaten wijzen op een toename van de gemiddelde dagelijkse groei en sterfte na interventie, terwijl voerconversie en AM-gebruik zijn gedaald. Technische prestaties zijn omgezet naar economische prestaties, uitgedrukt als de economische waarde van de verandering in technische prestatie alsmede het bruto saldo (d.w.z. winst minus variabele kosten). De economische prestaties zijn over het algemeen verbeterd na interventie. Echter, deze resultaten moeten voorzichtig worden geïnterpreteerd aangezien de kosten van interventie en de kosten die zijn bespaard als gevolg van een verlaagd AM-gebruik, niet zijn meegenomen. Gevoeligheidsanalyses op prijsveranderingen bevestigen de robuustheid van de resultaten. De resultaten suggereren daarom dat interventie kan bijdragen aan het verminderen van AM-gebruik en de vermindering in AM-gebruik hoeft niet noodzakelijkwijs negatieve consequenties voor de technische bedrijfsprestatie te hebben.

Hoofdstuk 6 synthetiseert de resultaten van de verschillende hoofdstukken en bediscussieerd implicaties voor toekomstig onderzoek. Deze dissertatie laat zien dat er in het algemeen mogelijkheden zijn voor het reduceren van AM-gebruik zonder dat dit noodzakelijkerwijs negatieve consequenties heeft met betrekking tot de technische bedrijfsprestatie. Uit deze dissertatie zijn de volgende hoofdconclusies getrokken:

- Een hoge technische bedrijfsprestatie en laag AM-gebruik zijn niet wederzijds exclusief in de vleeskuikenproductie (*Hoofdstuk 3-5*);
- Bedrijven hebben unieke combinaties van technische bedrijfsprestatie en AM-gebruik, en vereisen daarom een bedrijfsspecifieke aanpak om het AM-gebruik succesvol te reduceren (*Hoofdstuk 2-5*);

- Succesvolle strategieën om AM-gebruik te reduceren moeten worden gericht op gecombineerde interventies met betrekking tot de veehouder, het bedrijf en de dieren *(Hoofdstuk 2, 3 en 5)*;
- Micro-economische theorie postuleert dat de belangrijkste determinanten voor de economische waarde van AM-gebruik de prijzen van productive inputs, damage abatement inputs en output, de productietechnologie, de damage abatement functie, de risicohouding van de veehouder en de variantie van winst zijn *(Hoofdstuk 3)*;
- Risicomijdende boeren overschatten de daadwerkelijke economische waarde van AM-gebruik (*Hoofdstuk 3*);
- Verbeteringen in het productiesysteem, gericht op het bedrijf en de dieren, kunnen het *damage abatement* effect van AM-gebruik verbeteren en verlagen de noodzaak voor AM-gebruik (*Hoofdstuk 3 en 5)*;
- Vleeskuikenbedrijven kunnen hun technische bedrijfsprestaties verbeteren ongeacht de mogelijkheden voor verbetering met betrekking tot AM-gebruik (*Hoofdstuk 4)*.

About the Author

Jamal Luka Roskam was born on December 6th, 1990, in Amersfoort, the Netherlands. After graduating from secondary school he studied Management and Consumer Studies (2009-2012) and Management, Economics and Consumer Studies (2012-2014), both at Wageningen University and Research. During his bachelor program, he also followed various courses in economics at Utrecht University. He obtained his bachelor's degree in 2012 and his master's degree in 2014. During his bachelor and master program, he became specifically interested in doing research in the field of agricultural business economics.

In August 2014, he started his PhD research at the Business Economics Group of Wageningen University and Research, where he assessed the scope for, and the farm-economic impact of reducing AMU in livestock production. His research was part of the EFFORT project. His work has been presented on various international conferences and seminars. During his PhD research, he followed his education programme at Wageningen School of Social Sciences (WASS). Since September 2018, he is working as a researcher at Wageningen Economic Research.

Training and Supervision Plan

Jamal Luka Roskam
Wageningen School of Social Sciences (WASS)
Completed Training and Supervision Plan

Wageningen School of Social Sciences

Name of the learning activity	Department/Institute	Year	ECTS*
A) Project related competences			
AEP30806 Economic Models	AEP	2015	6
ECH32306 Advanced Microeconomics	EHC	2015	6
PAP30306 Designing Innovative Governance Arrangements	PAP	2015	6
Writing PhD Research Proposal	BEC	2014	6
Business Economics PhD Meetings	BEC	2014-2018	4
'Quality Management in Broiler and Pork Supply Chains Aimed at Reducing Risks of Antimicrobial Resistance (AMR): an elicitation workshop'	10th International European Forum on System Dynamics and Innovation in Food Networks (151st seminar of the EAAE), Innsbruck-Igls (Austria)	2016	1
'Economic Analysis for Decision Support to Reduce Risks of Antimicrobial Resistance in Livestock Supply Chains'	Pitch presentation, DIES symposium The digitalisation of nature, Session "A global one Health", Wageningen (The Netherlands)	2016	1
'Economic Decision-Making on Reducing Risks of Human Exposure to AMR through Livestock Supply Chains: a Conceptual Framework'	16th International Conference on Production Diseases in Farm Animals, Wageningen (The Netherlands)	2016	1
'Costs of Poultry and Pig Diseases, with Reference to Antimicrobials'	4th International Conference on Responsible Use of Antibiotics in Animals, The Hague (The Netherlands)	2016	1
'Impact of Developments in the Dutch Pig Production Sector on Future Classical Swine Fever Control'	28th VEEC symposium: A closer look at water, Lelystad (The Netherlands)	2016	1
'The Economic Value of Antimicrobial Use in Livestock Production'	7th EAAE PhD Workshop: Challenges for young agro-food and natural resource economists facing the future, Castelldefels/ Barcelona (Spain)	2017	1
'Antibiotic Use: the Farm Economic Perspective'	12th International European Forum on System Dynamics and Innovation in Food Networks (163rd seminar of the EAAE), Innsbruck-Igls (Austria)	2018	1
'Antibiotic free meat: (im-)possibilities from a supply chain point of view'	One Health & Food Safety Congress, Bonn (Germany)	2018	1

B) General research related competences			
Introduction course	WASS	2014	1
Information Literacy including Endnote	WGS	2015	0.3
Scientific Publishing	WGS	2016	0.3
PhD peer consultation – a powerful tool to tackle PhD challenges	WGS	2016	1.5
Scientific Writing	WGS	2017	1.8
Writing blog	-	2017	0.1
C) Career related competences/personal development			
Referee Stock Market Game: Corporate Financial Management	BEC	2014-2017	2
Supervising MSc students	BEC	2017-2018	2
Total			**45**

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

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