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Structural change in agriculture induced by innovative biobased technologies, an agent-based approach

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"The truth is, most of us discover where we are headed when we arrive."

Bill Watterson

Dankwoord

Dit boek is het eindpunt van een lange omzwerving. De eerste aanzet gebeurde een kleine vijf jaar geleden, toen ik de kans kreeg om dit doctoraat te starten. Het voorgeschreven onderwerp was "duurzaamheidsindicatoren voor de industrie". Waar een doctoraat normaal afgelijnd wordt door een beschrijvende paragraaf, of soms zelfs een volledig projectdocument, had ik één lijntje. Dit geeft een enorme vrijheid. En nu blijkt dat ik me zelfs niet aan de initiële restricties heb gehouden.

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English summary

Industry and policy makers pursue the development of a biobased economy. The biobased economy emerged first as a promising segment of new biotech applications. But during the last years, the term evolved to cover a much larger concept. It currently has grown to a vision for a new industrial structure where all products, from energy carriers, plastics and food to high value additives and pharmaceuticals, are entirely based on organic matter, thereby annihilating any need for fossil fuels.

Of all economic sectors that are concerned by this evolution, agriculture certainly will undergo some of the larger effects. New biobased products will increase demand for existing and new crops. Transformation technologies of agricultural waste flows will also change market conditions for farmers. One of the main interactions between agriculture in the new bioeconomy, is based on manure. In regions with high animal density such as Flanders, manure is the largest agricultural waste stream. Several alternatives are being tested to dispose of manure in a sustainable way, in order to use it as a primary resource for new products. These solutions are often based on the natural activity of plants, algae, bacteria or insects, and lead to the production of chemicals, biofuels, paper and feedstock.

There are several impacts on agriculture from this development. The market conditions for the disposal of manure may be changed. Also, several biobased solutions require large land surfaces, and this drives up the demand for agricultural land. Finally, the outputs of some processes are again inserted in the food chain as feedstock for animals or specialised fertilisers. Given the multiple interactions between the innovative manure treatment sector and agriculture, it is unclear precisely how the agricultural sector will be impacted.

This dissertation develops an economic model that simulates both the evolution of the Flemish livestock production sector, and the manure treatment sector. The model looks simultaneously at the adaptation of farmers and the emergence of technological innovations in the manure treatment sector. Different scenarios simulate the future development of both sectors. Various policies to support the bioeconomy are also analysed, and their impact on the evolution of agriculture in Flanders is discussed.

The results show that the growth of an innovative manure treatment sector depends first and foremost on the availability of investment capital. At the same time, the effect of the new industrial sector on agriculture is very small. The agricultural sector displays a very rigid behaviour, and its slow adaptation is a barrier for the development of an innovative manure treatment sector. The difficulty of agriculture to adapt is situated in non-adaptive behaviour

of a proportion of the farmers, and in the high volatility of manure prices. The rigidity of the agricultural sector is not in the advantage of the farmers. Market conditions for farmers, and farm profitability, remain low during the evolution.

The results also show that policies and subsidies to stimulate the biobased economy have very little impact in these cases. The development of an industrial sector, based on manure treatment, is hazardous when manure prices are uncertain. If policies for the bioeconomy are implemented without regard for the link with agriculture, the effectivity of the policies will be very low. The effort will not lead to the development of a growing bioeconomy, and the evolution will not improve the economic situation of the Flemish livestock production either.

It is more important for policies to take the lack of adaptability of the agricultural sector into account. This requires better insight in the determinants of adaptive behaviour of farmers, and the construction of efficient and transparent markets for the trade of organic matter and agricultural waste flows.

Nederlandstalige samenvatting

Overheden en bedrijven spannen zich in om een biogebaseerde economie vorm te geven. De biogebaseerde economie ontstond eerst als een veelbelovende economische sector die vooral steunde op nieuwe ontwikkelingen in biotechnologie. Dit sloot nauw aan bij de farmaceutische industrie en de voedingssector. Maar gaandeweg is het idee van een biogebaseerde economie gegroeid tot iets veel groters. Het idee is nu een visie voor een volledig nieuwe industriële structuur in Europa, waar alle producten gaande van energiedragers, plastics, voeding, tot hoogwaardige stoffen en geneesmiddelen, allemaal gebaseerd zijn op organische materie. Hierdoor zou de vraag voor fossiele grondstoffen drastisch verminderen.

Veel economische sectoren zullen beïnvloed worden door deze evolutie, en de landbouwsector zal zeker een sterke impact hiervan ondervinden. Nieuwe biogebaseerde producten zullen de vraag naar bestaande en nieuwe landbouwgewassen opdrijven. De opmars van technologieën die afvalstromen uit de landbouw omzetten naar waardevolle producten, zullen ook de marktomstandigheden voor boeren veranderen. Eén van de grotere interacties tussen de biogebaseerde economie en de landbouw, is gebaseerd op mest. In regio's zoals Vlaanderen, waar er een bijzonder veel dierlijke productie is, vormt mest de grootste afvalstroom uit de landbouw. Onderzoekers verbeteren en testen alternatieve en duurzame methodes om mest af te zetten, door mest als grondstof te gebruiken voor biogebaseerde producten. Deze technologische oplossingen steunen vaak op de natuurlijke activiteit van planten, algen, insecten of bacteriën.. Ze geven nieuwe productietechnieken voor chemicaliën, biodiesel, papier of veevoer.

De landbouw wordt op verschillende manieren beïnvloed door deze evolutie. De marktvoorwaarden voor de afzet van mest kunnen hierdoor veranderen. Enkele biogebaseerde technologieën vereisen ook grote landoppervlaktes, zoals de productie van eendenkroos or algen. Dit drijft de vraag naar landbouwgrond verder omhoog. Daarnaast worden de eindproducten van deze nieuwe producties vaak ook in de landbouw gebruikt, zoals nieuwe meststoffen of als veevoer. Als men de veelheid van interacties bekijkt, is het niet mogelijk om te voorspellen wat het finale effect op de landbouwsector zal zijn.

Deze doctoraatsthesis ontwikkelt een economisch model dat de evolutie van de Vlaamse dierlijke productie simuleert, parallel met de mestverwerkingssector. Het model kijkt tegelijkertijd naar de aanpassing van boeren aan hun veranderende omgeving, en de ontwikkeling van nieuwe technologische innovaties in de mestverwerkingssector. De

toekomstige ontwikkeling van beide sectoren wordt gesimuleerd voor diverse scenario's. Verschillende beleidsopties voor de ondersteuning van de biogebaseerde economie worden ook getest, en hun impact op de landbouwsector wordt geanalyseerd.

De resultaten tonen dat de groei van een innovatieve mestverwerkingssector vooral afhangt van de hoeveelheid investeringskapitaal die beschikbaar is voor nieuwe installaties. Daarnaast blijkt de impact van deze groeiende industriële sector op de landbouwsector bijzonder klein. De landbouwsector toont een erg stug gedrag, en past zich heel weinig aan. Deze trage aanpassing vormt een barrière voor de ontwikkeling van de innovatieve mestverwerkingssector. De landbouwsector heeft het moeilijk om zich aan te passen, vooral door individueel rigide gedrag van een gedeelte van de boeren, en door de volatiliteit van de mestafzetprijzen. De rigiditeit van de sector is evenmin in het voordeel van de boeren zelf. Tijdens de simulatie blijven de marktprijzen en de winstmarges van boeren laag.

De resultaten tonen dat in dit geval de beleidsopties ter ondersteuning van de biogebaseerde economie heel weinig effect hebben. De ontwikkeling van nieuwe mestverwerkingsinstallaties blijft risicovol. Als het beleid ontworpen is zonder aandacht voor de rigiditeit van de landbouwsector, dan is de effectiviteit van het beleid heel beperkt. De stimuli leiden niet tot een grotere biogebaseerde activiteit, en ze verbeteren evenmin de werkomstandigheden van de landbouwers.

Het is belangrijk voor het beleid om rekening te houden met het gebrek aan aanpassingsvermogen in de landbouw. Dit vereist een beter inzicht in het gedrag van landbouwers, en de ondersteuning van efficiënte en transparante markten voor organisch materiaal.

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Introduction

The main question of this dissertation can be stated as follows:

> *"What is the impact of the biobased manure treatment sector and the related policies on the evolution of Flemish agriculture?"*

Several elements of this question deserve a brief introduction. The research focuses on the economic structure of the Flemish agricultural sector. In this context, structure means the attributes and sizes of productive inputs. It concerns the distribution of different types of farms, such as mixed farms or specialised dairy, cattle and pig farms, the division between crop farming, farm acreages and livestock production, the distribution between family farms and industrial farms, and the range in farm profitability and future prospects.

The second element is the manure treatment sector. Excess manure is a pressing environmental problem in the Benelux, with a large impact on farm income. This situation has led to the recent development of innovative and sustainable technologies for manure treatment. Many technologies are being developed with a better environmental performance in mind. These recent developments may also have important effects on the future structure of agriculture. This dissertation therefore investigates the impact of this growing sector in an existing economic structure. It starts from the technical analysis at the level of one technology, looks at the evolution of the sector in theory and broadens this to the co-evolution between the manure treatment sector and the agricultural sector.

The third element is an investigation of policy impact. This implies a comparison of the technology introduction with a reference situation of the agricultural sector. The reference situation is not static, it has to account for many external forces that currently influence the structure of the agricultural sector, such as the dynamics of the food supply chain or the land markets. The reference is then compared with different policy scenarios.

Finally, a key element is the focus on evolution. This research investigates the structural changes over time, as an effect of new innovations being introduced gradually. The research of structural change in periodic steps allows to start from the present situation based on empirical data and to proceed to path-dependent results in the near future.

This dissertation is organised as follows.

Chapter 1 sketches the starting point. A description of external forces on agriculture leads to critical aspects to be included in the research, and to constraints for the scientific methodology. Chapter 1 reviews scientific methods and describes advantages and disadvantages. A state-of-the-art is presented of related projects reported in the literature. These examples provide guidance to determine the main focus of this dissertation. Finally an overall model architecture is presented, and the subsequent structure of the text is explained.

Chapter 2 describes the construction of the farms agents, their behaviours and interactions on markets. Each element is calibrated and the final set-up is compared to similar programs.

Chapter 3 is dedicated to the manure treatment technologies. It outlines the technical and economic data for each technology. The chapter specifies the simulation of technology introduction and evolution, leading to a simulation of the evolution of the manure treatment technologies disconnected from the agricultural sector. This independent simulation reveals the general dynamics of the innovations in the sector, and its effect on the sector structure.

Chapter 4 combines the farm agents with the manure treatment companies. This chapter describes the choices of future scenarios and all external variables that act upon the agricultural sector. Based on the scenario, the co-evolution between the two sectors is simulated. The simulation results are presented, and the main results are discussed. The discussion focuses on the reference evolution of agriculture and the influence of policy measures to stimulate biobased technology.

Chapter 5 summarizes the conclusions from this dissertation. Ideas for further research are outlined as well.

It must be remembered that there is nothing more difficult to plan, more doubtful of success, nor more dangerous to manage than the creation of a new system. For the initiator has the enmity of all who would profit by the preservation of the old institutions and merely lukewarm defenders of those who would gain by the new ones.

Niccolo Machiavelli (1513)

Chapter 1 The Research Approach

This chapter explains different research approaches used for policy modelling in the industrial and agricultural sector, and positions the chosen methodology within this range.

The first section describes the general trends influencing the structure of agriculture. These are the present low profitability of farming activities, and the emergence of a biobased economy. The second section collects insights from different scientific domains that contribute to the construction of the methodology. The third section reviews modelling solutions that are applied in related projects, and retrieves insights from these results.

Section four describes specific requirements for the methodology of this dissertation. An evolutionary economics approach is adopted, including the construction of an appropriate agent-based model to simulate the evolution. This leads to the description of the actual model in section five. Section six indicates the different steps followed in this dissertation.

1.1 General trends

New technologies for manure treatment induce pressures on the structure of Flemish agriculture. These emerging new technologies are part of a growing bioeconomy, and its pursuit is likely to influence agriculture on several levels. The introduction looks at these technological innovations, and at the capacity of farms in Flanders to cope with these changes.

1.1.1 Economic uncertainty for farmers

At the start of the century, studies showed that poverty was widely present among family farms in Flanders, and many did not earn more than minimum wage (Van Hecke, 2001). This situation has not improved in recent years, particularly for farms specializing in dairy, cattle or pig products (Deuninck et al., 2009). Farms specializing in piglet breeding had negative income from 2006 to 2008 (FOD Economie, 2010). In 2007 and 2008, the negative income was even present before subtracting the annual farm's household income. Farms specializing in pig fattening presented a slightly better profitability, and showed a small positive benefit during this period. However, profits remained under pressure from increasing fodder prices and decreasing prices for live pigs. A follow-up report showed that this situation again deteriorated during the years 2010-2012 (Vrints et al., 2013a). Similar results were uncovered for cattle farmers (FOD Economie, 2009). The annual income did not suffice to remunerate household labour on the farm during the years 2006-2007, and this situation continued during the years 2009-2011 (Vrints et al., 2013b). These negative results should be noted as a reflection of the average farm's income. Flemish farms with profitability below average continued to accumulate financial losses in prior years.

The discussions on the potential reasons for this economic pressure are still ongoing. The National Price Observatory dedicated several studies to the price and cost structure of the beef and pork supply chain (FOD Economie, 2009; 2010). On the input side of the farm, the costs increased both for fodder and for land acquisition. The pig and cattle farmers did not succeed to transmit these increased costs to their purchasers, because on the side of production outputs, the sales prices for live animals remained at very low levels. One potential explanation may be an inflexible price transmission in the meat supply chain. The slaughterhouses are a central player in this chain. They are the primary purchasers of live animals from farmers, and they are the main suppliers of carcasses to the retail sector and the food industry. The dependence of the animal farmers on the market prices for their animals indicates that the live animals market has to be included in the research approach, as well as the influence the farmers may have on price setting.

The situation also led to frequent consultations between farmers' syndicates and representatives of the slaughterhouse and meat retail sector. These consultations already resulted in agreements on a beef price index. Similar discussions are ongoing for the sales of pork. Still, despite these agreements, the situation for farmers remains precarious, especially for the pig farmers.

1.1.2 The Shift to a biobased Economy

A general trend that is likely to affect the situation of agriculture is the emergence of the Bioeconomy, or Biobased economy. Appearances of the concept of the biobased economy can be traced back to developments in different industrial sectors. Early appearances of this idea (Enríquez, 1998) are developed following recent evolutions in biotechnology. At the end of the last century, pharmaceutical companies and specialty chemical producers increasingly turned towards applied genomics for new products and processes. This change implied a strategic change of their core business, with a full integration of life sciences in these companies and a host of new partnerships, especially with large actors in agribusiness. The rapid growth of projects in genetic modification, new pharmaceuticals and agriceuticals (Goldberg, 1999) led to believe that a new economic structure was being built, based on biotechnological innovations.

The growing development of renewable energy projects added a new component to the scope of the biobased economy: the use of organic matter for the production of energy and fuels. This changed the scope of this economic segment drastically. Contrary to the production of high-value low-volume biotech products, renewable fuels and energy require high volumes of organic matter of various qualities. The quest for higher transformation efficiency of biomass streams led to research on biorefineries. Similar to refineries of fossil petroleum, these installations divide organic feedstock in its numerous components, each destined for a specific industrial purpose (Fatih Demirbas, 2009). The potential number of products rises significantly as this set-up can produce biobased bulk chemicals, animal feedstock, various energy carriers, fertilisers and additives (Lynd et al., 2005; Shen et al., 2009). This also magnifies the size of the new markets to be developed (Nowicki et al., 2008). The increased scope and volumes have repercussions on the demand of organic matter. Early biotech applications are mostly based on pure crops such as corn or sugarcane. The addition of renewable energy products and bulk chemicals enlarged the demand for organic inputs to pure crops but also to agricultural waste material, manure (Chen et al., 2003), algae (Lam et al., 2012), forestry residues (Bozell, 2008), or grasses of different types (Kromus et al., 2004).

The biobased economy emerged as a promising segment of new biotech applications. But during the last years, the term evolved to cover a much larger concept. It currently has grown to a vision for a new industrial structure where all products, from energy carriers, plastics and food to high value additives and pharmaceuticals, are entirely based on organic matter, thereby annihilating any need for fossil fuels (Swinnen et al., 2013). The interest in this vision is for a large part driven by pressing sustainability and scarcity concerns. The use of fossil fuels can be related to climate change, environmental degradation and toxicity (Huijbregts et al., 2010). Biobased products from biorefineries can reduce the emission of greenhouse gasses significantly (Brehmer et al., 2009; Brehmer et al., 2008). But the entire impact on other environmental pressures is less predictable, and caution is needed to prevent unwanted effects such as increased eutrophication or water scarcity (Miller et al., 2007).

The emergence of a biobased economy increases economic complexity. For instance the pharmaceutical, chemical, energy, biotech and food processing sectors are involved in the emerging biobased economy. An increasing collaboration between these sectors will also increase the number of complex effects, such as unexpected feedback loops, path-dependency or co-evolution. This raises additional problems for policy makers. When multiple sectors evolve towards a complex system with multiple interdependencies, caution is required for policies in order to avoid unexpected consequences. The correct design and implementation of policies will be as important to the emergence of the biobased economy as the development of new technologies. Bennett and Pearson (2009) show that the emergence of new biorefinery technology is not solely a question of technological development when system dynamics are taken into account. The emergence depends less on process efficiency and more on the historical context of the economic sectors and policy stability.

1.1.3 Manure-based innovation in agriculture

Of all economic sectors that are concerned by this evolution towards a bioeconomy, agriculture certainly will undergo some of the larger effects (Nowicki et al., 2010). There will be an increasing demand for organic materials of all kinds, fresh crops, agricultural waste streams and new cultures. A higher investment in agricultural R&D is required to ensure the capacity of the agricultural sector to meet this demand over the long term (Pardey et al., 2013). New approaches will be needed to meet the diversity of demand, such as agriculture based on multifunctional landscapes with perennial crops (Glover et al., 2010; Jordan et al., 2007). The total demand for organic material will increase as well, and so will the pressure on land, leading to allocation of land to different uses (Hertel et al., 2013). These increasing pressures require also innovative solutions. Increased nutrient cycling could increase the sustainability of production (Anex et al., 2007). The declining availability of water of sufficient quality requires new crop management practices and policies (Rosegrant et al., 2013).

One of the main interactions between agriculture and the new bioeconomy, is based on manure. In regions with high animal density such as Flanders, manure is the largest agricultural waste stream. The annual production of animal manure can cause large environmental impacts, such as higher nitrate and phosphate concentrations in soil and groundwater. This is for instance the case in Belgium, western France, Poland, Finland and the Netherlands. In order to control the environmental impacts, the spread of raw manure on land is regulated and increasingly restricted.

Alternative solutions to dispose the manure have to be created. Currently, manure is treated and transformed in exportable fertilisers, safe effluents or valuable new products. In Flanders, there are four traditional technologies to treat manure. The most common technology at the site of the farm is biology treatment (Lens et al., 2001; Verstraete et al., 1977). In 2012, about 60% of the installations in Flanders were based on the biology treatment of the thin fraction of manure (VCM, 2013). More centralised solutions apply composting or chalking. Another method dries the manure and transforms it into saleable fertiliser pellets. The common feature of these traditional treatment methods is that they transform manure into disposable waste flows, or in fertilisers, such as K-fertiliser or compost. Outputs of higher value are not produced with these methods.

Several new biobased alternatives are also being tested to dispose of manure in a sustainable way, or to use it as a primary resource for new products. These solutions are often based on the natural activity of plants, algae, bacteria or insects, and are part of the larger growing bioeconomy. There are several impacts on agriculture from this development. First, the market conditions for the disposal of manure may be changed by this evolution. Secondly, several solutions require large land surfaces, such as constructed wetlands, or algae cultivation. Finally, the outputs of some processes are again inserted in the food chain as feedstock for animals or specialised fertilisers. Given the multiple interactions between the emerging manure treatment sector and agriculture, it is unclear precisely how the agricultural sector will be impacted.

1.2 Retrieving insight from future scenarios for policy guidance

The main objective of this dissertation is to investigate the impact of new manure treatment technologies and related policies on the agricultural sector in Flanders. The research looks at the dynamics of this co-evolution, in order to provide policy guidance.

The manure treatment sector can possibly induce large changes in the agricultural sector, because it treats the largest agricultural waste stream, which is also a large operational cost for farmers, and has multiple links that affect market conditions in agriculture. The manure treatment sector is therefore particularly well suited as an empirical case study to provide insight on the more general effect from the growing bioeconomy on agriculture.

This question extends to agricultural and industrial policies. New policy measures are being designed to stimulate the bioeconomy. An empirical investigation allows also indicating the impact of new policies on the co-evolution of the two sectors. The European Union adopted in 2012 the Copenhagen Declaration for a Bioeconomy in Action (EC, 2012). The Commission bases the strategic actions to create a bioeconomy on three pillars, (i) investments in research, innovation and the related skills for the bioeconomy, (ii) increased interaction and stakeholder engagement for coherence between different policy domains, and (iii) creation of new markets and improved competitiveness of companies. The OECD recommendations for bioeconomy policies show a similar focus on empowering economic actors and removing barriers to innovative economic activity (Arundel et al., 2009). Interactions between the stimulated biobased activities and agriculture can have effects on the effectiveness of the policies. It is also important to analyse the indirect effect of this type of policy measures on the evolution of the agricultural sector.

The detailed simulation of future scenarios, and the investigation of policy effects, requires an empirical analysis of a co-evolution between two sectors. The methodology for this analysis can be based on previous projects reported in literature. Three related strands of literature provide insight for the creation of a research framework. These are transition thinking, innovation research and research on socio-ecosystems. The following sections review these scientific developments, and indicate the elements that are important to incorporate in the current scientific approach.

1.2.1 Transition thinking

The emergence of a biobased economy, and the implied replacement of incumbent industries, creates larger changes than technological innovation alone. The required changes imply periods of instability for many economic actors. Authorities and institutions are also challenged to follow. New needs for product handling, consumption patterns and biobased product valuation are likely to drive changes in the society at large. This emergence is accompanied by a socio-technical transition. According to Rotmans et al. (2001) a transition is "*a gradual, continuous process of change where the structural character of a society* [...] *transforms*." The structural modifications in a society compel changes in power structures, in habits and in expectations. Such a socio-technical transition affects and is affected by changes in land use, technology, environment, culture and institutions. A broad system view is required to investigate this regime shift. The interdependences between the environmental drivers, human adaptation, structural barriers and economic evolution create numerous complex dynamic effects. As a consequence, the outcome of technology introductions and policies cannot be grasped intuitively.

Transition thinking presents an alternative method to investigate structural changes, and allows for the inclusion of several aspects that are left out by standard economic models. The research domain of sustainability transitions has been growing in an effort to understand complex societal evolutions, and to a certain extent to guide and to steer transitions to desirable and sustainable outcomes (Markard et al., 2012). Based on earlier research on technological evolution and industrial change, several approaches have emerged based on strategic niche management (Kemp et al., 1998), transition management (Rotmans et al., 2001) or a multi-level perspective (MLP) (Geels, 2002). This approach has been used to design on a holistic and participatory basis new policies for the sustainable transition of economic sectors (Grin et al., 2011; Loorbach, 2010; Loorbach et al., 2010). The theoretical foundation of this method is strengthening over the years (Geels, 2010; 2011). Still it is subject to criticisms arguing that the use of central concepts such as regimes or systems can be hard to define in practice (Safarzyńska et al., 2012). This led to the research based on MLP methodologies within defined boundaries of economic sectors, for instance agriculture, energy, transport or recycling. But the concepts from the transition thinking approach can in practice be used in a loose manner, and when applied to one economic sector, the fundamental system perspective is reduced. This gives reasons to remain critical of these sector applications and stimulates the search for other research methods (van den Bergh et al., 2011). Many applications have been descriptive and qualitative (Geels, 2002). Conceptual and abstract applications have been elaborated as well (de Haan, 2008).

The approach of transition thinking is too broad to be applied in this case. The multi-level perspective distinguishes levels, building up from sectors, over regimes up to landscapes. The individual unit of analysis in transition thinking is the level of the sector. Distinctions are made between niche sectors and dominant sectors, the latter constituting the socio-technical regime. A regime is a stable configuration of sectors and institutions to provide a societal function, and is embedded in a socio-technical landscape. The landscape gathers sources of pressure and external trends that influence regimes, and the internal dynamics (Geels, 2002; 2011; Smith et al., 2010b). This dissertation looks at one very particular sector only, and application of the broad multi-level perspective on sector-related cases is not recommended (van den Bergh et al., 2011).

There are however four important insights from transition thinking to be included in the modelling approach for this dissertation. The first element is that technological transitions and the effect on related sector is a complex and path-dependent phenomenon. Technological lock-ins are path-dependent results from historical evolutions, and the same path-dependency applies to the emergence of niche sectors as the new regime players. Secondly, transition thinking looks closely at radical change coming from marginal niche actors, rather than incremental improvements of incumbent actors (Rotmans et al., 2009). This reversal of regimes based on niche actors may not apply to all transitions (Smith, 2005), but the option of radical structural change should be allowed by the modelling approach. Thirdly, the transition framework recalls that transitions may be induced by technology, but the reaction and adaptation of the concerned actors determine the outcome of the transition process. This leads to the importance of individual behaviour of economic actors in relation to the technological evolution that needs to be included as well. Finally, transition thinking emphasises that investigations have to maintain a holistic view. Coherent with the view of transitions as complex phenomena, the approach cannot be replaced by combining separate investigations of the dynamics within individual subsystems, or disconnected from larger societal and economic trends.

1.2.2 Evolutionary economics and innovation research

Evolutionary economics is an alternative scientific discipline that is capable of integrating essential features of transitions, such as complexity, multiple levels, adaptation, co-dynamics, emergence and heterogeneity. Evolutionary economics has since long focused on economic change and its underlying dynamics (Dosi et al., 1994). Evolutionary economics is interested in explanations of economic change over time, based on learning, selection and innovation. Evolutionary thoughts have been elaborated since the early developments of economic theory (Clark et al., 1988). The publication of the book of Nelson and Winter (1985) brought a revival of evolutionary theories in economics to light (Dosi et al., 1994).

Variety and diversity are of particular importance in evolutionary descriptions of the economic process. Evolutionary economics incorporate a variety of economic actors, combined with an innovative reproduction process fuelling this variety, and selection mechanisms reducing it. The approach stresses bounded rationality of economic actors, and realism in the analysis of economic behaviour (Nelson et al., 2002). This led to new theories of endogenous growth, fuelled by innovation and economic self-transformation (Metcalfe, 2005), and the creation of new sectors (Saviotti et al., 2004). Also a view of multiple levels of economic investigation have been part of this tradition, with the creation of a 'meso'-level of groups of economic actors, as a central point of view to translate findings from micro-behaviour to a macroeconomic level (Dopfer, 2011; Dopfer et al., 2004).

Evolutionary economics shows a sufficiently large potential, allowing this approach to be applied to investigate industrial and societal transitions. Safarzynska et al. (2012) demonstrate that evolutionary thinking and modelling are very well suited to enrich research in sustainability transitions. The evolutionary methods can be helpful to render more precise the definitions of transition concepts, and they are able to model and quantify tentative and qualitative transition scenarios. Moreover, Faber and Frenken (2009) demonstrate that the combination of evolutionary and environmental economics can be particularly fruitful. The evolutionary view can for instance give an alternative to the efficiency paradigm of policies based on neo-classical economics, and can provide new options to resolve the double externality problem for adoption of environmentally friendly technologies (van den Bergh et al., 2006).

There is a strong tradition of this approach in the investigation of innovation, knowledge creation and the consequent renewal of the economic structure (Fagerberg, 2013). There remain important principal differences between the regional innovation studies and the research on innovation following technological systems on the one hand, and transitions in socio-technical systems on the other (Coenen et al., 2010). But the experience in innovation research has enriched the multi-level approach of transition thinking (Markard et al., 2012; Markard et al., 2008).

Within the tradition of innovation research, there are elements that have been developed in more detail, which can contribute to the methodological development in this dissertation. The first element is the detailed analysis of firm behaviour. Contrary to neoclassical rational behaviour, the evolutionary approach looks at firms with limited information and an opportunity set restricted by knowledge and past decisions (Nelson et al., 2002). Evolutionary models of innovation detail the behaviour decision parameters according to empirical understanding of innovation in firms. At the level of the firm, this behaviour deviates from strict profit optimisation, and leads rather to firms incrementally satisficing their routines to new situations (Geels, 2010). There is a large scientific base in the domain of modelled learning and adaptation for individuals and firms (Brenner, 2006; Dosi et al., 2005). Appropriate learning simulations can be introduced in the behaviour description of the modelled agents, leading to precise models of firm innovation (Dawid, 2006).

Secondly, diversity is essential in evolutionary theories, as evolution can only create effects through variation and selection of differences between individual actors. Without heterogeneity between actors, emerging, growing and evolving niches are impossible. The role of diversity also shifts the base level of the investigation from the level of an economic sector in transition thinking, towards the level of the individual economic actor in evolutionary economics.

The third element is the knowledge on the process of innovation. Innovation studies have since long investigated in detail the emergence of technological change and innovation. For instance, Dosi (1982) proposed a model of technological paradigms, with the effects of incremental or radical innovations, explaining historical path dependence or lock-in. Other studies looked at different models of diffusion and adoption of innovations by firms, based on different theoretical assumptions (Metcalfe, 1988). The endogenous modelling of innovations has already been linked to transition analysis, especially when these are sparked by technological development (Smith et al., 2010b). However, innovation studies have only been scarcely applied taking social dynamics and consumer behaviour into account (Geels, 2010). The inclusion of innovation dynamics in a multi-sector model provides avenues for new insights.

1.2.3 Research on socio-ecological systems

A social-ecological system or socio-ecosystem (SES) is defined as a system that includes interaction between a human (societal) and a natural (ecological) component (Berkes et al., 1998). This coupled interaction leads to a combined evolution of all subsystems where societal changes are translated in changes in the natural environment and vice-versa (Gallopin, 1991). The level of analysis of SES can vary from local communities within their natural environment to the global scale of the earth and the human population. The essential understanding in SES-analyses is that these systems cannot be dissociated in their respective components. Investigation in the dissociated elements of an SES cannot yield insight in the actual dynamics governing these systems (Turner et al., 2003).

This research domain has been stimulated by the development of the resilience concept. The resilience approach has proved to be a strong framework to uncover the dynamics of coupled social and ecological systems. The origin of this concept is based on advances in ecosystem theory. Contrary to the earlier understanding of ecosystem stability, the resilience approach started from a representation of ecosystems in a dynamic non-equilibrium, hovering between several attraction poles. A resilient system is in this sense a dynamically changing system that can absorb shocks while remaining in the same attraction basin. Vulnerable ecosystems on the other hand can only take very few shocks or perturbations before tipping into an alternative configuration (Holling, 1973). This is the mathematical representation of a complex system that can undergo changes, while maintaining its main state variables, and thus keeping its identity. Applications showed that even seemingly stable ecosystems experience continuous change, and are in fact multi-stable (Holling, 1978). This approach shifted the focus of ecosystem management from the original idea of perpetuating ecosystem stability, to management of the ecosystem's ability to overcome and adapt to change (Folke, 2006). The resilience approach has been successfully applied in several cases of innovative ecosystem management. By identifying the different alternative states of the ecosystems, local communities could actively contribute to the establishment or preservation of the preferred state of their local environment (Walker et al., 2012).

By enabling social communities to respond to ecosystem changes, the resilience approach has been effectively expanded to applications in socio-ecological systems. This extension is a gradual process. Initially, the field of resilience research was directed from its origin in research on adaptation in ecosystems, and detached from other fields like research on vulnerability and adaptation. The latter concepts are more related to human and societal change, induced by changes in ecosystems (Janssen et al., 2006b). But the fields increasingly merged during the last decade (Janssen, 2007).

The extension of the resilience framework to the social sphere is meaningful, but the concepts have to be applied carefully. Social resilience is an equally important factor as ecological resilience for sustainable SES, and is measured in different variables, subjected to different shocks and linked to institutional and economic change in addition to transitions induced by the environment (Adger, 2000). The dynamics of social transitions are also different, because contrary to ecosystems, individuals and societies can act proactively as well as reactively, when confronted to change (Smithers et al., 1997). There are already divergent definitions and understanding of core notions like vulnerability, harm and transformation in ecological resilience research (Gallopín, 2006). The extension to the social domain connects these concepts with social theory and its insight on agency, power and knowledge. This enlarges the range of definitions, and makes precise discourse even more challenging (Cote et al., 2012). Despite these differences, the lessons from ecosystem research provide new ideas for research in socio-ecological systems.

The resilience concept has also been applied within transition thinking. Especially, the notion of multiple states and dynamic non-equilibrium can enrich the transition thinking discourse. When ecological resilience research often looks at maintaining a SES in the same state, transition thinking precisely investigates options to shift the SES state to new regimes. Also the origin of transition thinking in technological development and technology-induced changes in society, make it complementary to resilience research where technological innovation is mostly peripheral to the core theme of ecological dynamics (Smith et al., 2010a).

Several elements from research on socio-ecological systems have to be incorporated in this research approach. First, transition thinking already is founded on the idea that the economy is a complex system. Insights on change in SES further reinforces this point, and stresses the importance of maintaining the link between the social dynamics (investments, markets, institutions,…) with the physical dynamics of ecosystems. Natural environmental and resources strongly influence the evolution of related economic sectors, and this is certainly the case in agriculture. The insights from ecosystem evolutions also show that the transition does not necessarily follow a path between stable regime A and stable regime B. Complex systems can also follow cyclic evolutions and transit between several states of non-equilibrium. Secondly, the work on resilience in the social sphere accentuates the importance of detailed behaviour assumptions to approximate individual and collective adaptation to change.

1.3 Model requirements

The empirical analysis of a co-evolution between the manure treatment sector and agriculture calls for a modelling solution that is capable of integrating the four following characteristics.

- Complex: The model allows internal complex effects, by including feedback mechanisms and path dependence. The model shows the adaptation of the economic sectors during the entire evolutionary path.
- Holistic: As it is not possible to dissociate the dynamics into smaller subsets and separate developments, the model requires an interdisciplinary approach given the variety of elements to be incorporated: investments and finance, land use change, market dynamics, physical resource constraints, behaviour and adaptation, innovations in biotechnology and its effect on production efficiency.
- Heterogeneous: Both the emergence of niche sectors and the development of technological innovation require heterogeneity within a sector. The presence of diverse actors and behaviours creates the opportunity for radical change within a sector based on niche developments.
- Detailed in behaviour: The technological innovation has to be completed with behaviour assumptions of the economic actors. Both forecasting and reactive decisions are required, as well as the possibilities for adaptation and learning effects along the evolutionary path.

An appropriate modelling approach has to be selected. First, alternative options are reviewed. Then a state-of-the-art shows solutions that are capable of incorporating all required aspects, and indicates the research gap that is addressed by this dissertation.

1.3.1 Alternative modelling options

Policy makers can rely on research projects and specialised general and partial equilibrium modelling efforts at the Joint Research Centre of the EU. Computable General Equilibrium models (CGE) review price adjustments and trade shifts from a regional to a global scale. Partial Equilibrium (PE) models are very appropriate for more detailed views on market shocks and on policy evaluation in one or two sectors, keeping the other sectors constant. Both types of models are currently being extended to include biobased markets and growing biobased activities (M’barek et al., 2014).

CGE and PE modelling have to deal with some limitations. First, they are based on aggregated data, and have difficulties in incorporating important effects such as land use change, and network effects in innovation. Secondly, the models determine a new equilibrium. However, these models do not clarify what happens during the transition from the current situation to the new equilibrium. The evolutionary path for an equilibrium model is externally subscribed by the scenario that is being modelled. So they cannot uncover new aspects of historical path-dependency or lock-in effects, besides the path dependency elements that are already included in the scenario. Thirdly, the integration of niche markets is practically impossible, as a result of the level of aggregation that is required for the data collection. Niche markets are too small, and distinctions between biobased products and their alternatives are not always significant during the development of new biobased industries (M'barek, 2014). Fourthly, structural change remains difficult to incorporate. The model assumes a prescribed economic structure, and structural change indicates the limits of applicability of the results. Finally, the biobased economy is equally dependent on physical production capacities of agriculture. The tight relation between the emerging biobased economy and natural and physical resource flows poses an additional difficulty on quantification, because integrating this physical dimension into economic models is another challenge. It is essential to include natural flows and structures in the model, when investigating the growth of this type of industrial sector (Ayres, 2001). But this inclusion further limits the potential modelling techniques. Inserting the physical flows, entities and exchanges in an economic model amplifies the level of complexity of the model. In this case it is no longer possible to find a solution based on analytical formulas, but only numerical modelling techniques can be applied for these combined ecological economic systems (Costanza et al., 1993).

An alternative solution is dynamic modelling. This approach is designed and applied to incorporate various complex effects in the system under investigation. Complexity stems from the interdependence of actors, environments or groups and their mutual adaptation to each other. This construction can yield counterintuitive and unexpected outcomes. The interest in complex dynamic systems was facilitated by the emergence of system theory and its application to social sciences (Forrester, 1961; 1971). This has driven innovations in very diverse fields such as in interactive learning (Sterman, 1994), management science (Senge et al., 1992), and no-growth macroeconomics (Victor, 2008). Because of its reliance on non-equilibrium dynamics, and non-linear modelling, system dynamics can contribute to the development of new economic theories (Forrester, 2013). There is a long tradition of system dynamics in economic applications. Early interdisciplinary projects included resource constraints in a model of the economy and the biosphere, and this lead to the description of

"Limits to Growth" (Meadows et al., 2004). Other projects have used the advantages of system dynamics modelling in analyses of socio-ecological systems (Shaw et al., 1994), agricultural sustainability (Belcher et al., 2004), or uncertainty related to constrained natural resources (Kwakkel et al., 2013).

The system dynamics approach has the capacity to simulate complex system behaviour. This is combined with the fact that there is freedom to embed actors with detailed behaviour routines or rules. Given the large literature on interdisciplinary projects based on system dynamics, the approach also has the possibility to account for ecosystem interactions and resource constraints. However, the inclusion of heterogeneity is more complicated. System dynamics sketches aggregated groups of agents in clusters. Different groups can be available from the start of the simulation. But the emergence of new heterogeneous actors and niches during the simulation is very challenging in this approach.

1.3.2 State-of-the-art in related agent-based modelling

This dissertation has adopted an approach based on agent-based modelling (ABM). ABM models are founded on groups of autonomous agents that have individual behaviours, technical characteristics and communication possibilities. This provides possibilities to investigate interactions and relations in detail. . Agent-based models (ABM) are particularly suited for the simulation of economic evolutions (Pyka et al., 2007; Tesfatsion, 2003). An ABM model is built from the bottom up: the individual agents being each represented with their decision process and historical pathways. The model has to respect the agent's autonomy; after the initialisation, the agents evolve autonomously without external interactions from the modeller. ABM simulates economies as decentralised, complex and adaptive systems, without imposing market equilibrium or a functional form at higher levels (Basu et al., 1997). ABM can present modelling solutions with essential characteristics to represent socio-technical transitions, where alternative modelling approaches encounter problems: path-dependency, bounded rationality, heterogeneity, and innovation, learning and adaptation.

In various topics where traditional economic modelling techniques are ineffective, ABM can provide better insight, for instance for complex socio-ecological issues, such as governance of commons or interactions with the dynamics of ecosystems (Janssen et al., 2006a). And when traditional macro-economic models are under scrutiny, ABM can provide credible alternatives (Farmer et al., 2009).

Inclusion of complexity in ABM

Complexity is based on links between various elements in the model, and these links can take different forms. In principle, economic agent-based models follow the rules of evolutionary economics. Potts (2000) argues that complex system dynamics are inherently embedded in evolutionary economic analysis. Contrary to neoclassical economics, they assume no equilibrium of any kind. Economic change, as understood by evolutionary approaches, is based on dynamic non-equilibrium, irreversibility and path dependence. Therefore, it is essentially a complex system approach, as it takes account for the interconnectedness of economic actors, and the chaotic nature of the macro-economy that this implies (Potts, 2000).

Practically, the integration of system dynamics requires the inclusion of links between the different elements of a model, allowing communication and feedback loops. Markets are one of the most important features that can link elements in a complex system, because markets can generate and transmit information for the participants. ABM has been intensely used for studying economic markets (Cristelli, 2014). Projects have investigated the link between individual trader behaviour and macro-level market data (Hoffmann et al., 2007), or the effect of different types of behaviour of market participants (Neuberg et al., 2003). Game theoretical concepts have been used to optimise bidding strategies within a market context (Hailu et al., 2005; Moulet et al., 2008). New theories are being built about market efficiency, such as the adaptive market hypothesis (Lo, 2005), and this evolutionary market theory is also investigated in detail with ABM (Zhang et al., 2010b).

Especially electricity and energy markets have been studied using an agent-based approach (Sensfuß et al., 2007). ABM yields results that link electricity price determination to the behaviour of market actors, to production characteristics and timing (Cincotti et al., 2013), and to the multiple production constraints and policy measures for greenhouse gas abatement (Bing et al., 2010). The electricity markets are also a particular subject to investigate the role of industrial structure and technological lock-in for future industrial evolutions (Safarzynska et al., 2011).

The link between the details of market dynamics and structural change in the economy is less investigated. Details in market dynamics are important, because prices send signals to firms for innovation and change. The development of detailed submarkets and diversified prices are important signals to steer the innovation decisions of individual firms (Dawid et al., 2011), and this has also been used to look at the role of product quality in structural change (Saviotti et al., 2013). In most cases however, only one side of the market is included in a modelled analysis of structural change. The market signals only aggregated prices, and co-evolution between the demand and supply side of the market is excluded. This one-sided approach has been successfully applied to investigate the diffusion of environmental consumer goods (Schwarz et al., 2009), or the role of venture capital to fuel innovation (Colombo et al., 2012). In special cases, both the supply and demand side of markets are included, and this set-up is used to investigate groups that can present co-evolution. This has been applied to study the interaction between households and collective innovations for wastewater treatment (Panebianco et al., 2006), or interaction between competing and innovating sectors (Beckenbach et al., 2010). These projects reveal the importance of preserving the role of internal markets in ABM as gateways of detailed information during times of transition, in order to investigate co-evolution between sectors.

Inclusion of links with the environment or with natural resource constraints

The historical emergence of the semiconductor or pharmaceutical industry have been simulated (Malerba et al., 2008; Malerba et al., 2002). But contrary to those sectors, the biobased economy is much more constrained by the availability of organic matter, and as a consequence by the access to surfaces of agricultural land. Also, the growing biobased economy is partly encouraged by environmental concerns. So at different levels, the relation between the economic agents and the organic matter as an essential productive input needs to be maintained. The integration of environmental aspects in economic models can be built on historical examples. Early integrations of environmental and economic aspects have been done on a few occasions. Faber and Proops (1990) investigated in a Neo-Austrian model the interaction between the environment and the economic evolution in one of the early studies of ecological economics. Giampietro and Mayumi (1997) also presented a theoretical model of an economy connected with the environment, highlighting the evolution towards or developed countries with high energy-intensity, or developing countries with low economic sustainability.

Research on socio-ecological systems (SES) presents a strong tradition of simulations including the ecological dynamics (Schlueter et al., 2012). ABM is increasingly used to investigate these interactions in detail. Heath et al. (2009) provide a review of ABM practices until 2008, showing a growing use in the fields of ecology, agriculture and economics. In more recent years, especially investigations in Land Use, and Land Use Change turned towards theoretical and empirically-based ABM (see for reviews Parker et al.(2003), Matthews et al. (2007), and the special issue in EM&S (Filatova et al., 2013)).

The largest part of this discipline focuses on the interactions between land characteristics, and land use change. The dynamics reveal effects of land use on ecological parameters, which influence the decisions of land users again. Various ecological aspects of land use can be included, such as deforestation (Figueiredo et al., 2011), the provision of ecosystem services (Murray-Rust et al., 2014), irrigation and perennial crops (Berger, 2001; Schreinemachers et al., 2011) or the effect of forest clearing by farmers (Hoffmann et al., 2002). The focus on farmers as principle agents of land use change has even led to initiatives to standardise farm models in this context (Louhichi et al., 2010).

This large simulation experience provides guidance for this dissertation on how to connect natural resource constraints and land availability to economic dynamics. However, social dynamics are not often included in detail in Land Use modelling (Haase et al., 2012). For instance, only a small part of these simulations integrate a market for land exchange between farmers (Bakker et al., 2015; Sun et al., 2014). Land use modelling looks frequently at spatial effects and distributions of land types, but less at economic structural change in agriculture as a result of adaptation. A small and specific research discipline with full integration of the natural resource constraints and social dynamics in one model is agent-based agricultural economics. The first models in this field have been created by Balmann (1997), studying structural economic change in an abstract landscape. Further developments have elaborated this model to study impacts of policy changes in different regions in Europe (Happe et al., 2004; Happe et al., 2006; Sahrbacher et al., 2005). Lately, these models have been extended to include common features for SES-simulations, such as ecosystem services and environmental impacts (Brady et al., 2012). Another application reviews the effect of land markets on spatial distribution of farmers, and residential developers (Freeman et al., 2013). But these projects remain a minority, compared to the large literature on land use. The effect of land markets on land use, and the corresponding impact on the environment is been studied more often in the context of urban or semi-urban areas (Filatova et al., 2011; Magliocca et al., 2011; Parker et al., 2008).

Inclusion of behaviour details

Also the exact simulated behaviour of the agents requires sufficient detail. The inclusion of farms, including family farms, brings about a wide range of behaviours of economic actors, given the diversity of motivations and behaviour rules observed in farms' decision making (Viaggi et al., 2011). Bakker and Van Doorn (2009) specifically show that a variety of decision models is necessary to explain farmers' decisions on land use change. In general many advances are still possible to capture these motivations and diversities in an ABM. In principle, behavioural heterogeneity is possible (Tesfatsion et al., 2006). However the application of behaviour diversity in ABM is mostly reserved for diversity in consumer decisions, and less for simulation of diversity in behaviour of economic actors.

Research in socio-ecological systems has also contributed to the development of different behaviour algorithms for land using agents. An (2012) reviews in detail behaviour models in coupled human and natural agent-based models. The overview shows a large variety in principle decisions and practical elaborations to build behaviour models for human agents. Several studies choose for a process-based decision, and adopt individual profit or utility optimisation, subjected to practical constraints (Schreinemachers et al., 2006). These solutions can also be influenced by individual environmental concerns (Zheng et al., 2013). Other solutions adopt insight from psychological and social research, and base the decision patterns for instance on the theory of planned behaviour (Kaufmann et al., 2009). In order to approximate real decision heuristics, several projects let go entirely of process-based decision algorithms, and conduct field research with questionnaires and role-playing games to deduct empirical decision rules (Barreteau et al., 2014; Bohensky et al., 2007; Lamarque et al., 2013; Smajgl et al., 2013). The potential for detailed and diversified behaviour models is large, and the research experience on this subject is growing fast. However, the most detailed and empirical-based behaviour model is not always the most suitable solution (An, 2012). Projects that adopt very detailed behaviour patterns are especially focussed on the effects of these behaviours on the economic structure and the environment. Simpler behaviour models are required whenever the agents are embedded in larger model structures. The behaviour is crucial in defining the evolutionary trajectories of the agents, and simpler models allow then to keep the overview of the dynamics.

1.4 Focus for the research approach

This dissertation simulates the co-evolution between agriculture and a very specific part of the biobased economy: the sector of manure treatment companies. Manure from pigs and cows constitute the largest agricultural waste stream in Flanders. This organic stream is a particular source of environmental and economic concerns. The manure pressure leads to high concentrations of nitrates and phosphates in groundwater, with often detrimental effects on local ecosystems. A growing number of economic actors use a variety of technologies for manure treatment. This subsector can expect large changes in the future, induced by an ongoing emergence of biobased innovations. Many technologies for manure treatment are currently being investigated, and intend to create high value end-products from manure based on the activity of biological organisms. There are a large number of new technologies at the brink of industrialisation in this field. The focus on this subsector concentrates on dynamics with large biomass dependency, and significant environmental impact.

1.4.1 Choice of included elements

The emergence of new manure treatment technologies evokes several complex effects. Biobased treatment methods require large surfaces of agricultural land for their activity, entering thereby in competition with farmers on the land market. They can also provide alternative fertilisers and feedstock products for farmers. Finally, the emergence of more manure treatment actors can induce also a price change of the excess manure, leading farmers to increase their animal stocks. The emergence of the manure treatment sector can thus affect the economic situation of farmers first via the land market, via the manure market, and via markets for inputs for farmers such as mineral fertilisers and feedstock.

The dissertation looks thus at the co-evolution of two sectors, a livestock production sector and a manure treatment sector. Both are embedded in a larger framework. The set-up is a particular case of the emerging bioeconomy. This emergence is fuelled by technological innovation, and this innovation originates here in the sector of manure treatment companies. The innovation dynamics in the agricultural sector itself are totally different. Agriculture has been characterised as a sector where technological innovations mostly arrive from external sources, such as suppliers, clients or industrial partners (Pavitt, 1984). The sector adapts as a result of these external changes, rather than developing innovations internally. The investigation of the co-evolution between these two sectors is in this sense a close-up of the larger changes that are brought upon the agricultural sector by the entire bioeconomy. A detailed investigation shows how the agricultural sector adapts to external innovation, what barriers are present, and which farmers are more likely to benefit from the changes.

The review of research approaches highlighted the importance of complexity, diversity, behaviour and a holistic framework. A detailed approach demands a large number of aspects that can affect the co-evolution. In order to control the simulation, only the essential aspects can be retained. Other elements that interfere with the co-evolution have to be discarded. Table 1-1 gives an overview of the elements that have been retained and discarded.

Table 1-1 : Selected elements for the analysis of the co-evolution between two sectors

	Included elements	Excluded elements
Manure treatment sector	- Endogenous emergence of innovations on the market - Diversity in technologies - Diversity in R&D strategies	- Diversity in behaviour - Network effects in innovation
Connected by internal markets	- Price differentiation - Influence of external actors on the same markets	- Negotiations between market parties - Cooperation between agents - Long-term partnerships
Dairy, cattle and pig sector	- Behaviour details & diversity - Path-dependency - Diversity in farm structure and efficiencies - Land constraints	- Ecological impact and reactions - Geographical details - Business innovation

For the manure treatment sector, the essential elements are the dynamics of technological innovation and the technological diversity. The innovation is endogenously created and industrialised, so the arrival of new innovations on the market is influenced by the historical actions of the manure treatment companies and market dynamics. The simulation should replicate these aspects. Also the diversity of technologies is important, because new innovations have to compete with traditional solutions that are currently established. But conflicts between different emerging technologies may appear as well.

For the agricultural sector, the essential elements are diversity, path-dependent evolution, and detailed behaviour of farmers. The diversity is essential, because the agricultural sector is highly heterogeneous in terms of farm structure, agricultural products, farmer behaviours and capabilities. The path-dependency is also guiding the evolution for each individual farmer. Finally, the adaptation of the sector will flow from the adaptation of each individual farmer. Therefore a detailed view on the adaptation mechanism, the barriers to change, and the diverse objectives of farmers is critical to simulate the transition.

The framework that contains these two sectors is required to provide elements that simulate the economic complexity as well as the larger societal trends that both sectors are subjected to. The complexity is preserved with the inclusion of endogenous markets between that are accessible for the agents of both sectors. Especially the presence of endogenous markets makes the simulation of complex feedback and communication between the different agents possible. The larger societal trends are included by allowing a larger range of actors to interfere on these internal markets as well. Also, external price trends are simulated, consistent with long-term scenarios.

The focus of the simulation requires that other features, present in the evolution of the bioeconomy, are not included in the current research approach. These are the complex interaction with ecosystem services, the inclusion of geographical detail, and the internal innovation in the agricultural sector itself.

Ecological aspects that enter in the biobased evolution can for instance be the effect of land use change on soil fertility, the adoption of new crops and their effect on local biodiversity, or new agricultural practices that affect water availability, pollination or biomass provision. All these elements are interactions between human activities and natural organisms in the soil or in the environment. The inclusion of these complex interactions would require a third level of simulation mimicking the life cycles of several natural organisms. This type of ecological model is a large challenge, and is not feasible as an addition to the current economic model. Given the fact that the detailed interaction with the local environment is not a priority in this case, the reactions of ecological systems to land use change are not included.

The inclusion of geographical detail is related to the choice of the main level of the analysis. This dissertation looks at structural change on a regional level in Flanders. There exist local interactions in the emergence of new innovations that may lead to local differences in the emergence of innovations. Empirical investigations of local effects have led to the description of innovative regions, where local networks and clusters are important in the development and industrialisation of new technologies. Within the Flemish region, local effects may interfere with the innovation dynamics, such as the growth of local clusters around strong economic actors, or spill over effects from R&D institutions that are active in other sectors. These effects show the impact of networks and actor complementarity in innovation dynamics. Inclusion of these effects would require again a level of detail in the investigation of the innovation dynamics that is too advanced. The inclusion of geographical details would also oblige the model agents to develop algorithms for spatial optimisation. For instance, manure treatment companies would have to develop heuristics to find the optimal place for new manure treatment plants. The inclusion GIS-data leads to a much more complicated model than required for this investigation. However, precise GIS or grid-based location data would be beneficial for the simulation of the land market dynamics. The availability of land in close proximity of the agents is important in the price setting. Without geographical detail, it is an important challenge for this dissertation to design the internal land market in such a way to mimic effects from local restrictions correctly.

The last choice relates to the innovation in the agricultural sector itself. This analysis investigates the influence of external innovations on the sector. There are many internal innovations being implemented as well. As will be explained in the description of the farm agents, agricultural innovation is included as far as increased mechanisation and farm extension is concerned. Other innovations, such as business model adaptations or partnerships are not regarded. This restriction is important in the interpretation of the results.

1.4.2 Innovative aspects

The field of agent-based modelling has seen a sharp increase in interest during the last few decades. As a result, numerous advances have been reported that clarify how ABM can simulate complex phenomena. There are a few elements that the current dissertation can contribute to the existing literature.

First, simulations have been applied extensively in the domain of land use, and land use change. These projects are able to connect agent behaviours with land use patterns, and the consequent ecosystem reactions. The focus of these projects is principally on the interactions with the environment. The internal economic dynamics of exchange between farmers is hardly ever taken into account. This dissertation looks primarily at the change in economic structure, and the economic dynamics, while being constrained by land and biomass availability. So the focus lies principally on the economic dynamics, and does not include the ecosystem reactions. This type of focus is especially selected in agent-based simulations for agricultural economics, a much smaller domain. And within this discipline, no projects regard the co-evolution between two connected sectors. As a consequence no project investigates the emergence of innovations in a connected sector on the structural change in agriculture.

Secondly, the analysis takes a range of aspects into account. This approach follows the results from transition thinking. Transition thinking states that it is not possible to dissociate the complex dynamics into smaller parts for a partitioned analysis. The combination of all essential elements should be preserved to grasp the dynamics of the transition. Other projects have simulated co-evolutions between sectors, or between demand and supply, but none with the inclusion of heterogeneity, diversity in behaviour, land use constraints and grounded on empirical data.

1.5 Overall model architecture

This leads to the different steps that are required to build an appropriate simulation approach. This approach presents several innovative facets. The approach in itself is novel, being a combination of elements in different scientific domains, being market analysis, behaviour models, and sustainability science, complexity, and innovation studies. Advances are made in specific fields as well. A new method for environmental sustainability assessment is proposed, tailored to biobased processes. And the empirical calibration of the simulation model leads to better insight in the actual behaviour of economic agents, in market power in the supply chain, and in land market dynamics.

The model includes new manure treatment technologies and the livestock production sector. This already gives two distinct classes of model agents to be implemented: the animal farmers and the manure treatment companies. Figure 1-1 presents a schematic overview of the model. The animal farmers contain all dairy, cattle and pig farmers, and are modelled as a heterogeneous group of autonomous farm agents. The farm agents are the central entities in the model, and are connected with markets for production inputs and outputs. Several in- and outputs are handled by exogenous markets. These relate to products that are traded on a larger scale than the national scale of the modelled economic subsector. The exogenous markets are capital, labour, fertilisers, feedstock, investments and output markets for different products. Their prices are governed externally through trends laid out in scenarios.

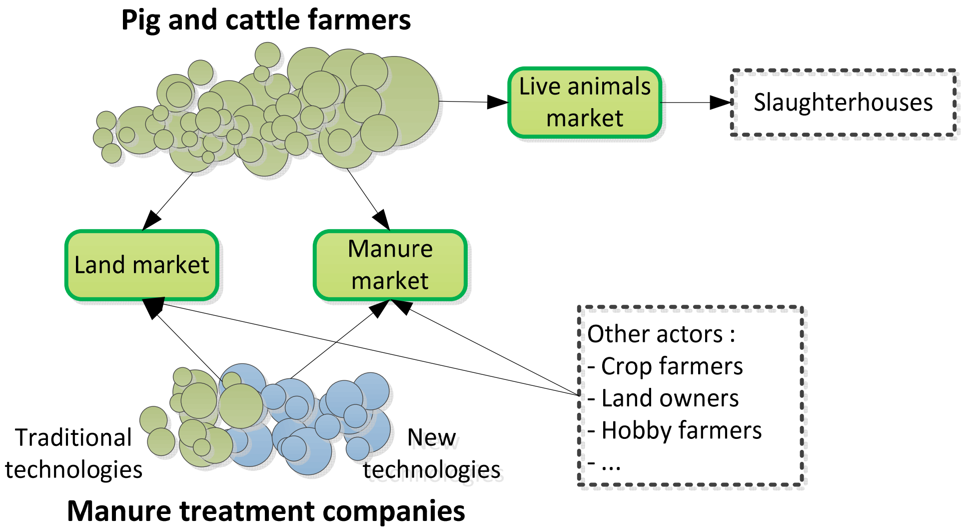


Figure 1-1 : Model structure

The second group of agents represents the manure treatment companies, including the traditional existing companies, and the newly emerging companies based on innovative technologies. Existing manure technologies are modelled, and gradually, new innovative, sustainable and biobased initiatives can appear on the market.

All these agents are in connection with the manure market. These agents are in connection with the land market as well. Some manure treatment technologies require agricultural land, and compete thus for this resource on the land market, together with the animal farmers.
The systemic effects in this model are preserved with the inclusion of endogenous markets for the significant products in this evolution. The endogenous markets react to the quantities and prices requested by the model agents. This is the case for land, for manure, and for live animals. The two markets for land and for manure are implemented as double auction markets (MacKie-Mason et al., 2006). The market for live animals considers the exchange with slaughterhouses. The slaughterhouses are not included as independent entities, so the price determination is based on an econometric model of market power in the meat products supply chain.

The modelled agents are not the only actors on these markets. Other actors interfere as well on the land and the manure market, such as crop farmers, land owners or hobby farmers. These are the entities that are indicated in Figure 1-1 within the dotted lines. These actors are not explicitly modelled in detail. But their actions are included, focusing on the effect of their actions on the market price determinations, and thus indirectly on the evolution of the animal farmers and manure treatment sector.

1.6 Research steps and text structure

Many steps have to be taken for the model to be constructed. These steps are grouped in the different chapters. The second chapter contains all decisions related to the farm agents. The third chapter gathers the information on the manure treatment companies. The fourth chapter builds future scenarios, presents results of the combined model and provides an interpretation. The fifth chapter concludes and gathers the different lessons learned.

The model is built up from the starting blocks – the farm agents. The construction of the farm agent starts with the internal dynamics and the market dynamics. An evolutionary farm agent requires three connected modules: production, sales and evolution. In the first module, the farm agent produces based on his personal characteristics and inputs. The current production structure of the Flemish farms is reviewed to make a production module that can mimic this situation with a micro-economic equivalent set of production functions. The second module proceeds to the purchase of inputs and sales of the products in markets. The different markets require rules and structures to make price setting possible. The rules determine how average prices are fixed following the interaction of many different actors. The final module allows the farm agent to adapt his structure to start a new year. This module regulates the evolutionary steps that the farm agent can take. This evolution module is in practice a representation of the adaptive behaviour of the farm agent. The calibrations confront each part with empirical data, giving insight in the model details, its variables and results. This clarifies how the results of the modelled agents can be interpreted, knowing the details and boundaries of this approach. The chapter concludes by comparing the present set-up with the approach of similar models reported in literature.

The third chapter details the manure treatment options. The model agents represent all manure treatment companies in the model. These agents present similar features as the farm agents, and combine a production, sales and evolution module. A supplementary feature is the endogenous appearance of new innovations. The chapter concludes with a disconnected simulation of the manure treatment sector independently of the agricultural sector.

The fourth chapter investigates future scenarios and policy options. It describes the guiding tendencies and policy options that compose the different scenarios. It also reports and discusses the results of the policy simulations for the combined model.

The fifth and final chapter concludes. The lessons from this research are collected, and avenues for further research are outlined.

[Friedman's profits-are-everything philosophy is] a dreary and demeaning view of the role of business and business leaders in our society… Making a profit is no more the purpose of a corporation than getting enough to eat is the purpose of life. Getting enough to eat is a requirement of life; life's purpose, one would hope, is somewhat broader and more challenging. Likewise with business and profit.

Kenneth Mason (1979)

Chapter 2 Farm agents and market interactions

The farm is a central agent of the Agent-based model (ABM). The model is built bottom-up, with the intention of simulating real dynamics based on empirical data. So the farm agent has to be constructed with realistic features. This chapter gathers the concepts and structures that are set up to simulate the farm agent. The first section clarifies the choices made, based on the sector characteristics. The following sections give the details on the variables, characteristics and evolution of the farm agents. The chapter concludes by comparing the present architecture with other established agent-based models that have been used for investigation of the economic structure in agriculture.

2.1 Modelling choices based on sector characteristics

The model has to reflect particular dynamics that are specific to the local situation in Flanders. Also, the focus of the research on interaction between agricultural and related industrial sectors implies a simplification of the farm agent model itself. The full modelling of all farming details would make the entire exercise overly complicated and might lead to results that are too difficult to interpret. This section reviews some important empirical dynamics that should be retained in the farm agent model.

2.1.1 Sector characteristics

Four aspects of this evolution are highlighted in this section, in order to determine some important characteristics that the farm agents need to incorporate. These are the growing importance of investments, diversity in crop and animal types per farm, the farmer's age and farm bankruptcies.

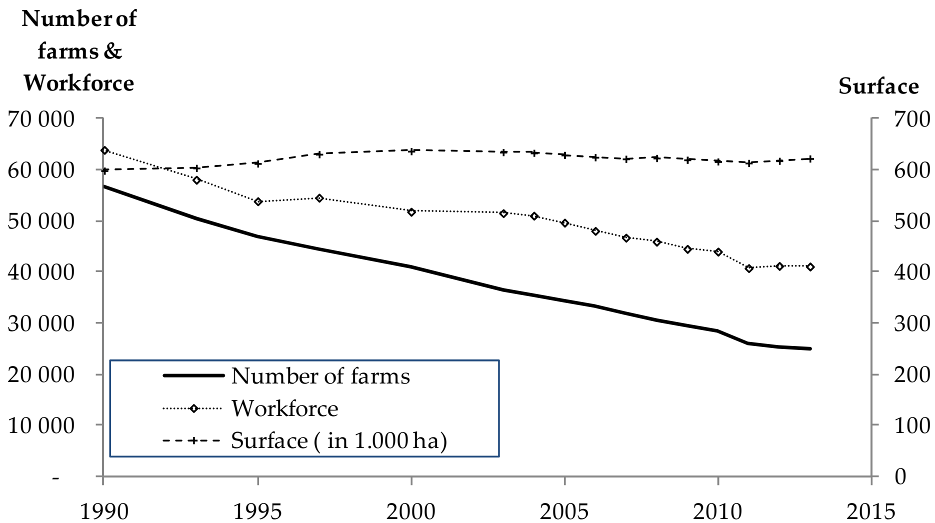


Figure 2-1 Change in total cultivated surface and number of active farms during the last thirty years (ADSEI, 2014)

Figure 2-1 illustrates the gradual decline in number of active farms during the last decades. From over 56.000 active farms in 1990, only 25.000 remain in 2012. Despite this reduction, the total surface of cultivated land remained relatively steady. As a consequence, the average surface per Flemish farm has grown considerable during this period, from 11 ha in 1990 to 25 ha per farm in 2013. This growth did not imply a similar growth in workforce. The average full-time equivalent (FTE) employment at the farm rose from 1.13 in 1990 to 1.97 in 2013. This indicates a strong investment in machinery and automation for farms to keep up with this growth in size.

The division of the agricultural land in different crops shows a very stable distribution, as illustrated in Figure 2-2.

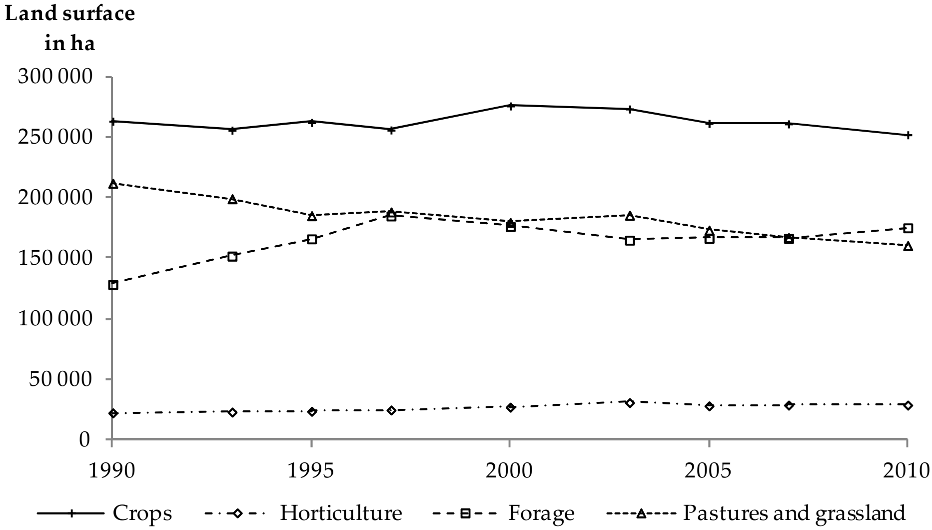


Figure 2-2 Total acreage dedicated to different types of crops (EUROSTAT 2014)

A majority of the Flemish farms raise at least a small number of cattle or pigs. During the last decades, the proportion of farms without animals has been growing. There remains a large dispersion of animal stocks amongst the Flemish farms, as illustrated in Figure 2-3. Fewer farms keep small animal stocks, and the proportion of large specialised farms with large animals stocks, over 100 livestock units (LSU), is growing.

This trend for more specialisation is not all-defining. There remain a large part of farms with an animal stock between 1 and 50 LSU. For individual farms, diversified activities remain very common. Many farms are mixed farms. Even specialised dairy farms maintain the cultivation of crops that are not intended for feedstock, such as cereals, potatoes or vegetables. There is also a large proportion of the specialised dairy farms that raise suckler cows, cattle for meat, chickens, pigs or piglets (Van der Straeten et al., 2012). Mixed farms are an important part of Flemish agriculture. Multiple economic studies focus on specialised farms (Berentsen, 2003; Meul et al., 2007; Nevens et al., 2006; Van Passel et al., 2007; Van Passel et al., 2009). But Flemish agriculture contains different forms of mixed farming. This combination of different animal products and crops can be historical, but can also be strategic in response to economic adversity or low productivity (Meert et al., 2005). Mixed farms keep different production options open, allowing for more evolutionary pathways than specialised farms. So co-production and mixed farming should in principle remain possible for the farm agent. Data on farm structures are available for the entire Belgian agricultural sector.

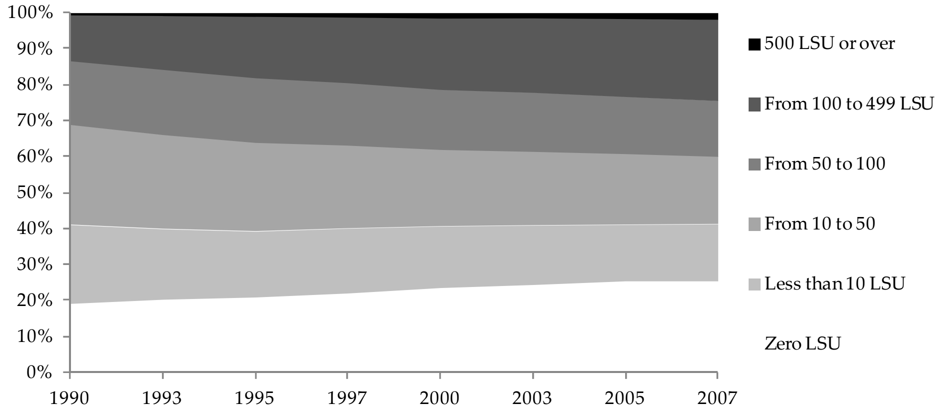


Figure 2-3 : Distribution of animal stocks amongst Belgian Farms (EUROSTAT data)

Table 2-1 : Distribution of Farmer's age for different farm sizes (Landbouwtelling, 2007)

	Farm size in ha		
Farm owner age	Less than 20ha	Between 20 and 50	Over 50
Less than 35	1 008	1 024	550
Between 35 and 44	3 888	3 591	2 160
Between 45 and 54	5 856	4 349	2 566
Between 55 and 64	5 520	3 259	1 446
Over 65	7 728	1 077	280

Another aspect of diversity is related to the age of farmers and the sizes of their farms, reported in Table 2-1. The average age of the Flemish farmer is quite high, and increased from 49 years in 2005 to 51 years old in 2010 (Platteau et al., 2012). There are also distinct differences in the age pyramids. The smaller farms are led by a much older group of farmers than the large farms. 75% of the farms over 50 ha are held by farmers younger than 55. Whereas 55% of the farmers that have an active farm smaller than 20ha, are over 55 years old. It is remarkable that numerous farmers remain active past their retirement age. There is even a small group that continues on relatively large farms.

This relation between age and farm structure is included in the simulation. Because the model has to preserve a coherent evolution, it is not possible to reduce the farm size automatically with the growing age of the farmer. However, the age influence is included indirectly, by relating the age to an increasing risk aversion, and a total stop in investments for retired farmers.

The final aspect relates to the profitability of the farms. As briefly explained in 1.1.1, the profitability of cattle and pig producers has been very low and even negative for the last couple of years. The same situation can be found with dairy farmers. Van der Straeten et al. (2012) report that dairy farmers present on average a negative annual result for each year between 2006 and 2010, when including the remuneration of the farm family. On the other hand, this low profitability does not translate in a large growth of bankruptcies. As illustrated in Table 2-2, the number of farms closing down annually is rather large, following the steady decrease in the number of farms. It is estimated that the number of new farmers starting a new business is about 240 annually. This leads to the estimation of the total number of farms closing down. Only a small fraction of this number closes due to bankruptcy. In general, the number of bankruptcies in agriculture is very low, and remains at 0.2% during the last years.

Table 2-2 : Comparison of the total number of farms with the number of farms closing and bankruptcies (ADSEI, 2014)

Year	2000	2008	2009	2010	2011	2012
Total number of farms	40 990	30 666	29 394	28 331	25 982	25 217
Estimated number of new farms	240	240	240	240	240	240
Total number of closed farms	1231	1032	823	2109	525	93
of which closed farms due to bankruptcy	58	67	76	66	54	55
Percentage of closed farms that went bankrupt	4.7%	6.5%	9.2%	3.1%	10.3%	59.1%
Percentage of all farms that went bankrupt	0.14%	0.22%	0.26%	0.23%	0.21%	0.22%

These characteristics indicate important aspects of the evolutionary dynamics in Flemish agriculture. The consequences for the model of the farm agent are as follows:

- The mechanisation of agriculture has to be reflected. The model of the farm agent has to account for investments and the related improvements in production efficiency.
- Diversity in crops and animals at the level of a single farm are the rule rather than the exception. The full diversity of crops is large, and cannot be included, but a distinction has to be made between crops for animal feedstock and other crops.
- The diversity in animal types should also be possible. A single farm agent has to be able to combine different animal types.
- The age of the farmer has a large influence on the farm strategy. This implies that a farm agent is related to a farm owner with a defined age. The behaviour of the farm agent has to change according to the age of the owner.
- Finally, the low bankruptcy rate requires additional detail in the financial structure of the farm agent. A simplified economic approach with annual profits and losses does not cover all elements. The farm model needs to incorporate the variability of the remuneration of the farm owner, as well as the financial buffers that the farm disposes of.
- Bankruptcies can occur in practice for two main reasons: destruction of capital or zero cash flow. The financial structure requires keeping track of both these elements. This can be done most accurately if the farm agent model is based on the accounting structure of the farm. In that case, investments, owner remunerations, loans, losses and liquidity of assets can all be followed realistically.

2.1.2 Model granularity, limitations and time cycle

On a microeconomic level, a farm is a complex undertaking, whose production is influenced by land characteristics, by investments and investment history, by the options for co-production of different outputs, and by the capabilities of the farm manager. Not all these characteristics and influences can be integrated in sufficient detail. Only the most appropriate variables can be chosen. The decisions on the farm variables directly limit the potential scope of the investigation. Distinct characteristics of farms have to be preserved in the model, not only to simulate the annual production of the farm, but also its evolution over time, and most of all its characteristics that determine the farm's strategic options and decisions. Before the definition of the variables, broad outlines are determined that indicate which characteristics are to be preserved or discarded.

The main research orientation looks at the evolution of the agricultural sector in Flanders, and the influence of new manure-treatment methods on this evolution. More particularly, the focus is directed towards the investigation of structural change in agriculture. Structural change has been investigated as shifts between different types of producers (Baumol et al., 1985) or shifts in labour allocation per sector (Ngai et al., 2007). Generally, structural change can be regarded as shifts in productive assets at the level of an economic sector. The definition of the farm agent should thus include different types of productive assets, and allow seeing modifications in asset compositions over time. The most important factors that contribute to a better comprehension of farm agent's choices in this regard should be included. The chosen productive assets cover different types of animal stocks and land types for each individual farm agent. The farm agent can therefore specialise on one type of production, or he can choose to combine multiple stocks and create a mixed farm.

Simplifications were made at the definition of subsidies in the farm model. Subsidies play an important role in the microeconomic result of a farm, and in the farm decisions. However, precise determination of subsidy levels requires a highly detailed definition of the farm agent, details that follow the growth of different types of livestock, or extensive linear programming (LP) (Buysse et al., 2007; de Frahan et al., 2007). This has been built for the analysis of specific subsidy regimes, for instance with regards to manure production and spreading (Van der Straeten et al., 2010).

For investigation of trends over longer time periods, till 2030 or 2050, the subsidy structure is much more uncertain. On-going deregulation of agricultural markets and productions contribute to policy changes that can be introduced during the coming years. Both the level of detail at farm production and policy evolution, make that specific subsidy regimes should not be replicated precisely in this case. The impact of subsidies in this model is replaced by generalised trends. For instance, subsidies are integrated in the farm economics by estimation, and general legal restrictions (for instance on land rent increase) are respected. Future scenarios include also restrictions of subsidy schemes and shifts in priorities. But the detailed subsidy mechanisms are not replicated in this model.

The model operates with annual cycles. This makes sense in an evolutionary model of farms, because of the annual growth cycle of crops (Kellermann et al., 2008; Robinson et al., 2007; Schreinemachers et al., 2011). Also the choice to found the model on accounting principles aligns the model with annual time steps. Shorter cycle durations or indeterminate durations have been applied in other studies (Smajgl et al., 2010), but these applications do not relate to the growth of crops. The evolution of a farm agent during the course of one year is illustrated in Figure 2-4.

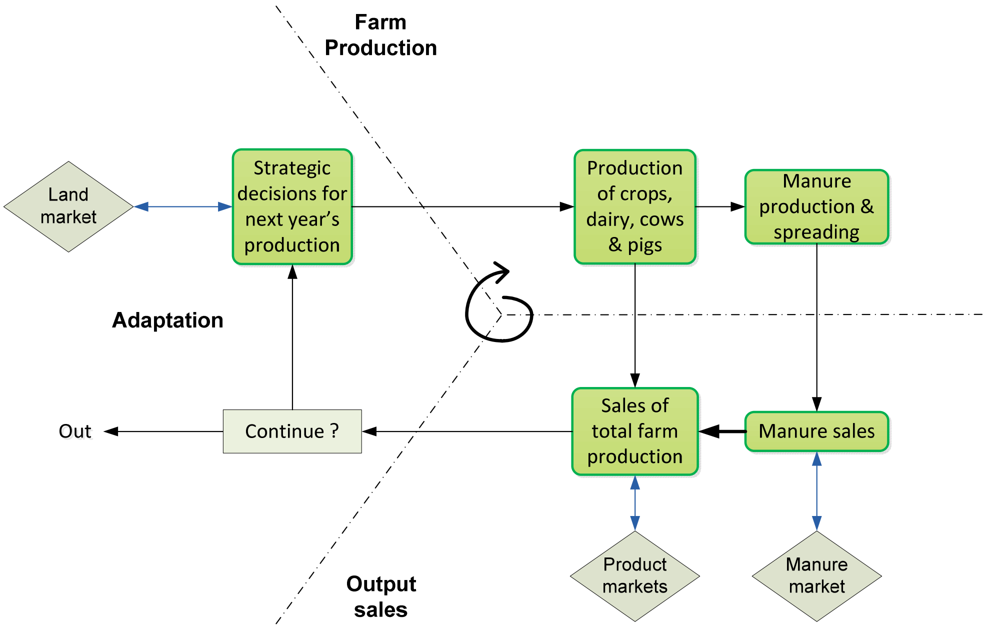


Figure 2-4 : Annual cycles for the farm agents in the model

The annual process is divided in three steps: (i) After the initialisation of the model for the first year, the agent starts producing. Whenever possible, the manure is first spread on the fields of the farm itself. The remaining manure has to be sold in the manure market. (ii) The second step is the sales of output products and manure. After the sales, the total annual turnover can be calculated and farm agents decide whether they want to continue farming or not. Reasons to cease activity are bankruptcy, death of the farm agent or a decision to leave livestock production and to focus on crops only. (iii) If the farm agent continues, he adapts his farm structure to the new market situations, and optimises assets for next year. This step contains the behavioural decisions and the impact of learning. After the rearrangements, the farm agent starts the next year.

2.1.3 Effects of the current legislation

As stated in the previous section, the restrictions of legislation and subsidies are simplified in this approach. The current legislation that links animal husbandry with nitrate restrictions is sophisticated in Flanders. This legislation has an impact on the current structure of Flemish farms. It is therefore important to review the current legislation. The results will have to be controlled taking the simplification in mind.

The current manure disposal legislation is derived from the European Nitrates Directive (91/676/EEC), introduced in 1991. This directive imposed a maximum nitrate content of surface and ground water of 50 mg/l. In regions, such as Flanders, with a high animal density, this limit was sometimes exceeded. The regional manure restrictions were introduced by the manure decree in 1991. This decree intended to incite transport of manure within Flanders from areas with a manure surplus to areas with a manure deficit. In some cases, farmers could no longer dispose of their manure on their own land. Two options remained available: the transport of manure to the land of another farmer, or the treatment of manure.

In a second phase the first Manure Action Plan was created in 1995. This action plan introduced disposal limitations for manure on individual parcels of land. These limitations have been gradually made stricter. At the same time, several actions were set up to limit the total manure production in the region, such as the stimulation of nitrate-low feedstock, stimulation of manure treatment for alternative disposal, and reduction of the total animal stock in the region.

The current policy combines thus two major restrictive elements; these are the fertiliser dispersal limitations, and the maximum nutrient emission rights. The fertiliser dispersal limits are strict upper limits on the amount of nitrate, phosphate and nitrate from animal origin that can be spread on a plot of agricultural land. Because the limits are intended to reduce nitrate and phosphate leaching into the groundwater, the limitations count for the total of animal manure and artificial fertiliser. The system is based on detailed distinctions according to the soil type of the land, and the crops that are grown. In specific cases, such as crop sequences with high-nitrate demand, derogations can be requested, increasing the limit for these specific land parcels (Van der Straeten et al., 2010).

The nutrient emission rights, on the other hand, are tradable emission rights that are connected to the animals that are the source of the manure. If a farmer has an animal stock, he is required to obtain the nutrient emission rights for the size of this stock. These rights are tradable, so a farmer who is willing to increase his animal stock, has to find a seller for the equivalent emission rights for his stock increase (Claeys et al., 2008).

Both elements influence price levels. Because the details of the legislation are not implemented in the current model, the interpretation of the results has to account for indirect price effects of these legislative restrictions. The fertiliser dispersal limits are land-bound, and land prices are expected to include the shadow price of the manure dispersion on the land. At the same time, when a farmer intends to increase his animal stock, the investment costs are not only intended to cover the costs for extra animals, buildings and installations, but also for the appropriate nutrient emission certificates. In practice, the market for nutrient emission certificates is not very efficient. This leads to high prices for certificates. It also leads to the situation where farmers take over an entire neighbouring farm in order to grow. This total takeover gives the farmer a possibility to increase his available acreage, and his animal stock completed with the necessary emission certificates. The model does not incorporate the possibility for farm agents to take over other farm agents. It has been assumed that the nutrient emission market is smoother, so incremental animal stock increases are more likely. This will result in smoother development paths for individual farm agents compared to the real situation.

2.2 Individual costs and production of the farm agent

As discussed in the first section, the farm agent structure enables mixed farming. The chosen farm model allows for a simultaneous production of crops and animals. However, the categories of production do not detail specific crops or products. The different types of crops are divided in four categories:

- Forage : cultivation of plants destined for animal nutrition
- Pastures and grasslands
- Horticulture
- Crops: all other types of crops.

The animal products are grouped in three broad categories:

- Pig products: The output of this category consists mainly of live pigs.
- Dairy products: This output does contain raw milk, but also live old dairy cows for sale.
- Cattle products: All other live cattle are grouped in this category.

Pastures constitute a particular category, as in this model the farmer cannot directly draw profit from the grassland. The available grassland is integrated in the production for dairy products and cattle. The production of the other categories can be used internally or can be sold, leading to six potential types of revenue for each farm. Specialised farms will focus on one category only. Mixed farms can combine different revenue streams.

These seven categories are governed by as many variables. The land types lead to the acreage of each category, and the animal types lead to the average size of the animal stock in the farm, as described in Table 2-3. These seven variables define the farm structure, and are also the main starting points for all economic calculations of the farm agent.

Table 2-3 : Definition of the major structure-defining variables of the farm agent

Variable	Symbol	unit	Revenue possible?
Acreage for crop cultivation	A_{Cr}	[ha]	X
Acreage for horticulture	A_{Ho}	[ha]	X
Acreage for forage cultivation	A_{Fo}	[ha]	X
Acreage for pastures	A_{C}	[ha]	
Animal stock of Dairy cows	An_{D}	[LSU]	X
Animal stock of other Cattle	An_{C}	[LSU]	X
Animal stock of Pigs	An_{P}	[LSU]	X

2.2.1 Accounting structure

Section 2.2.2 defines the different costs and income sources for the farm agent. Every farm agent has an individual accounting structure that gathers costs and income, calculates the annual revenue, updates the annual balance and controls the cash flow.

The calculations of the revenue, the cash flow and the balance reflect the practical situation for farmers in Flanders. The calculation structure is a reproduction of the accounting structure used by the Farmers' Union. Traditionally, the farm is not an independent company. The revenue is declared as personal income for the farmer. It also explains that liquid assets are kept out of the farm balance, and remain in a personal account of the farmer. The calculated balance and revenue follow the official accounting rules, and represent the figures that are declared to the tax administrations. The cash flow however, follows the real liquid assets that result from farm activity. These are not included in the balance, but are available as capital if new investments are required.

Table 2-4 : farm agent Results

Annual revenue		Cash flow	
A) Income		**A) Income**	
	Sales of products		Sales of products
	Subsidies		Subsidies
B) Costs		**B) Costs**	
Variable costs	Purchased Feedstock	Variable costs	Purchased Feedstock
	Annual costs		Annual costs
	External labour		External labour
	Manure disposal		Manure disposal
	Fertilisers		Fertilisers
Fixed costs	Land rent	Fixed costs	Land rent
	Fictional land rent[1]		
	Depreciation of buildings and materials		
	Interest		
	Fictional interest[1]		
C) Annual revenue (C=A-B)		**C) Cash flow(C=A-B)**	
		D) Loan burden	
			Capital reimbursements
			Interest on loans
E) Tax (Tax = b% x C) [2]		E) Tax	
F) Net annual revenue (F = C-E)		**F) Farm Family income (FFI = C-D-E)**	

[1]: The use of owned land is internalised by accounting for an annually updated fictional rent. Likewise, the use of own capital is internalised by accounting for fictional interest to be paid on own capital.

[2]: Taxes are calculated as a percentage of the declared revenues. The percentage increases according to revenue scales.

Scale	Percentage	Scale	Percentage
0 – 25.000 EUR	24.25 %	90.000 – 322.500 EUR	34.5%
25.000 – 90.000 EUR	31.0 %	> 322.500 EUR	33.0%

The net cash flow is used to remunerate household labour, invest in future capital assets, and to save liquid assets for future years. The FFI is thus divided in three parts:

Farm Family income (FFI)
= Household remuneration + Investments + Liquid Assets (LA)

The household remuneration is the annual payment for the farm household. The payment is calculated as 25.000 EUR per household member. This is similar to the average household payments that farmers have received during the last years (FOD Economie, 2009; 2010). Whenever the FFI is not sufficient to allow this household payment, it is reduced to the maximum amount available. Negative amounts are not permitted. Whenever the FFI is negative, the household remuneration is zero and the available liquid assets are used to compensate the losses. The farm has to stop activity and is declared bankrupt when the available cash (= the liquid asset stock) is below zero for two consecutive years.

Once the financial results of the year are known, and the money to remunerate the household is withdrawn, the farm agent can start the decision process to prepare the next year. The actual decision process is explained in section 2.4. The farm agent can change his land use, his animal stocks and his material investments. Each of these changes is reflected in the balance.

Table 2-5 : Farm agent Balance sheet

Year t-1	Change	Year t
Assets		
Owned land	+ Land purchases - Land sales	Owned land[1]
Buildings, materials and rights	- Depreciation + additional investments	Buildings, materials and rights
Animal stock	- stock reductions + new investments	Animal stock[2]
Liabilities		
Own capital		Own capital[3]
Loans	+ new loans - capital reimbursements	Loans

[1]: The value of the owned land is evaluated every year according to market prices.
[2]: Animal stocks can only change by investment decisions to in- or decrease operational capacity. The value is evaluated each year according to market prices.
[3]: The value of the entire holding, and therefore also the owned share of the holding is recalculated every year.

2.2.2 Annual costs and benefits

The acreage and animal stocks determine also to a large extent the various costs and benefits for the farm agent during the year. There is a specific labour demand for each part of the farm's activities. Labour costs for pastures are assumed to be integrated in the labour required for animal production. The total labour need is approached allowing for economies of scale:

$$L_I = \sum_{Animals} \alpha_I An_I^{\beta_I} + \sum_{\substack{Crops \\ Excl.grassland}} \alpha_I A_I^{\beta_I} \quad (1)$$

Annual costs are also included, and reflect annual recurring expenses, as indicated in Table 2-7. All baseline estimations are related to regressions of FADN farms, details on these regressions are given in Annex A (page 205).

The grassland is distributed between the dairy cows and the other cattle. There is an absolute maximum in animal density of 4 LSU/ha. The feed requirements are split between a requirement for roughage, and for fodder. The majority of the roughage is made available by the pastures and grasslands. An average roughage need is set on 1.85 kg DW/day per 100 kg live weight (Remmelink et al., 2011). The average weight of dairy cows is higher, given their longer lifetime. This leads to the average roughage requirements indicated below. The fodder requirements are based on the regressions of FADN farms.

Table 2-6 : Fodder requirements for different types of animals per year

		Dairy cows	Other cattle	Pigs
Fodder requirement	t DW/LSU.year	1.505	1.383	2.336
Roughage requirement	t DW/LSU.year	4.25	3.7	

Subsidies are an important part of the total balance of the Farm agent. The complexity of the subsidy schemes is not transferred in the model. The aim is to investigate different scenarios including gradual and structural adaptations of the current subsidy schemes. The initial subsidy amounts have thus been implemented in relation to the farm's fixed assets, and the quantity of productive inputs. Future scenarios will adapt these relations. Investment subsidies are imbedded in the total investment costs. The estimation regression is reported in Annex A (page 205). The same regression also structures the relations between the acreage and animal stocks on the one hand, and the labour requirements, annual costs and production characteristics in Table 2-7.

The labour requirements are determined while accounting for scale efficiencies. The total labour requirement has to be met at the firm level. The farm agents are simulated with different farm households, ranging between 1 and 3 members. Whenever the total labour requirements exceed the number household members, any additional labour has to be supplied by off-farm employment. These can take the form of employees, labourers or seasonal workers, and the model assumes that these services are available. In each case the additional expenses for off-farm labour are calculated and added to the annual costs.

For the production based on the different acreage and animal stocks, a similar approach has been adopted. The individual characteristics of the Farm agent include different types of land and animals. The production model establishes consequently a general production approximation based on the animal stock and the different acreages. This function determines the average production. The deviation for each individual farm is defined by the production efficiency f_{It}. Over time, this efficiency factor describes also the individual evolution in production. During the evolution of the model, farms are allowed to invest in new equipment and installations that increase production efficiency.

The production efficiency in the model makes the link between the general production that is averaged over all farm agents, and the individual development trajectory of each farm agent. The efficiency is altered by investment in new equipment, by aging of the farmer, or by farmer decisions. The efficiency captures the individual historical and learning effects. The actual production can therefore differ significantly among farm agents, even if it is founded on the same baseline.

The resulting expression to predict the production quantities for each farm agent for the three land types is:

$$Y_{It} = f_{It}\alpha_I A_I^{\beta_I} \tag{2}$$

With:

I = Cr, Ho, Fo (Crops, Horticulture or Forage)
Y_{It} = Land product output
f_{It} = Time-dependent production efficiency for production I
α_I = Average production factor (Table 2-7)
β_I = Average production factor (Table 2-7)
A_I = The acreage in ha

Similarly, the production for the three animal types is :

$$Y_{It} = f_{It}\alpha_I An_I^{\beta_I} \tag{3}$$

With :

I = D, C or P (Dairy cows, other Cattle or Pigs)
Y_{It} = Animal product output
f_{It} = Time-dependent production efficiency for production I
α_I = Average production factor (Table 2-7)
β_I = Average production factor (Table 2-7)

An_I = The number of animals of type I in LSU

Table 2-7 : Average costs and production for different acreages and animal stocks

	Annual costs	**Labour demand**		**Production**	
	[€/ha]	α_I			
Crops	634	0.0455	0.675	1211 [€/ha]	1.132
Horticulture	2716	0.591	0.108	3636 [€/ha]	1.237
Forage	405	0.151	0.241	0.23	1.317
	Annual costs	**Labour demand**		**Production**	
	[€/LSU]	α_I	β_I	α_I	β_I
Dairy cows	129.5	0.00813	0.947	5.70	1.093
Other Cattle	89.5	0.399	0.201	0.20	1.199
Pigs	64.6	0.0177	0.669	1.015	1.091

2.2.3 Manure production and use

The farm agent also produces manure. The quantity of manure that is annually produced is calculated based on the total production of animal products of the Farm agent. The model proceeds in four steps to determine the manure production, the quantity spread on the land of the farm itself, and the remaining quantity to be treated. The four steps are based on the farm characteristics and structure. Based on the animal stock, the farm agent calculates the total amount of produced manure, its nutrient content, as well as the emission losses due to manure transport and storage. The amount is further reduced by spreading manure on land at the farm itself. The remainder will be traded on the manure market. This calculation is very deterministic and only based on the farm's characteristics and structure. There are no evolutionary improvements or adaptations in this specific part of the Farm agent.

The total amount of manure production is calculated based on the annual norms and references published by the Flemish Land Administration VLM (VLM, 2012b). The official references are very detailed. The following decision procedure establishes an approximation of the manure production.

The manure production of dairy cows is approximation in relation to their average milk yield:

- N-production : 1.05 ${M_y}^{0.52}\ DC$
- P_2O_5-production : 0.23 ${M_y}^{0.57}\ DC$

With M_y being the average milk yield per dairy cow, DC is the total amount of dairy cows at the farm. Manure production of dairy cows and other cattle on grasslands is applied directly, and therefore separated from the rest. This part cannot be sold on the manure market. The manure production for other cattle and pigs is presented in Table 2-8.

Table 2-8: Values for manure production used in the model

	N-production kg N / LSU	**P_2O_5-production** kg P_2O_5 / LSU
Other Cattle	75.0	27.5
Pigs	66.4	40.0
The deposition of manure during grazing is calculated as :		
Per LSU	24.3	9.3

The nitrate losses due to emissions during manure storage and transport depend on the origin of the manure and the type. The manure type, in turn, is determined by the stable type and agricultural practices. Solid manure originates from straw-lined stables. Solid manure is more valuable than liquid manure and leads to higher emission losses. However, the type of stables is unknown for the sample farms, so this will depend on farm-specific factors that need to be calibrated to macroeconomic data. The used values for manure density, manure nutrient content related to the stable types are illustrated in Table 2-9. The actual effective nitrate content is a measure used to estimate the nitrate quantity from the manure that is taken up by the plants when the manure is spread on a field.

The model assumes that a maximum amount of liquid manure will be dispersed on the lands of the farm itself. The actual legislation is very detailed and dependent on numerous local factors and restrictions. The model can only take a simplified version into account. There are different dispersion regimes for standard agricultural plots, for phosphate saturated and low phosphate binding areas. The last two categories account for 3.019 ha, or 0.44% of the total agricultural area in Flanders. The model bases thus the dispersion only on the references for standard phosphate unsaturated areas, while averaging between the values for sandy and non-sandy soil.

Table 2-9 : Estimated manure emission losses

		Traditional fodder	
Cattle manure		Solid manure	Liquid manure
Emission losses	% of N-content	20%	10%
Effective nitrate content		30%	60%
N-content	Kg/ton	7.1	4.8
P_2O_5-content	Kg/ton	2.9	1.4
Density	Ton/m³	0.8	1
		Traditional fodder	
Pig manure		Solid manure	Liquid manure
Emission losses	kg N/LSU.year	21.9	11.5
Effective nitrate content		30%	60%
N-content	Kg/ton	7.5	5.8
P_2O_5-content	Kg/ton	9.0	2.9
Density	Ton/m³	0.8	1

Table 2-10 : Fertiliser dispersion limits

	Effective N	Total P_2O_5	Maximum N from animal origin that can be dispersed
	kg/ha.year	kg/ha.year	kg/ha.year
Crops	175	75	170
Horticulture	95	75	125
Forage	305	90	170
Grazing areas	240	90	170

The average percentage of dry manure at the farm is 15% of the total manure production. The actual value is distributed normally, with a standard deviation of 5% over all farms. Farmers can achieve some reduction by adopting fodder with low nitrate content. At the start of the model, an average reduction of 5% is achieved over all farms. This reduction is normally distributed with a standard deviation of 2%.

These values enable the calculation of the remaining manure quantity to be disposed on other lands, or to be treated. These remaining quantities will be proposed to the manure market. In this market, liquid and solid manure are two distinct products, with different applications, values and prices. On the other hand, the quantities of effective N and P that are not taken up by manure on the land parcels are to be completed by artificial fertiliser. At the end of the manure spreading calculation, the farm agent also calculates the remaining quantity of artificial fertiliser that has to be added, and this cost is added in the simplified accounting framework of the farm agent.

2.2.4 General variables and diversity

Concluding this section on farm agents' costs and production, the origin of the most important variables is reviewed.

Some variables are important because they are key in the determination of the production, or because they provide unique individual characteristics that guarantee a sufficient diversity in the initial farm agent population. The total description of an individual farm agent relies on a large set of data and parameters. These parameters evolve over time, and indicate the changes in the finances, structure or production of the farm. The overall farm agent dataset contains 170 variables, and is added in the Annex B . However, only a key group form the basis for all other calculations. All other variables can be derived from these key determinants.

Table 2-11 : Origins of the principal variables for the farm agent

Farm general data & structure	Source
Farmer's age & household size	FADN
Initial surface of rented land	FADN
Initial Risk factor[1]	FADN
Dry manure percentage	Randomly assigned
Nitrate reduction due to low emission feedstock	Randomly assigned
Availability of successor	Randomly assigned
Average production determinants	
Acreages for each of the 4 types of land	FADN
Animal stock sizes for each of the 3 types of animals	FADN
Individual production efficiencies[1]	FADN
Financial determinants	
Overhead percentage[1]	FADN
Depreciation percentage[1]	FADN
Total assets	FADN
Total available cash	FADN
Total Loans	FADN

The key variables are replicated from data reported in the FADN database. These coherent sets each represent the real data on a single individual farm. At the initiation of the model, each farm agent is based on data from a single real farm set from the FADN dataset. The calibration procedure described in 2.3, determines which FADN farms have to be chosen and their respective weight in the initial farm agent population. For some determinants, specific data are not available. The initial figures for these determinants are assigned in a random distribution to ensure sufficient diversity among the farm agents in the model. This means that the individual farm agent model has been constructed relatively straightforward and based on a limited set of key determinants, as illustrated in Table 2-11. Further calibrations

[1] These data are not directly available from the FADN dataset, but are calculated based on these data. To avoid annual discrepancies, the data are calculated as an average over the year 2006-2008.

determine other variables of the model, such as market characteristics or behaviour distributions. But calibration does not interfere with the data of the individual farm agents.

At this point, the essential characteristics that have been identified are included in the farm agent's attributes:

- The farm agent can accommodate for growing farm size and economies of scale, as well as for off-farm labour. It accounts for historical investment path and its effect on individual production efficiency, thereby allowing the approximation of the real evolution to less numerous but larger farms.
- A division of the farm acreage in different cultivation categories has been maintained, and different animal types are allowed simultaneously. This allows the approximation of mixed farms and the gradual evolution of mixed farming towards more specialised farms.
- The age of the Farmer is connected to the Farm Model. This has an effect on the farm agent behaviour, as explained in the discussion on behaviour and objective functions, in section 2.4 of the present chapter.
- Finally, a full accounting approach is adopted. The approach includes a variable remuneration of the farm household and a continuous control of the cash availability at the farm. This gives more possibilities than a strict economic benefit-loss approach to approximate the real dynamics at the farm, and especially the low bankruptcy rate in the sector.

In general, this chapter constructed the production side of the farm agent. The construction is sufficiently simplified to keep the model transparent. The remaining options for the farm agent allow an approximation of the real empirical characteristics that are seen in Flemish agriculture. This chapter leads to the total production of the farm agent. How this farm agent will evolve over time, by selling on markets and by adapting to market conditions is explained in the following sections.

2.3 Calibration of the starting situation

In order to populate the model with the initial group of farm agents in the starting situation, the model selects reference farms from the Farm Accountancy Data Network (FADN) database. This type of detailed information is necessary to shape the reference situation of the farm agent on a realistic basis. We need to select particular farms from the database, and attribute weights, a positive natural number that indicates how often the particular farm is duplicated within initial population of the model. The total initial population then represents as closely as possible the Flemish livestock production sector in 2008. The farm selection can be based on expert knowledge. This leads to a manual selection of units from the database. However, when the number of agents of the model is increasing, or several conditions are required, this approach is no longer feasible. We follow the solution of Happe et al.(2004) and Sahrbacher et al.(2005) to automate the selection of farm data.

There are m farms, and $\boldsymbol{b} \in \mathbb{R}_{m\times 1}$ is the vector containing the weights per firm. There are n criteria defined, $\boldsymbol{y} \in \mathbb{R}_{n\times 1}$ is the vector containing the total quantities for each criteria. The matrix $\boldsymbol{V} \in \mathbb{R}_{n\times m}$ contains all elements v_{ij}, v_{ij} being the contribution of farm j to criteria i.

$$\boldsymbol{y} = \boldsymbol{V} \times \boldsymbol{b} + \boldsymbol{\varepsilon} \tag{4}$$

The column vector $\boldsymbol{\varepsilon} \in \mathbb{R}_{m\times 1}$ contains the errors of this approximation. For each criterion we implement an influence factor a_i, to have to possibility to attach more importance to certain criteria. A numerical minimisation of the errors of this approximation leads to the minimisation of the following quadratic problem:

$$min_b \left\{\frac{1}{2}\boldsymbol{b}^T H \boldsymbol{b} + G\boldsymbol{b}\right\} \tag{5}$$

Where:

$$H = \boldsymbol{V}^T \boldsymbol{D_a} \boldsymbol{V} \in \mathbb{R}_{m\times m} \tag{6}$$

$$G = -\boldsymbol{y}^T \boldsymbol{D_a} \boldsymbol{V} \in \mathbb{R}_{1\times m} \tag{7}$$

$$\boldsymbol{D_a} = Diag[a_i] \in \mathbb{R}_{n\times n} \tag{8}$$

For standardisation, the criterion influence parameter a_i takes the following the form:

$$a_i = {\acute{a}_i}/{y_i^2} \tag{9}$$

Here $\acute{a}_i$ is the standardised influence. If all $\acute{a}_i$ for all criteria are equal to 1, then all corresponding selection criteria are equally treated in the numerical minimisation above.

Selection criteria are determined to ensure that the population of agents in the model shows the same macroeconomic production and the same structural characteristics. The sample should represent the subsector by showing the same macro-economic outputs for:

- Cow production
- Pig production
- Milk production

These data are collected over a three years period, from 2006 to 2008 included. The sample of farms needs to be calibrated to this historical evolution of macroeconomic inputs and outputs. These data are calculated based on the total amount of slaughtered animals, provided by the Federal Agency for the Safety of the Food Chain. Animal imports and exports are obtained from the VLAM (Flanders' Agricultural Marketing Board) and sales prices are obtained from the BIRB (Belgian Intervention and Restitution Bureau). At the same time, the sample also needs to represent a similar diversity of farm sizes and farmer's ages as in reality. This leads to 29 more selection criteria based on real-life data of the structure of the agricultural sector. These data are obtained from the five-yearly agricultural monitor.

The reference agents for the initial population are based on farm-level data from the FADN-database. The FADN database contains farms that have been selected in order to create a stratified sample of the national agricultural sector. The stratification rules follow three criteria: region, economic size and type of farming. The stratified sample has not been created in order to allow extrapolation from the sample to the entire sector. The main aim is to reflect the existing diversity of farms within the regions. When these selected farms are used as reference agents for the initial model population, we cannot rely on the diversity in the FADN sample as such. A selection procedure is required to select the right farms in order to ensure that the extrapolation to the entire population is a close as possible to the macro-economic characteristics of the agricultural sector in Flanders.

The reference farm agents are chosen to reflect as a group the production of the Flemish agricultural sector. This production concerns all activities related to the production and treatment of pig and cattle manure. There is only an artificial division between the animal production and the rest of the agricultural sector. The majority of farmers that produce animals or milk, also produce crops. The FADN methodology delimits categories of farm types dependent on the main crop. Specialised dairy farms for instance obtain most of their income from dairy products. This FADN categorisation according to farming type has not been applied here. The selection procedure here needs to include all farm categories, even those where income from animal products is very small. Given the importance of mixed farming in Flanders, the reference agents also need to represent mixed farmers with very small animal stocks, even if these are categorised under crop farming. Therefore, the selection method is applied to all farms present in the FADN database of Flanders with at least one output product derived from cows or pigs. This product is not necessarily the dominant part of the farm's turnover.

The data and observations from the FADN database are filtered accordingly. In a first step the farms that produce products derived from cows, milk or pigs amongst other products are retained. The FADN database does account for contract rearing as a benefit in 'other outputs'. Contract rearing is quite common, certainly among pig farmers. But the necessary data for modelling is lacking with open farms. These farms account for the animals present at the farm, but not for the fodder costs neither for the sale of live pigs or cows. Whenever a farmer derives some turnover from contract rearing, the correlation between fodder intake and animal production does not hold any longer. It has therefore been decided to exclude farms that present more than 5% of their livestock output from contract rearing. Finally, we reduce the selection to farms for whom a continuous set of observations is available from 2006 to 2008 included, and a balanced data set was build. An unbalanced data set was avoided as this leads to deviations in the automated selection procedure. Sparse data sets are automatically preferred because they allow an easier approximation of the criteria objectives.

This leads to a balanced panel database of 704 farms and 3.431 observations. This has to be matched against 9 criteria based on macroeconomic production and 29 criteria related to sector structure and size distribution.

The macro-economic criteria have been weighed with $\acute{a}_i$ equal to 1/9 and the structural criteria equal to 1/29. The maximisation procedures yields real numbers as weights for the farms. The weights are rounded to the nearest integer, and this results in a selection of 65 farms from the original group of 704 with a weight of 1 or higher. The results are reported in Table 2-12.

The selected group of farms is based on 29 reference farms. Each farm is replicated at least once in the initial model population, and the total number of farm agents at initialisation is 25073. This is much lower than the total number of pig and cattle farmers in Flanders in 2007, 31 984. However, the total production of the selected group is very close to the total production of the total Flemish pig and cattle sector.

Table 2-12 : Weights results and comparison of the selected farm agent population with the real situation in Flanders

Calibration subjected to all criteria				
# farms selected		29		
Total number of agents		25073		
Weights	Avg	SDv	Min	Max
	865	973	7	4 332

Calibration with macroeconomic criteria	Cow meat production			Pig meat production			Raw milk production		
Year	**2006**	**2007**	**2008**	**2006**	**2007**	**2008**	**2006**	**2007**	**2008**
Real production	379	369	361	1 353	1 264	1 498	595	559	433
Approximation	108%	100%	103%	103%	97%	103%	103%	105%	98%

Number of farms according to farmer's age and farm size in ha						
Age	**18-34**	**18-34**	**18-34**	**35-44**	**35-44**	**35-44**
Farm size	**< 20**	**20-50**	**> 50**	**< 20**	**20-50**	**> 50**
Real number	1 173	923	298	3 911	2 798	1 013
Approximation	87%	99%	102%	67%	106%	111%
Age	**45-54**	**45-54**	**45-54**	**> 55**	**> 55**	**> 55**
Farm size	**< 20**	**20-50**	**> 50**	**< 20**	**20-50**	**> 50**
Real number	4 836	2 782	988	10 030	2 603	628
Approximation	96%	106%	109%	41%	104%	105%

Number of animals according to farm size in ha	Cattle				Pigs			
[in LSU]	**< 20**	**20-49.9**	**50-99.9**	**> 100**	**< 20**	**20-49.9**	**50-99.9**	**> 100**
Real animal stock	29 610	56 000	245 330	664 370	11 865	46 329	1 202 223	616 266
Approximation	114%	89%	64%	85%	107%	88%	95%	99%

Number of animals according to animal stock	Cattle					Pigs			
[in LSU]	**< 10**	**10-19.9**	**20-49.9**	**50-99.9**	**> 100**	**< 15**	**15-30**	**30-150**	**> 150**
Real animal stock	14 393	27 221	119 254	322 947	804 049	11 118	43 412	1 126 540	577 471
Approximation	97%	116%	113%	90%	74%	81%	96%	92%	110%

Some parts of the real sector are underrepresented. This is the case for the smaller farms, larger farms are relatively overrepresented. And especially the group of small farms with owners over 55 years of age are strongly underrepresented. One major reason is that this group contains in practice also a lot of farmers above the retirement age, who remain officially active. However, it seems that removing this group from the agent population does not reduce significantly the total production of the sector.

The total animal stock in the agent population is also a less than in reality. The total number of modelled cattle is 1 069 794 LSU, whereas 1 287 864 LSU are present in reality. The modelled pig stock is 1 723 794 LSU against 1 758 541 LSU in reality. This difference is particularly strong for the cattle population, and cannot be solely explained by the removal of the retired small farmers from the sample. It also seems that the average productivity of cattle in the FADN database is larger than the average productivity of cattle in the agricultural sector in Flanders. The difference in the pig productivity is less outspoken.

2.4 Dynamics over time: history, behaviour and evolution

The third part of the annual cycle of the farm agent assembles the different parts of the decision framework of the farmer. This part gathers the choices and heuristics that are defined by the behaviour of the farm agent, as illustrated in Figure 2-5.

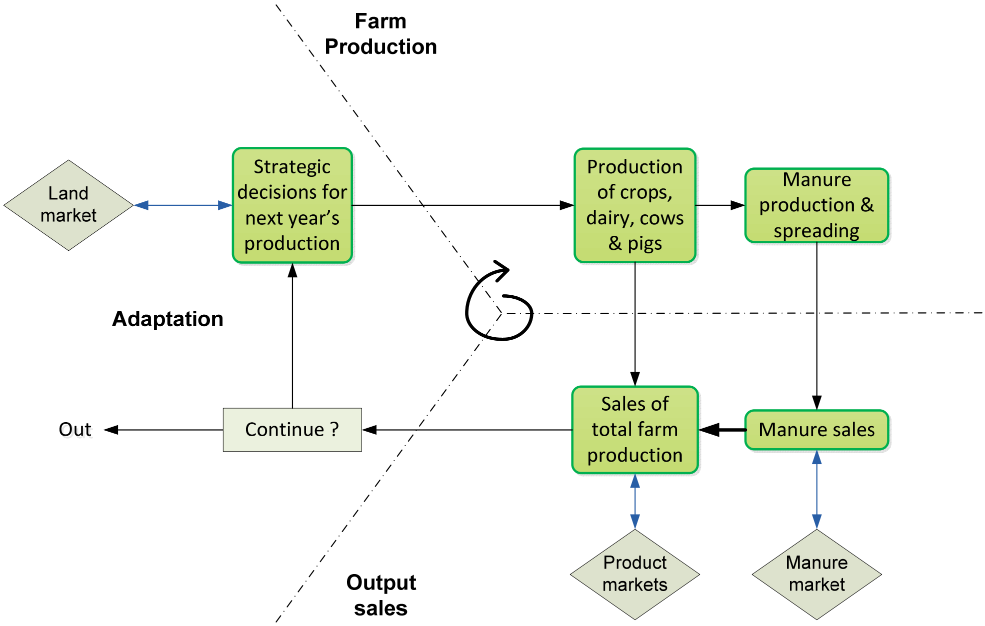


Figure 2-5 : Annual cycles for the farm agents in the model

The behaviour defines routines that structure the way the agent decides (Nelson et al., 1985). New routines can emerge over time (Dosi et al., 1999), signalling behaviour change. Change in behaviour reflects learning and adaptation. Evolutionary models do not always include learning features. Even if behaviours are fixed over time, diversity of agents can lead to structural changes emerging in the model through selective reproduction of agents (Epstein et al., 1996). However, in multiple models, learning and adaptation are embedded at the level of individual agents. This is related to the bounded understanding and knowledge of the agents in the model (Janssen, 2004). As agents progress and evolve, they receive a lot of information as well as feedback from their own production, and this allows them to adjust practices, beliefs and behaviours.

Especially farmers are obliged to show fast adaptability, because of changes in markets, climate and regulations. In a complex dynamic approach, adaptability of farmers is essential to prepare for unknown changes in the future (Dosi et al., 2005). Also diversity of responses and diversity in behaviours are required to keep the sector as a whole sufficiently flexible

(Darnhofer et al., 2010). This diversity appeared also in empirical investigations of Land Use Change (LUC). Bakker and van Doorn (2009) show that empirical analysis of land abandonment, restoration or reforestation, reveals different types of behaviour, linked with the individual characteristics of the farm agents.

This particular design of the adaptation procedure has been chosen in response to the overall aims of this research. These aims are first the design of an empirical model that allows more insight in different parts of the decision procedure in reality through calibration. Secondly the model has to integrate diversity at various levels in the Agent population, and finally the design has to allow model stability but also large freedom in the choices made by the agents.

The research has to provide insight into the dynamics of change in agriculture. The adaptation model separates therefore decisions in two distinct groups: strategic and incremental decisions. The strategic decisions are not taken every year, and their frequency is matched with empirical data.

Secondly, the model allows for behaviour diversity in the farm agent population. Diversity has been integrated for the technical characteristics of the farm. This is extended to heterogeneity in behaviour rules as well. Matching these with empirical data also gives a richer view on the actual dynamics in Flemish agriculture.

Finally, the large number of potential decisions for the farm agent poses difficulties for model stability. The potential solutions for this problem are situated between two extremes. On the one hand the adaptation model can be designed with very straightforward and crude adaptation rules, accompanied by choice constraints in order to avoid unrealistic choices or highly unstable behaviour. On the other hand, the adaptation model can also be designed with very detailed and complex rules, trying to approximate realistic decision patterns. The first alternative is the easiest solution, but it will lead to a model that cannot show any unexpected behavioural outcome, as it is only limited to very constrained choice sets. The other extreme is only valuable if it can be accompanied by detailed field work exploring the real heuristics of farmers' decision making, which in this case is not available. This study applies a solution that balances between both extremes. By adopting a structural framework to develop behavioural heterogeneity, coupled with technical characteristics, much more potential behaviours are implemented. At the same time, the decision rules at the level of a single behaviour type can remain relatively simple without overly constraining the choice sets. It creates an adaptation model for the farm agent that is sufficiently simple for a first application.

2.4.1 Adaptation steps and variables

The adaptation part of the annual cycle combines all steps to decide on the future lay-out of the farm agent. The decisions concern a number of variables that cover all assets and efficiency investments. The adaptation part of the farm agent is structured in four steps, each grouping related decisions, as illustrated in Figure 2-6.

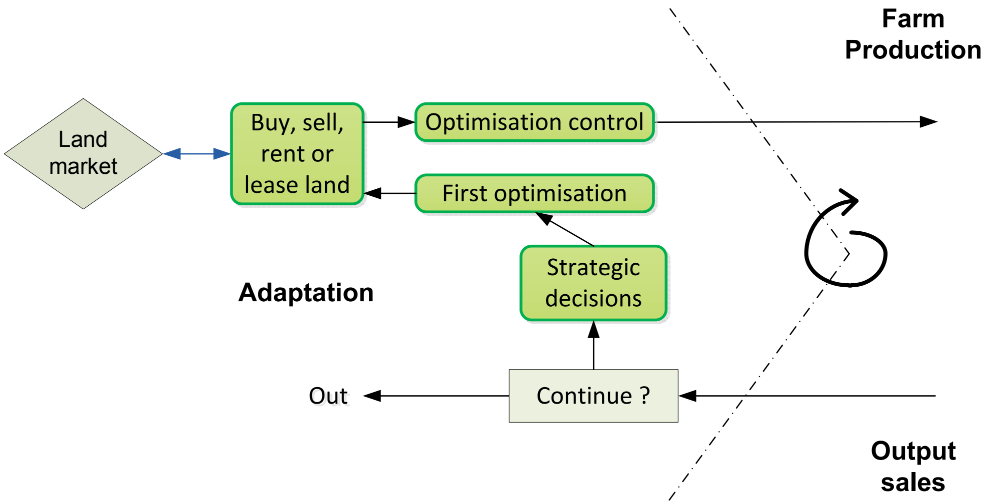


Figure 2-6 : Consecutive steps in the adaptation procedure of the farm agent

In the first step, the large strategic decisions are taken. Secondly, incremental optimisation is planned with limited modifications of the farm's assets. This planning allows the farmer to engage with the land market in the third step. Some final adjustments can be made in the fourth control step.

The first step of the decision process is the overall strategic decision, allowing the farmer to review the types of animals on his farm. This means that the agent can decide whether or not to continue raising a certain type of animal. The agent can also decide to invest in an innovation to improve production efficiency. Efficiency improvements are modelled as finite increases in production efficiency for either cow, dairy or pig production. The price for this investment is relative to the size of the particular livestock of the farmer. The design includes two types of variables to alter the change dynamics. These variables make it possible to calibrate the behaviour to the changes in reality:

- Transaction costs: Changes at farm level do not immediately yield their optimal return. When taking a strategic decision, changing the structure of the farm, the farm agent has to adapt to the new specialisation or investment. This learning period is implemented as a transaction cost, proportionate to the investment cost of the change, separately for each of the three animal productions.

- Population adaptiveness: The general framework provides the option for the farmer to change his overall strategy every year. In reality there are several reasons that induce a farmer not to change his strategy every year. First of all, large strategic changes require willingness to change and a learning capacity. Secondly, large changes are disruptive at farm level. They reduce the options for future production and render some past investments obsolete. Finally, there can also be a form of persistence or stubbornness that explains why farmers continue production with an existing configuration rather than 'giving up' one type of animal or crop. The model integrates this lack of adaptability. The overall population adaptiveness is defined as the percentage of the farmers that review their strategy during one year. The determination of this variable through calibration brings insight into the speed of change for radical modifications at farm level.

In the second step, the farm agent can change his acreage and the crop allocations. These are changes of a much less radical nature. The farm agent optimises the production assets by incremental de- or investments and allocates different crops to the remaining available acreage. Based on the type of animals and the acreage available, the farm agent can adjust the amount of livestock with a maximum of ± 20%. Increases in animal stock are accompanied by investments for additional stables and machinery, and the farmer has to respect a minimum surface of grassland per cow at all times.

Step three captures the process of the land market. For the individual farm agent, the land market is an unpredictable process. The farm agent may propose bids or offers, but this does not necessarily mean that a suitable corresponding Agent will be found that is willing to close a transaction for those bids or offers. So the farm agent potentially can engage on the land market, but he cannot be sure to sell or buy his land at the requested price. Because of this uncertainty, the farm agent reviews in a fourth step his optimisation plans after the land market and adapts his asset allocations according to the results of the exchanges on the land market. Step four follows by adjusting in a similar way as step two.

2.4.2 Adaptation drivers and Objective functions

During this process, three aspects that determine the adaptation and learning capabilities of the farm agent are historical path-dependence, the ability to forecast, and the individual objective function. Adaptation of an agent requires the maintained link with the historical

evolution of the agent. The agent follows a path during its development, and the effects of learning are determined by the past experiences of the agent.
The second obliged concept in relation with adaptation is the ability to forecast. Even in situations where high uncertainty is prevalent over future trends, agents are obliged to determine forecasts for future productions and prices (Dosi et al., 2005; Ziervogel et al., 2005).
Finally, adaptation obliges the definition of an objective function or fitness measurement. The agent will then adapt his situation in order to maximise his fitness (Holland et al., 1991). For this ability to forecast, each farm agent individually optimises his annual income based on personal price predictions. These price predictions are formed by averaging the prices the farmer received for this output during the last three years. External trends that could influence future prices are not taken into account by the farm agent. This is narrow foresight, similar to foresight methods used in other projects (Happe et al., 2004).

The definition of the objective function and the related constraints determine the largest part of the adaptation procedure. Multiple models use an objective function based on various forms of profit-optimisation. In these models, every farmer decides on his strategy and assets while optimising his annual profit. Profit-optimisation has been applied before in agricultural agent-based models, but rarely in the strict neoclassical sense. Several adaptations to this basic decision model have been applied to bring the behaviour closer to reality. The Agripolis model (Happe et al., 2004; Happe et al., 2006) utilise a farm income maximisation decision module. This maximisation is based on limited information and personal prediction of future output prices. Similar constrained and bounded rational optimisation of annual farm income is found in agricultural models such as MP-MAS (Berger et al., 2006; Schreinemachers et al., 2011) or CATCHSCAPE (Becu et al., 2002; Becu et al., 2003), the latter combining optimisation with linear programming.
Because behavioural diversity is used in this model, as explained in the next section, two different objective functions are used as well: one function pursuing maximum farm value, and a second function pursuing an ideal farm configuration.
In the first case, the farm agent decides on the optimal quantity of land, animals and animal types for a maximum farm value next year. Annual profit maximisation is a very short-term planning horizon for the farm agent. In order to incorporate a focus with a longer time-frame, farm agents maximise the entire value of the farm rather than solely their profit. This entire value includes liquid and fixed assets and agricultural land. This type of farmers does not pursue the largest profit for next year, but they pursue the creation of a large and rich farm, yielding important annual profits each year.

The second objective function is not based on a value, but on an ideal farm structure. This ideal is pursued under the same restriction of financial risk and loan availability. Maximisation implies that the agent disposes of a range of choices. For instance, the choice of a mixed farmer to stop raising pigs and to specialise on dairy farming instead, can be part of the decision process. But this is not a valid choice for one type of farms called 'stable family farms'. The 'stable family farm' is based on characteristic behaviour of Flemish small-scale farmers. This type of farmers is passionate about their specific farm type or about the animals they raise. Entirely driven by personal preferences and conviction, this type of farm can for instance prefer pigs. Despite the fact that crop farming presents larger marginal benefits, this farm will continue to raise pigs. There are no alternatives considered during a maximisation process. Their objective is the creation of an 'ideal' farm configuration and size, based on personal preferences of animals and crops. The 'ideal' farm configuration is entirely personal and different for each stable family farm. It contains a certain acreage, and a specific stock of animals. This ideal also consists of a full ownership of all the land under cultivation. Every affordable step that can bring the farm closer to the ideal, is implemented. When achieved, the farmer stops the farm growth and invests only in efficiency.

In this model, the objective maximisation of the farm agent is constrained by the availability of loans and by the level of financial risk the farm agent is willing to take. New investments in land, animals, farms or installations may require loans. Banks will not restrict the maximum amount of the loan based on the future business plan, but based on the value of the land of the farm that the farmer can give as a guarantee. The maximum loan that a farm agent can obtain is therefore the value of the owned agricultural land, reduced by existing loans.

However, the farm agent will not always take the maximal available loan. This depends also on the financial risk the Agent is willing to take. The financial risk of the farm agent is defined as the ratio of liabilities over owned assets. Every farmer disposes of a unique maximum level of risk he is willing to take. This maximum financial risk level RF is age-dependant. The fixed level RF_0 is exponentially distributed among the agents with mean 0.246, corresponding to risk levels in 2008. With growing age, the risk preference of farmers decreases and falls to zero at the age of 65: $RF = RF_0\left(1 - e^{\frac{x-65}{10}}\right)$. This financial risk limitation introduces the age dependence in the behaviour of the farm agent.

2.4.3 Behaviour diversity

Advanced research that details interactions and decisions of farmers, shows a very complex decision framework. In the case of land use change decisions, role playing games have clarified the multiple decision drivers and criteria (Lamarque et al., 2013). The results indicate how general scenarios of climate change can have very different results in terms of land use change, not only depending on local characteristics of the land and adaptability of the farmers, but also due to diversity in decision rules. The model implements behavioural diversity, constructed according to the procedure of Smajgl et al. (2011). Diversity is a key feature in evolutionary analyses. Following the variety of farmers in Flanders, the implementation of technical diversity leads to a large range of technical variables, combinations and characteristics in the model. The additional implementation of behavioural diversity adds another level of differentiation between the agents, leading to a multiplication of variable combinations. This large combinatorial freedom could signify in practice that the model is very hard to build empirically. But the application of diversity in both technical and behavioural characteristics is feasible because one can rely on the coherence between the two aspects. This coherence leads to the construction procedure, illustrated in Figure 2-7.

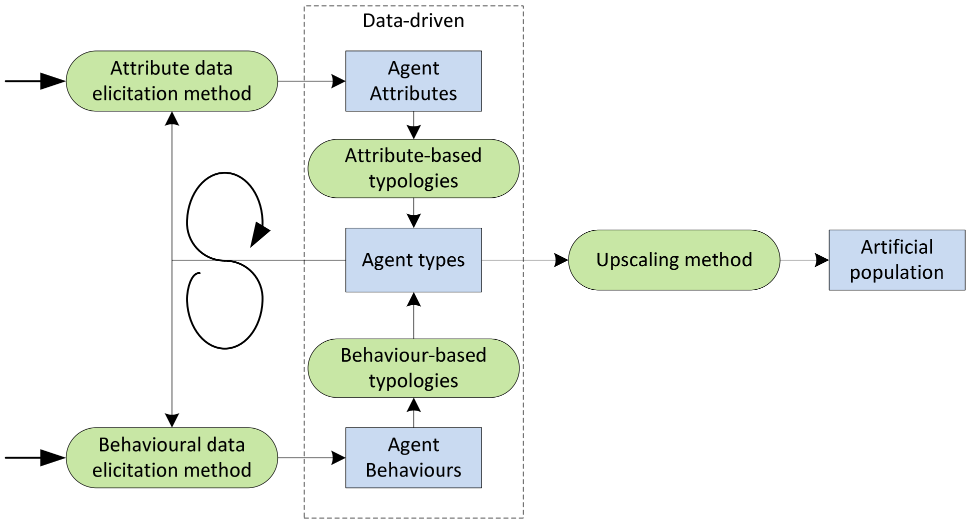


Figure 2-7 : Agent-characterisation method according to Smajgl and Barreteau (2014)

Farm agents are classified in different groups based on their technical characteristics, including farm size, type of activity, location, profitability, or age. This defines the attribute data, and attribute-based classes. The behavioural diversity is also explicitly integrated by forming classes of farmer behaviour. When one considers certain behaviour to be continuous, it will influence the lay-out and structure of the farm over the long term. Mixed farms will not be held by farmers pursuing maximum production efficiency, or large farms require a certain willingness to take risks from the farmer. Through recursive optimisation of the classes, groups of farmers are constructed that combine each a technical type and a behaviour class.

In each case, the method integrates empirical datasets and qualitative information to build the full model (Valbuena et al., 2008).

These combinations of behaviour and technical characteristics form the reference farm agents. In the last step of Figure 2-7, these reference agents are multiplied to create the initial population of the model. The procedure to determine the multiplication weights for each of the agents is detailed in the former section.

In this case, different types of farmer behaviour have been distinguished through discussion with experts from the innovation unit at the Farmers' Union. For this application, five different types of farms have been determined: (i) growing family farms, (ii) stable family farms, (iii) innovator farms, (iv) elderly farmers and (v) industrial farms. The links between the different types are illustrated in Figure 2-8. Every behaviour type is related to technical farm characteristics, as described in Table 4.

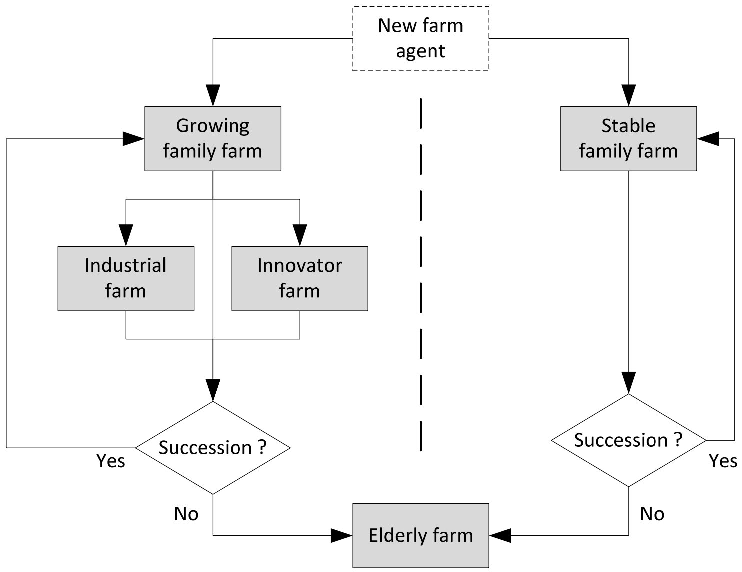


Figure 2-8 : The links between the different farm agent behaviour types

At the start the farm agent can be defined as a growing family farm, or as a stable family farm. The two types have very different behaviours. Stable family farms are based on one family pursuing a stable surface of land and stock of animals. The main objective of these farmers is to obtain a stable farm configuration, while increasing ownership of the land under cultivation and achieving a growing income and farm value. The farmer does not optimise the value or the income of the farm. The farmer defines an ideal farm containing a specific acreage, and specific quantities of animals. He pursues this structure over the years, and every step that can be financed to bring his actual farm closer to the ideal, is executed. Investments to increase efficiency are implemented when affordable. The farm size is limited; the total amount of external labour does not exceed 1 FTE.

Growing family farms on the other hand, have a very different behaviour. These farms are also created from one family with a growing surface of land and stock of animals. But the main objective of these farmers is to grow steadily. Growth of production can be achieved both by acquisition of production assets as by implementing innovative technologies for increased production efficiency. Through multiple adaptations, the growing family farm can become an innovator farm or an industrial farm.

The innovator farm adopts a long-term strategy based on high specialisation and innovation. Growth is pursued, but it is no longer the primary objective. Investments in efficiency increase and in niche production are preferred. The farmers of innovator farms are over 45 years old, allowing them to achieve sufficient experience and background to invest in multiple innovations. These farms achieve the highest production efficiencies. The type is most commonly associated with specialised pig and dairy farms, less with cattle farmers. The industrial farms on the other hand, are less specialised, but larger than innovator farms. Industrial farms are managed as industrial plants. The farms maximises the total value of the farm in the long run. The strategy is based on economies of scale, and leads to intensive growth of the farm. These are the largest farms but do not require specialisation.

Finally, at the end of the lifetime of the farmer, the farm has to find a successor, or he is to evolve into an elderly farm. Succession is a crucial step in the history of family farms. This is increasingly the case, as farms grow larger in size, to a point where it is difficult to start a new farm without any capital or assets available from a predecessor (Calus et al., 2010). However, the current rate of farms that find a successor on time is low. Farms without a successor can present zero growth or decrease in total farm assets (Calus et al., 2008). But in the case when no successor is present, elderly farmers do not retire. Elderly farmers stay active after their pension age, and continue farming without further adapting their farm structure.

So the typology of elderly farms consists of farmers that remain active, and don’t find a successor. Currently, a succession rate of 41% is implemented in the model. Any farm that fails to find a successor on time becomes an elderly farm when the farmer’s age reaches 65 years.

The elderly farmers live up the farm’s assets, maintain the land in ownership and do not invest in higher efficiency or new innovations. The activity only stops when the owner passes away. Starting from 65 years old, each agent has an increasing chance of departure, up to a chance of 100% at the age of 85. Besides the high age of the farmer, these farms also present low efficiencies and high stability of activities or even decreasing activities.

So the behaviour typology can be divided in two very different evolutions, one based on stable family farms, the other on growing family farms that can potentially evolve towards industrial or innovator farms. Both types turn to elderly farms at the end of their life. The difference between the two evolutions is especially a difference of adaptability. The growing family farm is responding to market prices by adapting his production assets. Growing farms can also decide to specialise their production and to discard one type of animals. This characteristic is shared with the innovator and industrial farms. On the other hand, the stable family farms remain focused on their ideal farm structure. Stable family farms do not adjust their production according to market prices. At most they delay investments because of insufficient liquid assets. The stable family farms represent a very stubborn and fixed behaviour. The other farm types represent a very flexible and adaptive behaviour. The percentage stable family farms in the total farm population is therefore an important factor for the overall adaptability of the agricultural sector. This percentage also has to be determined through calibration.

Table 2-13 : Translation of the behaviour in modelled rules

Name	Evolutionary traits	Technical characteristics	Optimisation objectives	Optimisation constraints
Industrial farms	These farms set out from the start to behave strategically as industrial firms and have a relatively high chance to find a successor.	Farm owner is older than 45 years. Farm size exceeds 350 LSU. Farm is not specialised in one animal type.	The farm maximises the value of the firm.	Growth is constrained by a maximal financial risk of 60%.
Innovator	These farms start as family farms. When the farm achieves sufficient experience, efficiency and specialisation, it can become an innovator. These farms also have a relatively high chance to find a successor.	The farm owner is older than 45 year, and is specialised in one animal type. The farm production efficiency exceeds 110% for dairy farms, 135% for cattle farms, and 150% for pig farms.	The farm maximises a double objective, maximum farm value and maximum production efficiency.	Growth is constrained by a maximal financial risk dependant of the owner's preference. And the total labour burden should remain smaller than 20 times the farm household size.
Growing family farms	Farms start as growing or as stable family farms. Only growing farms are interested in an evolution towards industrial or innovator configurations.	The farm owner is younger than 65 years, or has a successor. There is no other technical restriction for this type of farms. Farm types are randomly designed growing or stable family farms at the creation of the farm agent.	The farm maximises the total value of the farm, composed of liquid assets, and fixed assets including land.	Growth is constrained by a maximal financial risk dependant of the owner's preference. And the total labour burden should remain smaller than the farm household size plus one.
Stable family farms	Farms start as growing or as stable family farms. These farm remain in this category unless they fail to find a successor in time.		The farm pursues a size of land and livestock, determined on beforehand as ideal. Whenever land is available or financial reserves allow it, these farmers grow their assets until they reach their ideal size.	Purchase of new assets is constrained by a maximal financial risk dependant of the owner's preference. And the total labour burden should remain smaller than the farm household size plus one.
Elderly farmers	All farms that do not find a successor in time become elderly farms.	The farm owner is older than 65 years, and has no successor.	The farm doesn't change investments any more, nor does it invest in efficiency improvements. The same activity is maintained with slowly declining efficiency.	
Remarks: • Farms that are facing bankruptcy due to negative cash flows, revert to cash maximisation as a short term survival strategy. When the danger of bankruptcy is averted, they return to their standard optimisation procedure.				

2.4.4 Calibration to define behaviour dynamics

Empirical calibration of evolutionary models has been gaining attention lately (Fagiolo et al., 2007), and several approaches are available (Boero et al., 2005). Still, calibration has been noted as a critical problem in applications of empirical ABM's and solid calibration methods are required to guarantee the credibility of the results (Robinson et al., 2007). Standard calibration takes two steps. The first step calibrates the input data of the model on realistic data sets and benchmarks. The second step compares the output with empirical data for the output and determines the validity of the model. A specific and pragmatic calibration method, the Werker-Brenner method, adds a third step (Werker et al., 2004). The method uses specificities of evolutionary models, exhibiting often numerous degrees of freedom. The Werker-Brenner approach labels itself as 'critical pragmatist' in the sense that the model is not required to deliver one correct solution. The more pragmatic approach is to allow for several realistic solutions that are able to explain the same phenomenon. Several acceptable sets of input data are determined that return solutions in line with the calibration constraints. The third step is thus to investigate the underlying dynamics, similarities and differences between the inputs sets. These patterns show underlying principles common to all acceptable data sets. This approach narrows the sets of possible entry data down to more realistic figures, and this improves robustness of the model (Russo et al., 2006).

In order to determine the main behaviour variables, this Werker-Brenner calibration method is applied. First the initial situation is fixed. This initial situation is calibrated to technical and production characteristics of the Flemish agricultural sector in 2000, in a similar procedure as explained in section 2.3. A limited number of immeasurable parameters, especially those related to behaviours, are selected at random. The model is executed with the heterogeneous behaviour rules. After hundreds of model runs with random parameters, the results are chosen that correspond best with the historical evolutions in the period 2000-2011.

When assuming heterogeneity, several scenarios can be determined that bring the simulated evolutions closer to the real annual productions. The variables that need to be determined through calibration are: the adaptation capacity of the farmers' community, the annual availability of land, the transaction costs, the efficiency increase/innovation cost for efficiency improving investments, the proportion of growing family farms compared to the number of stable family farms.

Not all of these variables exert a similar influence on the evolution of the model. An essential role remains for the proportion of growing family farms compared to the proportion of stable family farms. This can be clarified by highlighting the large differences between the two. The growing family farms are very reactive to their environment and to the price signals they receive. They are also the basis for the emergence of larger and more innovative farms. The stable family farms however, are mostly driven by internal motivations and constrained by personal limits on size and labour. A high proportion of growing family farms yields a model that is highly reactive to price evolutions. Consequently, a high proportion of stable family farms yields a model driven by changes in acreage and by the age pyramid of the farmers.

The calibration has been done for a varying proportion of growing versus stable family farms. The optimal values for the corresponding parameters are reported in Table 2-14. Figure 2-9 shows the simulated evolution when no Stable farm agents are included in the initial population. This simulation shows that even the closest approximation cannot replicate the actual production levels between 2000 and 2011. When all farmers are farm-value optimisers, they tend to disinvest and move away from livestock husbandry.

Growing family farms change their farm structure during the evolution based on market prices. The prices help the farm agents to forecast future income and the farm structure changes are evaluated accordingly. The real prices have been relatively low in this period; so many adaptive farm agents decide to focus on crops or to leave farming altogether. A decrease in sales prices for one year has the immediate effect that the least productive farmers leave this segment of production.

The assumption of immediate change is related to several other suppositions. It implicitly assumes that farmers have multiple alternatives to choose from and that they also consider these choices annually. This is not supported by the actual evolutions of animal production. As discussed above, because of lack of skills or knowledge, several alternatives can be unattainable for the farmer. The farmers prefer a longer time-frame, and present certain persistence. They avoid making disruptive changes to their farm. Finally it has to be stressed that the considered decade 2000-2011 has not been very profitable for Flemish farmers. The prices for their production were and are still relatively low. Several segments of the market contain active farmers that have a very hard time to cope with these negative market developments. Still bankruptcy remains very low in agriculture. This is again a sign of strong persistence.

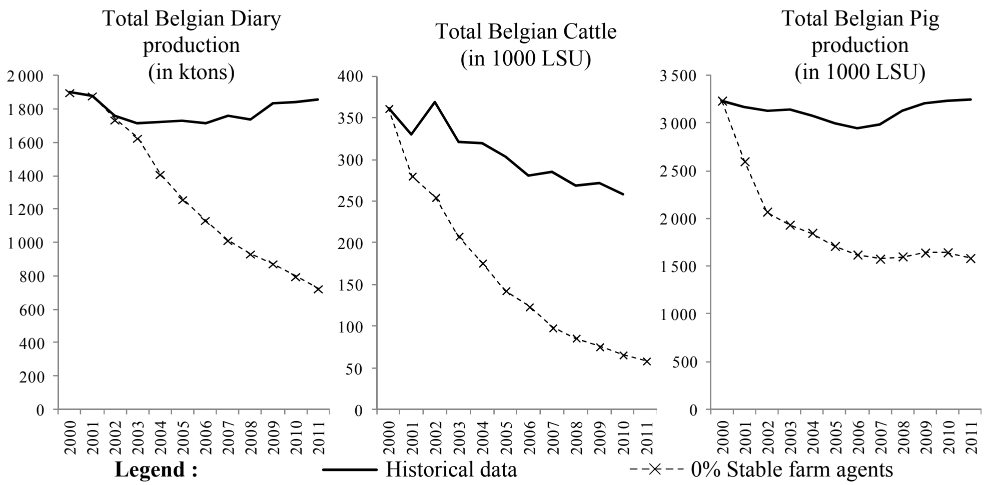


Figure 2-9 : Evolution of regional production without Stable farm agents

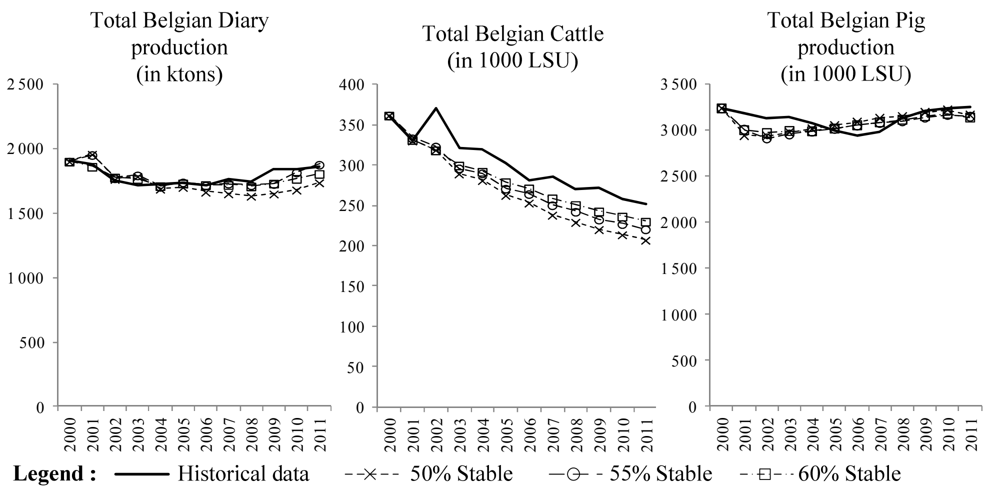


Figure 2-10 : Evolution of regional production with different proportions of Stable farm agents

Table 2-14 : Optimal parameter sets to simulate the actual production

Proportion of stable family farms	**0%**	**15%**	**30%**	**45%**	**50%**	**55%**	**60%**	**75%**	**90%**
Adaptation capacity[1]	3%	5%	10%	55%	55%	60%	60%	60%	40%
Land availability[2]	2%	2%	10%	20%	30%	35%	30%	30%	10%
Transaction costs[3]									
Dairy	20	20	-	-	-	-	20	-	-
Other cattle	20	20	-	-	-	40	40	30	30
Pigs	40	40	80	5	40	40	40	15	15
Approximation quality[5]	23.7%	18.8%	11.6%	9.3%	6.5%	4.7%	3.9%	11.3%	20.3%

[1]: The adaptation capacity is the proportion of farm agents that execute the strategic decision process per year.
[2]: The Land availability is the proportion of farm agents that has land available for purchase or for rent in his neighbourhood per year.
[3]: The transaction costs are defined as an additional cost when change is undertaken, of x times the price of the livestock quantity change.
[4]: The cost of an efficiency improving investment is the e/c ratio times the size of the livestock, per percentage efficiency improvement.
[5]: The average relative differences with the real macroeconomic productions is used as a measure of approximation quality for the scenario.

The results from the model applying diversified behaviour are closer to reality. The three best approximations (with 50%, 55% and 60% of stable family farms) are illustrated in Figure 2-10. The evolutions for pigs and dairy can be approximated closely. The closest predications can be made assuming a proportion of stable family farms between 50% and 60%. Both below and above this range the simulations remain further from the real historical productions.

With a low proportion of stable farmers, higher transaction costs, low adaptability and rigid land markets are required to match the real evolutions. Reduced adaptability, closed land markets and high transaction costs all serve as a barrier for change. When considering a change, the farm agent calculates the benefit. Large transaction costs indicate that the additional benefit from the change has to be substantial, before the change is considered. This indicates that farm agents that maximise their farm value, have to be restrained as much as possible from making any change.

With an increasing proportion of stable family farms, the transaction costs diminish, the sector adaptability has a tendency to increase, as well as the land availability. However, these increases are non-linear, indicating intricate dynamic relations between the different parameters. The best approximation, with 60% stable family farms, stays each year within a range of 5% of the historical dairy and pig production, and within a 10% range of the cattle production. With increasing proportions of Stable farm agents, rigidities in adaptability and in the land markets can be reduced. However, transaction costs start to rise again. This time, the transaction costs are required to dissuade the Stable farm agents from growing too quickly.

At the highest proportions of stable farmers, 75% and 90%, the variables are no longer very influential. All simulations with these high proportions of stable farmers consistently overestimate the live cattle production in Flanders. At 90%, variations of adaptation or land availability no longer influence the total production. The available variables do not permit a closer approximation of reality either. This shows that the assumption of a complete sector of stable farmers is not realistic either. A specific mix of adaptive and stable farmers yields the best results.

The common patterns between these parameter sets are the resistance to change in the agricultural sector. With low proportions of stable farms, there is rigidity in the market and in the learning processes. With growing proportions of stable family farms, the rigidity in the market and in learning can be reduced significantly. In these last cases, the rigidity resides in the behaviour of the farm agents themselves. Stable family farms are modelled to remain on an evolutionary track that they determine themselves at the start of their activity. Adverse price conditions or market pressure do not change their strategy. This rigidity is required if one is to explain the reasons behind the evolution of Flemish agriculture during the last decade. Whenever a modelled farm agent gets a chance to review his own situation and to consider alternatives, he chooses in most cases to leave livestock production and to do something else. But large exits from livestock production did not happen in reality. Farmers rather continue to produce and invest despite low output prices. It is mostly because of this behaviour that Flemish agriculture is capable of presenting a stable annual production.

It should be noted that models of the farm agent's behaviour are not linked to an actual reason of the farmer's motives. For instance, Stable Family Farms focus their personal evolution on a predetermined ideal farm structure. But this simulating approach does not imply a reason for this behaviour. Actually, several different reasons can result in the same behaviour pattern. A first situation can be the evolution an idealistic farmer. This idealistic farmer builds his personal ideal farm over time and is content with a lower profitability than average, as long as he can proceed towards his personal ideal farm. In this sense, it can be expected that the idealistic farmer sees the trend of evolving towards his ideal as very positive. However, the same behaviour can be possible for farmers who are stuck or restricted. Due to a lack of knowledge and skills, lack of examples and alternatives, or poor understanding of his personal situation, the farmer who is stuck maintains the farm in his specific configuration. This farmer has very limited options. This also means that this type of restricted farmer sees the trend of evolving to his ideal farming structure not at all as a good evolution. These farmers are not content with their personal situation, but they see no possibility for change. Both types are covered by the behaviour type of 'Stable Family Farms'.

In general, the diversified behaviour model distinguishes between adaptive and non-adaptive farm agents, without detailing the personal reasons for this behaviour. More detailed behaviour models will require this type of modelling to be coupled with detailed field investigations of actual decision patterns, and their related motives.

This application of a model with diversified behaviour yields promising results, given the fact that it flows from a first tentative construction of such a model for Flemish agriculture. The model results are capable as such to indicate the existence of important rigidities in the evolution of farms. But it cannot pinpoint the exact location of this rigidity in this first application. The current application can only present the first step in an iterative refinement of the model through questionnaires, participatory techniques or mediated modelling. The present shortcomings include the difficulty to adequately predict the production of live cows, and the simplicity of behaviour rules for certain farm agent types. Further research on behavioural typologies and decision strategies can help to gain a better understanding of the evolution of Flemish agriculture over the last years.

2.5 Dynamics of interactions: markets

In the second part of the farm agent cycle, illustrated in Figure 2-4, the farm agent interacts with the different markets for sales of outputs and manure. At this point it is important to refer to the overall model architecture as illustrated in Figure 2-11. The farm agent interacts with several markets, but only three of those are reactive: the market for live animals, for land and for manure. All other markets are exogenous, and are thus not influenced by the actions of the farm agents.

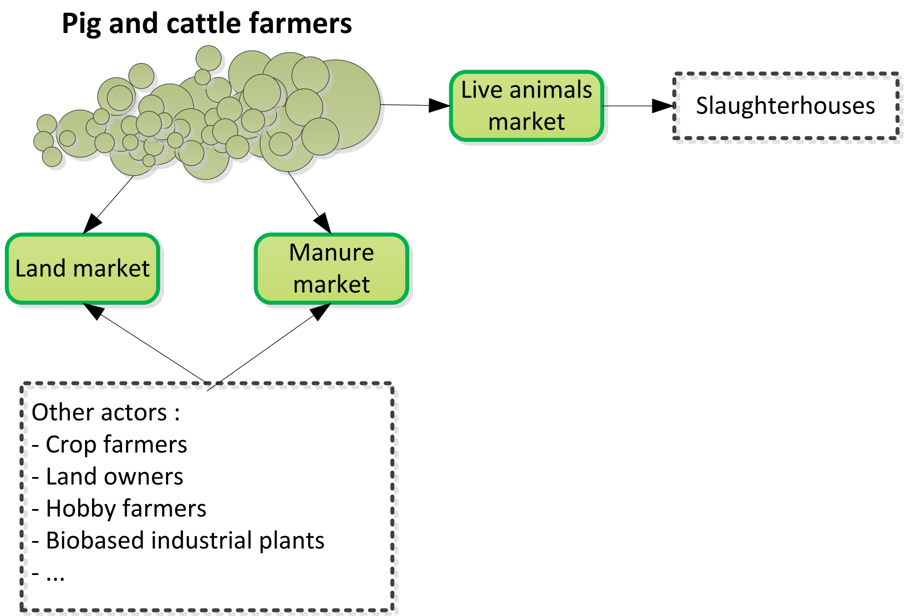


Figure 2-11 : Model structure

The exogenous markets determine the prices for artificial fertilisers, labour, loans, animal fodder, crops, and horticulture products. On these markets, the prices are determined externally and imposed on the farm agent. The price evolutions are dependent of the particular scenario that is under investigation. For the sales of crops and horticulture products, the baseline already specifies a fixed price (see Table 2-7). Evolution over different years is given by a price index, following the deviations from this baseline.

This section details some characteristics of the markets in Flanders, and based on these characteristics the models for the endogenous markets for land, manure and live animals are built. The first two markets, for land and manure, are fully endogenous, where both the supply and demand side of the market are gathered in a double auction market model.

The market for live animals is also influenced by the production of the animal farmers, but the demand side is related to the overall meat demand in society. The full connection between the two ends of the meat supply chain is established by a market power model, and is explained in 0.

2.5.1 Land market characteristics

Before designing the different actors on the land market, some particularities of the agricultural land market in Flanders are reviewed. The land prices for land purchases are influenced by several important trends. A first characteristic of the Flemish market for agricultural land is that the rental prices are fixed by the legislator. The long-term lease prices are regulated for the lease of agricultural land plots, and the minimum lease duration is nine years. Increased land rents are allowed if the lease durations are increased to 27 years, or to the remaining active lifetime of the renting farmer. Lease prices are determined for different agricultural regions following different soil characteristics in Flanders. This situation ensures that land plots remain available and affordable over the long-term for farmers, despite increasing sales prices. The average rent prices for the last years are illustrated in Figure 2-12. This causes the land market model to distinguish rent and sales transactions for agricultural land, and the rent market has to operate with prescribed prices.

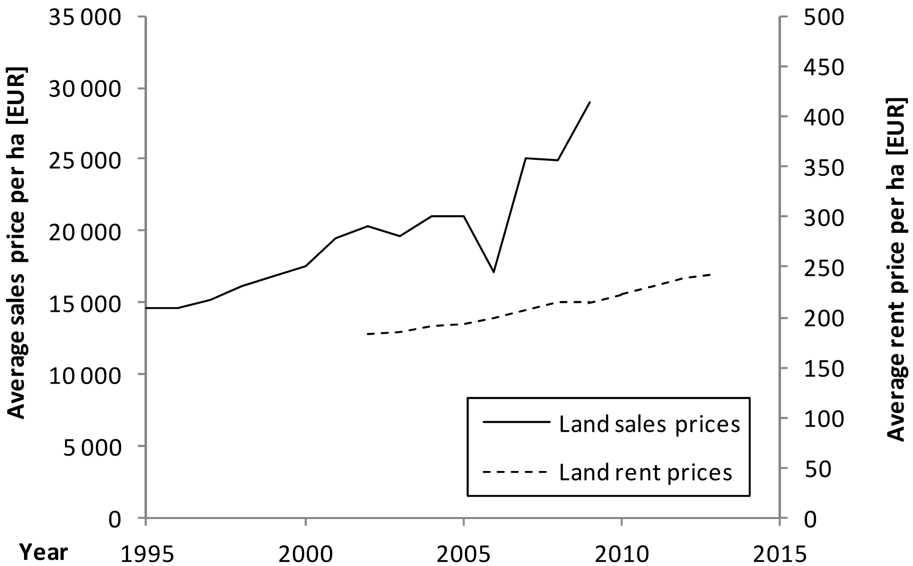


Figure 2-12 : Average sales prices for agricultural land (Bergen, 2011), and average rent prices (ADSEI, 2011)

There is no prescription for the sale of agricultural land. Strongly growing prices are shown, but this effect cannot be explained by a single trend.

First, by comparing land use data between 1990 and 2006, Hatna and Bakker (2011) showed that especially Flanders was characterised by simultaneous abandonment and expansion of agricultural land. This abandonment was not related to poor quality in terms of agricultural revenues, but was more related to proximity to roads and large cities. As a consequence, the quantity of available agricultural surface is slowly declining. According to EUROSTAT, the total surface of agricultural land was reduced with 25.000 ha between 2005 and 2010, a reduction of 2%. This corresponds to a general reduction in open space measured in Flanders over the last decade (Poelmans et al., 2014).

Secondly, there are also important shifts within the use of existing agricultural land plots. There are several growing types of land use that gain importance. These are for instance the 'horsification' and the 'garden sprawl'. Both terms are the labels of a growing number of agricultural land plots being used for hobby farming, respectively for horses and for private gardens (Bomans et al., 2010b). Especially these latest trends have an impact on land prices, because they lead to a growing number of active agents on the land market. These new agents are active in farming but not as primary profession. And this growing demand can have a pressure on land prices, because of the high financial capacity of these new agents.

There are compensating trends as well. As indicated by the structural calibration, there are a decreasing number of active farms, indicating a growing number of farms that sell their land. Secondly, the agricultural space that is available is not entirely used for agricultural production either. There is an underestimated and large proportion of land that is destined for access roads, agricultural buildings and stocks, ditches… This proportion has been labelled "tare land" (Bomans et al., 2010a), and can represent a large part of the gross agricultural area. For horticulture farms, this can reach up to 50% of the surface. The current evolution is that the proportion of tare land is declining, indicating a growing efficient use of the available surfaces.

2.5.2 Land market actors and calibration variables

The construction to replicate the land market dynamics should be as simple as possible. The level of detail in the description of the agricultural land is highly dependent on the objectives of the study. For instance, many projects incorporate geographical data of land parcels to study local characteristics and geographical proximity as determinants of land transactions. This can be spatially explicit in a theoretical land framework (Epstein et al., 1996; Happe et al., 2004), or based on real geographical information (Smajgl et al., 2013). This has been used to study water management options, regional farm structure, or management of common resources (Matthews et al., 2007; Parker et al., 2003).

In this case however, the objective is not on the geographical characteristics of the farm. The main objective is to study the emergence on the market of new technological solutions for manure treatment. Given the small size of the region under consideration – Flanders – differences in regional characteristics can play a role in reality, but are not preponderant. The emergence of these technologies is studied as a result of technology evolution, learning, and acceptance by farmers and related policy measures. Other studies also investigate agent-based dynamics without geographical specification (Möhring et al., 2010).

If geographical information is not included in the land market, then this requires specific assumptions for the land market model. Because in reality geographical limitations impose specific dynamics on the exchanges of land between farmers, the implemented market model ensures that these are preserved. Not every farm agent has access to available land every year. Even if land is sold, this land can be too far away from the farmer to consider the purchase. So only a few times the farm agent can have the opportunity to buy or rent new land plots. The percentage of farm agents that have access to new land plots during one year is the 'Land Access factor'. This factor is determined through calibration.

Groups of agents have to be integrated, leading to a set of variables that allow calibration of the land market to the real price evolution. The total surface of available land is divided between four groups. The first large group of farm agents is known in detail, these are the cattle and pig farmers. The model determines the different land plots that are offered on the land market, each with a different agent-specific price. The second group is similar, and consists of the manure treatment agents. These agents are described in the next chapter, and exactly like the animal farmers, their land transactions are known in detail for each agent. As the bids and offers are known in detail for these two groups, no additional calibration variables are needed to match their behaviour with empirical macro-economic data.

The third group is a group of hobby farmers. The hobby farmers distinguish themselves by buying relatively small plots of land. As this group represents the effect of growing trends, it can be assumed that the number of hobby farmers grows over time. The main interest to include this group here is to know the total proportion of agricultural land taken up by this group. So these actors will not be replicated individually in the model. Only the main characteristics of this group will be integrated in the land market model, leading to variables that have to be determined through calibration. Their bidding price is different from the average market price. This leads to three calibration variables:

- S_{HF} : the initial surface of land owned by hobby farmers;
- g_{HF} : the annual growth rate of the surface;
- α_{HF} : the ratio of the average price a hobby farmer pays per ha, compared to the average market price;

Finally the fourth group consists of the land farmers, owning the remaining proportion of the land. It is assumed that land farmers use similar pricing strategies as animal farmers. The surface held by this group is known, and is the remainder of the total surface of agricultural land in Flanders. It is not known however what percentage of their plots is annually offered for sale or rent. Again, the individual land farmers will not be modelled entirely, only their effect on land market dynamics. A group of dummy interventions in the land market is modelled, the combined effect of the group being the total effect of the land farmers on the land market. The calibration variables for this group are:

- l_{LFS} : percentage of owned land offered for sale;
- l_{LFR} : percentage of owned land offered for rent;
- l_{LFP} : percentage of land demanded for purchase;
- l_{LFL} : percentage of land demanded for leasing;

2.5.3 Double auction market rules

The markets for land and manure are endogenous, and are implemented as double auction markets (LeBaron, 2001; Poggio et al., 1999; Preist, 1999). In these double auction markets, any party can propose bids or offers for respectively the sale or the purchase of a good. Both a bid and an offer are a combination of a proposed quantity and a requested price. The double auction mechanism combines sales bids with purchase offers and establishes a negotiated price for the transaction.

The actual dynamics of the markets are heavily dependent on the implemented market rules. While the overall rules are the same for both auction markets, there are some differences in details:

- The manure market is split in two: one market for the dry fraction, one market for the liquid fraction. The markets are cleared every year. Quantities that are unsold at the end of the year cannot be kept at the farm, but have to be disposed of. The clearing solution is the most expensive treatment solution (drying and exporting) available with unlimited capacity.
- The land markets are split in two. A first land market regulates sales and purchases between parties. The second market regulates rents and leases of land.
- The land market is entered by different groups of agents, as described in the former paragraphs. Only farm agent and Technology Agents enter the market directly. Other agents on this market are modelled as dummies, based on the general characteristics of the groups of hobby farmers and land farmers.
- The land rent market is highly regulated and acts with fixed prices.

The integration of land markets in agricultural agent-based models is not common. The first applications implemented an auction mechanism where price were weighed between shadow prices for farmers and regional averages (Happe, 2004). A review from Huang et al. (2014) shows that the diversity and complexity of land auction models has grown considerably during the last years. These auctions are increasingly chosen , because they can integrate land transactions that account for myopic behaviour, heterogeneity of agents, and interaction with land characteristics (Filatova et al., 2010). In each case, the prices are determined both by individual characteristics of the agent, and market indicators. Filatova et. al. (2009) further developed auctions for land markets, with detailed solutions for both supply and demand. This approach has been used in several theoretical and empirical applications (Bakker et al., 2015; Filatova, 2014; Le et al., 2008; Magliocca et al., 2011; Robinson et al., 2013; Valbuena et al., 2010). Also in this case, the farm agents decide on the prices for bids and offers by balancing information on the land market with their own shadow prices for land use.

When preparing an offer or a bid for the land market, the farm agent is obliged to predict the land prices for next year. At the end of last year's auction, some data are published that reflect the overall dynamic: the minimum and maximum price obtained for the good in year t ($p^{A}_{t\,min}$ and $p^{A}_{t\,max}$), and the weighted average price over all concluded transactions in year t ($p^{A}_{t\,Av}$). During the auction, not all bids or offers find a corresponding match. So a large part of the proposed bids and offers cannot close a deal. This may be the case if the bid price is too high for any offer, or inversely if the offered price is too low for any bid. To show the proportion of the bids and offers that actually has been served, the market also communicates the percentage of the total bid or offered surface that actually has been traded (f^{A}_{Bt} *and* f^{A}_{Ot} respectively). This information is used by the Agents to make a prediction for the next bids and offers proposed to the auction.

The important indicator is the spread between the percentages of successful bids and successful offers : $\Delta^{A}_{t} = f^{A}_{Ot} - f^{A}_{Bt}$. If this spread increases it means that the number of offers is increasing, or the number of bids decreasing. Both indicate a rise in land prices. A decreasing spread indicates a decrease in land prices. . Inversely, a decrease of Δ^{A}_{t} over the last years indicates a high supply on the market, and allows reducing the predicted price for next year. Therefore, the farm agent determines a predicted land market price, as the current average price, multiplied with the change in spread over the last two years:

$$p^{Pred}_{Av\,t} = p^{A}_{Av\,t-1}(1 + \Delta^{A}_{t-1} - \Delta^{A}_{t-2}) \tag{10}$$

On the other hand, the farm agent also looks at the value of the land for his own farm. The farm agent determines the shadow price for an additional ha of land, $\widetilde{p^{n}_{t}}$. For pastures, an additional ha allows the extension of the animal stock with 4 LSU. The shadow price for pastures corresponds to the additional output of diary products or cattle minus the required investments and annual costs for the animal stock increase.

In the end the offer or bid is composed with the most advantageous price of either the predicted market price or the shadow price of the land. This leads to the price rules in Table 2-15.

Table 2-15 : Price calculations for bids and offers

Price	Symbol	Calculation	
Actual requested price for the bid	$p^{n}_{t\,Rq\,B}$	$\max(\widetilde{p^{n}_{t}}, p^{Pred}_{Av\,t})$	(11)
Actual requested price for the offer	$p^{n}_{t\,Rq\,O}$	$\min(\widetilde{p^{n}_{t}}, p^{Pred}_{Av\,t})$	(12)
Established transaction price	$p^{n}_{t\,TR} = p^{m}_{t\,TR}$	$0.5(p^{n}_{t\,Rq\,B} + p^{m}_{t\,Rq\,O})$	(13)

The auction proceeds with the following consecutive steps to combine compatible offers with bids.

1. All bids are collected and sorted according to selling price. The first bid has the lowest proposed price.
2. All offers are collected and randomized.
3. The auction runs down list of offers until an offer is found that is compatible with the first bid.
4. A transaction is established between the bid and the offer and a transaction price is calculated. The related quantities are removed from the offer and bid tables. If the quantity is reduced to zero, the bid or offer is removed entirely.
5. The process repeats from step 3, until no bids are remaining, or until no compatible offers can be found for the bid on top of the list.

This process avoids combining the lowest bids with the highest offers, as this would lead to a lower number of successful combinations. The randomisation of the offers increases the chance of a higher number of successful transactions. Figure 2-13 shows the maximum surface with compatible bids and offers that can be achieved.

This information is interpreted by the farm agents in their pricing strategy.

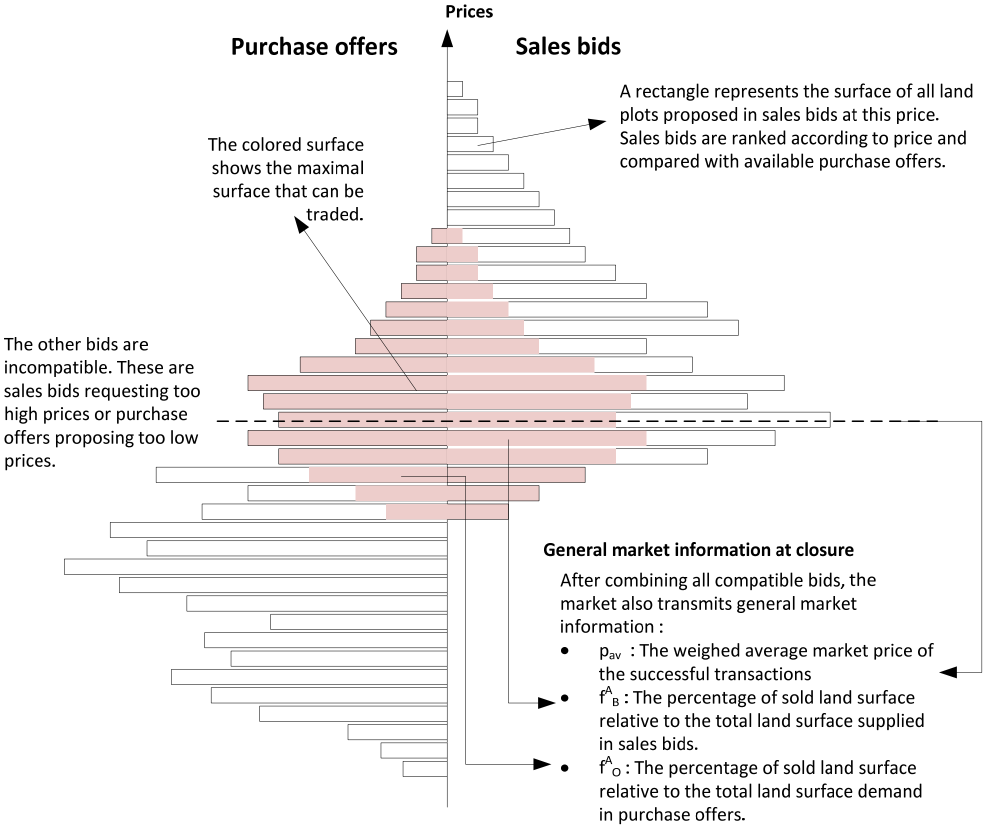


Figure 2-13: Schematic representation of the functioning double auction market

The final transactions are concluded when the requested bid price is below the requested offer price. The final transaction price is the average of the two. This leads to the calculation rules of the different prices, for farm agent n, illustrated in Table 2-15.

2.5.4 Calibration of the land market

During the behavioural calibration, the actual land prices are being used, and the price-setting capacity of the double-auction markets is not integrated. This is because the farmers of cattle and pigs are not the only actors present on the land market. Other agents interfere on the land market as well. There are land farmers and also larger land owners, who rent out their land to farmers. The behaviour of these other actors is not known in detail.

During the construction of the land market, four groups of actors have been distinguished; the animal farmers, crop farmers, hobby farmers and technology agents. This last group is not yet sufficiently developed during the calibration period, so it is not included for the land market calibration. The other groups get more detailed characteristics through the calibration.

The calibration chooses randomly the starting values and compares the computed outcome of the land sales price evolution with the empirical data. The calibration variables are related to the hobby farmers and crop farmers (7 variables in total). An automated selection procedure chooses at random a calibration point, a set of starting values for these seven variables. For each randomly chosen calibration point, the land market procedure is executed for every consecutive year between 2000 and 2011. The land market auction is a process that involves a long list combining offers and bids from all four types of agents. The process requires that the list of offers is randomised at the start, which induces uncertainty in the process. To deal with this uncertainly, every calibration point has been evaluated by 100 simultaneous iterations of the land market, between 2000 and 2011. The distribution of results is then compared with the empirical land prices. The closest approximations have been reached with the following values.

The hobby farmers are a relatively small group, with a potentially large effect on the price. This effect was notable, but not very large according to the calibration. The resulting descriptors of the hobby farmers group are:

- S_{HF} : 72.000 ha the initial acreage;
- g_{HF} : 1% the annual growth rate of the surface;
- α_{HF} : 10% offered land price mark-up;

The more influential parameters are the determinants for the crop farmers' group. These determinants define the percentages of the land owned by crop farmers that enters the sales and rent market for land, through offers or bids.

- l_{LFS} : 8% percentage offered for sale;

- l_{LFP} : 13% percentage demanded for purchase;
- l_{LFR} : 17% percentage offered for lease;
- l_{LFL} : 15% percentage demanded for leasing;

The distribution of outcomes is shown in Figure 2-14. This distribution illustrates the close resemblance of the average price formation with reality. However, the distribution of the price trends diverges towards the end of the calibration period.

Figure 2-14 : Comparison of the land market simulation and historical prices for land sales

The prices in the land market are determined by offer and demand, and also on the information of the land market of the past year. The results show that the demand for land is consistently higher than the offer. On average over 80% of the proposed land plots were sold, whereas the demand for land was much higher. Only 35% of the requested land was met during the land auctions. This leads to a continuous increasing price trend. The divergence is building on random factors accumulating over the years. Table 2-16 shows a gradually increasing deviation from the mean price trend for a series of 100 independent simulations. The standard deviation remains however within 1% of the average trend.

Table 2-16 : Real and simulated price trend, and standard deviation of for 100 simulation runs

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Real data	17.600	19.500	20.300	19.600	21.100	21.100	17.200	25.000	24.900	28.900	30.000	32.000
Average	18.216	19.499	20.443	21.465	22.500	23.519	24.653	25.775	26.949	28.276	29.605	31.051
St. Dev	25	88	73	86	98	132	148	174	195	219	229	234

2.6 Comparison with alternative models

As a conclusion of this chapter on the farm agent architecture, the general characteristics of this construction are reviewed and compared with other applications in similar research projects.

Agent-based models of farmers have been built on numerous occasions. Many of the research projects with these applications have focussed on land use change and management. (For reviews see Bousquet and Le Page (2004), or Matthews et al. (2007)) These models differ markedly according to the research objectives, and the level of interaction that is created with farmers, stakeholders and policy makers during the implementation. A specific feature of these models is that the geographical representation is very detailed. Also related ABM research integrating environmental and ecological dynamics has advanced significantly during the last years (Filatova et al., 2013). The results give new insights for landscape or biodiversity management (Anselme et al., 2010; Polhill et al., 2013), climate change adaptation (Balbi et al., 2013; Balbi et al., 2009) and water demand (Arnold, 2010).

Applications for agricultural economics, and more specifically for investigation of the structure of agriculture, are less numerous (Kremmydas, 2012) . This section compares the present model in detail with two similar models in order to clearly differentiate how research objectives for each of the models led to differences in model implementation. The two reference models are Agripolis and MP-MAS. These are both established models that have been elaborated over the last years, and have been applied in a variety of projects and publications.

Agripolis (Sahrbacher et al., 2012) was initiated by Balmann (1997) and further developed at the Leibniz Institute of Agricultural Development in Central and Eastern Europe (IAMO, Germany). The initial publications investigated the effect of agricultural policy changes on agricultural structure (Happe et al., 2008; Happe et al., 2006). Further developments (Kellermann et al., 2008) also integrated a relation with nitrogen flows and environmental impacts (Happe et al., 2011). Further developments are on-going and applications to different European regions enlarge the field for the Agripolis model.

Mathematical Programming-based Multi-Agent Systems (MP-MAS) (Berger et al., 2012) is a model developed by Berger (2001) at the University of Hohenheim, Germany. The model combines economic analysis of agriculture and biophysical layers for crop development simulation within a geographical setting. The model has been applied to study the impacts of irrigation in different countries (Arnold, 2010), land use change (Schreinemachers, 2007; 2010) and climate change in Germany (Troost et al., 2014).

Table 2-17 compares the inner workings of Agripolis and MP-MAS with the model elaborated in this dissertation. Despite strong correspondence between the research subjects, the research approach leaves many choices open and each model clearly focuses on different part of the evolutionary dynamics in agriculture. This results in three different agent-based model implementations.

Table 2-17 : Detailed Comparison of the different models

Name	Present model	Agripolis	MP-MAS
Farm production			
Crop types	Four land types only (crops, horticulture, forage and pastures)	Seven types of crops and grassland, and fallow surfaces.	Unlimited number of different crops, both annual and perennial.
Crop yield	Proportionate to land, dependant of evolving efficiency of the individual farm agent	Linear production characteristics, with detailed relations to seed costs, fertiliser needs, linear labour costs, etc…	Very detailed crop yield model, accounting for chemical soil composition, irrigation, and management practices…
Livestock	Three types of animals (Dairy, other Cattle and Pigs);	Six types of livestock production: Sows & piglets, pig fattening, Beef cattle, Suckler cows, Dairy cows and turkeys.	Cattle and goats
Livestock yield	Proportionate to stock size, dependant of evolving efficiency of the individual farm agent. Large variations in initial efficiencies, depending on FADN data.	Proportionate to stock size, dependant of the managerial ability of the individual farm agent. The managerial ability gives a variation of ± 10% on the average production. Each livestock activity is implemented in detail with an individual linear programming structure.	Detailed growth cycle and forage composition with impact on yield.
Sales			
Crop prices	External prices	Implemented demand elasticity, and accounting for price trends	External prices
Livestock	Detailed econometric model based on slaughterhouse market power.	Implemented demand elasticity, and accounting for price trends	External prices
Land prices	Double auction market with various actors	Detailed price determination for Bids, based on land shadow prices for the individual farm agent and average regional rent prices.	External prices
Manure market	Double auction market with various actors	External prices	External prices
Innovation and evolution			
Investments	Generic investments to accompany every change in animal stock size.	Empirical list of investment options.	No detailed account of mechanisation Diffusion of innovations through a network, accounting for different groups

			of farm agents according to their propensity to adopt innovations. Innovations in this model are adoptions of new types of crops or animals, no mechanisation.
Subsidies	Generic impact of subsidies by accounting for generalised relation between subsidy amount and different farm structure characteristics.	Linear programming of real subsidy schemes	No detailed account of subsidies
Efficiency evolution	Production efficiencies are affected by investments, allowing learning effects	No evolution in managerial capabilities. Investments alter farm agent growth, and not the production efficiency	Individual efficiency changes through innovation adoption.
Farm costs and financial structure			
Labour costs	Economies of scale, no off-farm labour	Linear relations, off-farm labour included	Seasonal calculation of labour limitations, farm household labour contribution
Specificities	Detailed financial structure	Detailed financial structure	Detailed relation with farm household consumption of produced goods.
Behaviour and interactions			
Decision strategy	Behaviour diversity with five different types of decision routines	Mixed-integer optimisation module, maximising the household income	Linear programming including poverty levels, household consumption, and disinvestments as coping strategies for food insecurity.
Spatial aspects	No geographical representation	farm agent located on theoretical lattice	Farm agent located on theoretical lattice, in first models. Later adapted to include geographical data
Interactions	Interaction through markets	Interaction through markets	No interaction besides network effects for innovation adoption.

The comparison in Table 2-17 reveals that despite the similarities in research objectives, large differences appear in the actual model implementation. Agent-based models display a large level of freedom for the designer, and the practical implementation forces of the model to make choose between including additional complexities and simplification for practical reasons. The choices show the focus and the limitations of each model.

The MP-MAS model has devoted a large effort to biophysical influences and household consumption. The agricultural production is related to the biophysical situation of the land including accounting for mineral stock, water availability and irrigation. The household decision scheme puts a strong emphasis on detailed decisions for own consumption of produced food, and coping strategies in case of food insecurity.

On the other hand, the inclusion of evolutionary adaptation of the farm agent is less developed. The considered investments are the adoption of different crops and livestock. But the growing mechanisation is not included. The undeniable strengths of the MP-MAS model lay in the studies of complex interactions between agricultural evolution and biophysical land characteristics, such as soil fertility degradation or water scarcity. Later improvements of the model have focussed on more detailed biophysical and geographical models. Also the emphasis on household consumption and low mechanisation make the model very appropriate for investigations of agriculture in developing countries.

The Agripolis model displays a strong emphasis on the development of the land market, subsidies and policies, and on the detailed financial structure of the farm agent. Also, the implementation of output prices dependent of the output quantity makes the simulation of complex feedback possible. The investment structure, and production characteristics of the farm agent in Agripolis are very detailed as well.

On the other hand, the innovation possibilities of the farm agent are prescribed. The Agripolis model uses more detailed and empirical data on investment options. But these investment options are based on the current state-of-the-art. This is more precise for short and medium term scenarios. But this also implies that for longer-term scenarios, no new innovation options appear towards the end of the period. Even though the innovation options are externally prescribed, the model incorporates the endogenous decisions of innovation adoption, and learning effects. This makes AgriPolis capable of simulating the effects of growth and innovation.

The Agripolis model is therefore especially appropriate for the explicit analysis of subsidy schemes and their impact on the structure of agriculture over the short and the medium term.

Compared to these established models, the current dissertation does not provide the same level of detail for every aspect. However, there are distinct properties that are absent in the previous models and show where the current dissertation can provide an addition to the scientific literature:

- The detailed price models for the output and land markets. The variability of the output prices is one of the major reasons for farm risk and evolution in the agricultural sector. The detailed models of price determination intend to simulate precisely the feedback mechanisms between agriculture and the demand for agricultural products.
- There are two different endogenous markets implemented as double auction markets. This brings a lot more complexity in the model evolution because auction markets allow different prices for individual transactions and offers or bids that are not fulfilled. There are also several types of actors from different sectors that interact on the same land and the manure market. This allows the detailed simulation of the interaction between agriculture and the other sectors.
- This model is the first model to implement behavioural diversity. The applied framework for behavioural diversity allows a divergence from the standard household income maximisation for each farm. The optimisation procedure is also more detailed, distinguishing between strategic and incremental decisions. The calibration to real historic evolutions gives additional insight to the importance of different types of decisions and types of behaviour of the farmers in Flanders, and this additional insight is then included for the simulation of the future scenarios.
- The model incorporates the effect of innovation. The generic innovation capacity of the individual farmer allows a simulation of the effect of innovation over longer time periods. Longer term scenarios should allow the possibility for continuing innovation efforts, even if the specific nature of the future innovation is not yet known. The generic implementation of innovation at farm level allows for this simulation of innovation over longer time periods.
- Finally, the implementation of innovation in a related sector is entirely novel. These actors of technological innovation in manure treatment have direct access to the same markets as the farm agents, simulating the interaction with agriculture in detail.

Different parts of the model have been calibrated in order to approximate the real situation. Each calibration is an application of the partial model to real-life data, and this leads to a better understanding of each particular aspect in the model dynamics. The calibration of the initial

model population led to a representative sample for the construction of the farm data. The calibration of the behaviour types unveiled the existence of important resistance to change in the agricultural sector. Finally the calibration of the land market showed that the influence of the other actors on the land market is highly influential for the evolution of the land prices.
The first remark following these calibrations, is that heterogeneity is shown to be important. The large variety of reference farms that is necessary to replicate the total population, shows that the sector cannot be dissociated in several specialised subsectors. There are a large variety of mixed farms that work on several markets at once. Also the same variety is not entirely represented in the FADN data. The monitored data from the network present a markedly higher production efficiency than the sector average. The calibration method attempts to provide a remedy for this difference. But it comes with a cost that the modelled number of animals is significantly less than in reality. Also, a large group of retired farmers with very small acreages cannot be included in the total population either.
A second remark is that these calibration reveal resistance to change. The behaviour analysis hints in this direction by showing that a significant proportion of the farm agent population does not adapt its farm structure following the market prices. The steadily increasing land prices also results from a growing excess in demand for land, and this implies that despite this large land demand, farm agents are not very willing to sell, notwithstanding the high value. The analysis of the slaughterhouse market showed market power in favour of animal farmers, despite the low profitability in the sector. This market power in the animal market may also result from overproduction and from an animal stock that has not adapted to the prevailing animal prices. All these barriers to quick adaptation are integrated in the simulation of the future evolutions of the agricultural sector.

The comparison of the present model with Agripolis and MP-MAS shows that the strengths of the present model are the diversity in behaviour and detailed behaviour rules, the generic implementation of innovations, and the interaction of agriculture with related sectors. The model is designed to investigate the influence from other sectors on agriculture, taking the particularities of farmers' behaviour into account. External actors influence the agricultural sector through market interactions. In this case, the influence is exerted by the rapidly changing sector of manure treatment companies. The description of these technologies, as well as the models of the technological innovation are developed in the next chapter.

Economic progress, in capitalist society, means turmoil. […] These new products and new methods compete with the old methods not on equal terms but at a decisive advantage that may mean death to the latter.

J. A. Schumpeter (1942)

Chapter 3 Manure treatment technologies and agents

This chapter collects all essential parts to describe and evaluate manure treatment technologies, and to build a simulation module of each technology.

The chapter starts in the first section with a short description of the different technologies, their inputs and outputs, their performance and current development stage. The second section explains the architecture of the manure treatment agent in the model, including the effects of innovation. The full module also includes a detailed model of the effects of innovation. An evolution of the sector is simulated independently of the agricultural sector to clarify the dynamics of the manure treatment agents.

3.1 The current manure treatment sector

Manure is an important by-product of livestock production. In regions with high animal density, such as Flanders, the annual production of animal manure can cause large environmental impacts, such as higher nitrate and phosphate concentrations in soil and groundwater. Following European constraints for the protection of ground and surface water quality, Belgium implemented stringent and complex manure processing regulations. Figure 3-1 illustrates the manure flows in 2011 in Flanders, where detailed figures are available for the different disposal and treatment methods (VCM, 2012; VLM, 2012a). The figures are expressed in tons of nitrogen contained by the manure. The main part of the manure is produced by cattle and pigs. Most of the untreated manure is spread on agricultural land. This spread of raw manure on land is being restricted and heavily regulated. Therefore, alternative treatment methods for manure are required to reduce the total quantity of the manure in this region. Currently, various methods are used to dispense of the manure, providing an alternative to land spreading. A small proportion is directly exported as raw manure. At the moment, most of the treatment happens with traditional technologies, such as biology or composting. Other methods are especially designed to reduce weights and volumes of the manure, in order to reduce export costs. Most export happens after treatment.

The most applied technology at the site of the farm is biology treatment (Lens et al., 2001; Verstraete et al., 1977). In 2012, about 60% of the installations were based on the biology treatment of the thin fraction of manure (VCM, 2013). More centralised solutions apply composting or chalking. These installations have on average a larger capacity, and account for 12% of the installations, but over 40% of the treated manure in Flanders. Other existing technologies apply drying and pelletisation, or the transformation of the thick fraction in substrate for mushroom cultivation.

The common feature of these traditional treatment methods is that they transform manure into disposable waste flows, or in fertilisers, such as K-fertiliser or compost. Outputs of higher value are not produced with these methods. The innovative methods mostly focus on the production of added value, rather than on the reduction of the pollution from manure.

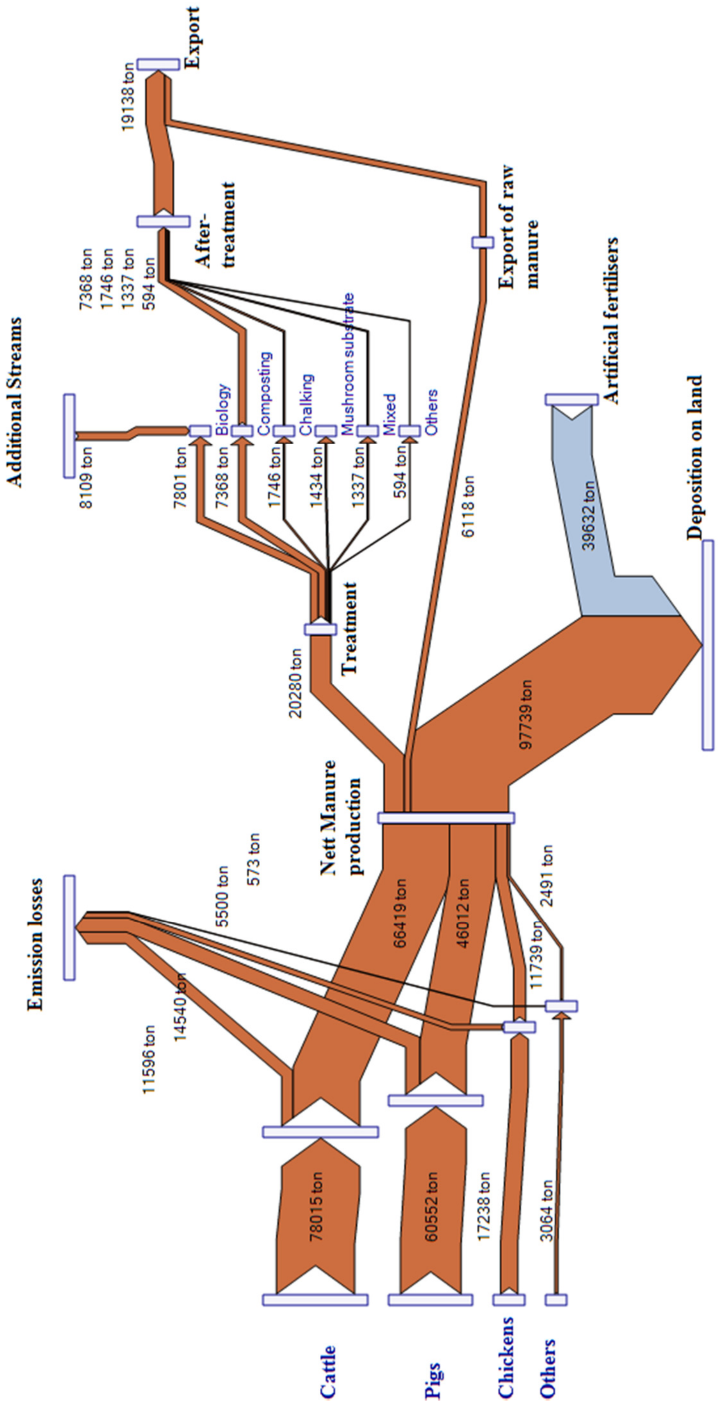


Figure 3-1 : Representation of manure flows of 2011 in tons of N in Flanders.

Several new technologies for manure treatment are under development. Six technologies are not mature yet, but are close to reach the industrialisation stage in Flanders. These technologies are based on constructed wetlands, reverse osmosis, the cultivation of micro-algae, duckweed culture, larvae breeding and pyrolysis.

The constructed wetlands are the only new innovative solution that does not directly provide a valuable output. The main purpose of the wetlands is to purify water or digestate to an acceptable level for disposal, with a minimum of cost. These systems have now been installed in three installations (Meers et al., 2008). The solution has shown significant benefits for local biodiversity (Boets et al., 2011).

The second innovative method to treat manure at farm level, is reverse osmosis. This filtration technique extracts a concentrate with high nutrient content from the manure, creating a valuable fertiliser, and facilitating the disposal of the remaining elements in manure. There is a growing experience with this technology (Masse et al., 2007; Mondor et al., 2008), and the number of practical applications is growing (Hoeksma et al., 2011b).

A third solution is the cultivation of duckweed, based on a circular raceway pond in open air. The pond is fed with moderate quantities of the thin fraction of manure, and duckweed is regularly harvested to maintain the optimal growth conditions in the pond. The cultivation of duckweed requires less specialised equipment. The duckweed can be sifted out of the water and once rinsed, can be added to the diet of the animals. This makes duckweed cultivation a practical approach, creating a closed mineral cycle. It also connects manure, a waste stream from livestock production, directly to the production of nutrition for the same livestock. A schematic representation is shows in Figure 3-2.

A fourth method is similar and based on the production of micro-algae. The production of algae on the thin fraction of manure is more demanding in terms of infrastructure and equipment. Micro-algae are grown on a diluted thin fraction, also in an open raceway pond, similarly to duckweed production. But the extraction of the micro-algae from the water requires more expensive centrifuges. The algae can be sterilised and used for fodder production, but also the use for bioenergy or biofuel is possible. However, the contents of the thin fraction of the manure are not precisely known. Chemical pollutants can be present in the thin fraction, and this uncertainty is the cause that the production of higher value outputs from the resulting algae, such as food additives or pharmaceuticals, is not possible.

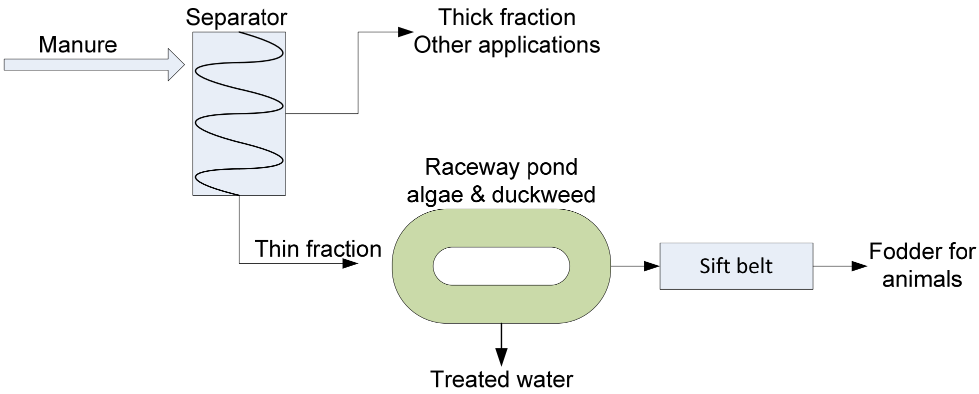


Figure 3-2 : Schematic process flow for duckweed cultivation at the farm

More precise compositions of the feedwater for the algal pond can be obtained by combining reverse osmosis with algae production. The reverse osmosis delivers a clarified liquid fraction of the manure that is better suited for algae growth. The cultivation of the algae themselves can then be done in an open raceway pond, or in closed bioreactors (see Figure 3-3).

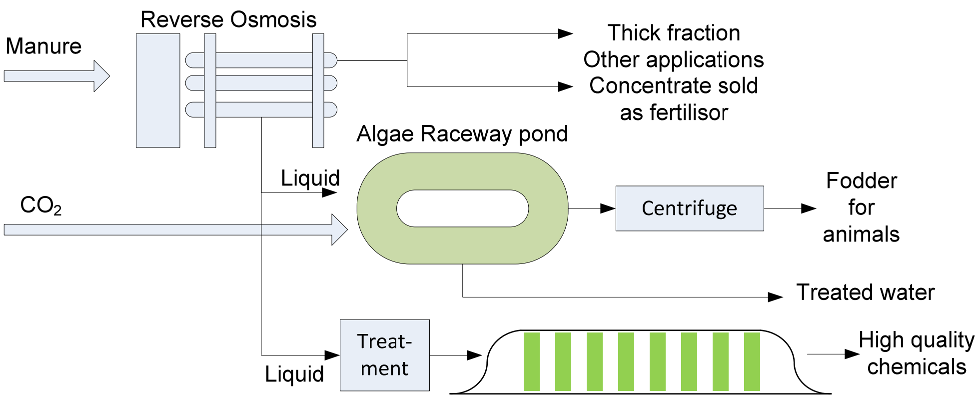


Figure 3-3 : Schematic process flow for micro-algae production from reverse osmosis liquid

Especially the closed bioreactors can provide better protection against contamination of the algal cultures, and can therefore be the base for higher value outputs.

A fifth pathway is the cultivation of larvae on the thick fraction of manure. The interest in this approach has been increased by the development of new uses of larvae. These can now be transformed in biofuels, specialised chemical bulk products and animal feedstock. This process is only at its early stages of development (Li et al., 2011; Myers et al., 2008), and can therefore not be included in this analysis.

Finally, the pyrolysis is the only thermo-physical process considered. Pyrolysis heats the organic inputs in an oxygen-free environment. The heat causes the organic matter to dissociate into three groups. The gaseous substances form a combustible biogas, the liquid phase forms a thick fuel, and the solid phase is extracted as ashes or char. The three phases each provide added value. The pyrolysis process can modulate the weight percentages attributed to each phase by modifying process speed and temperatures. A part of the outputs, mostly the biogas and a part of the fuel, are required again as an energy input to keep the process going (Thewys et al., 2008). The flexibility of the process allows the integration in larger treatment plants, and also the inclusion of streams with variable organic compositions, such as manure (Van Dael et al., 2014). The valuable outputs are the remaining biofuel and the solid biochar. Biochar has multiple uses, for soil improvement (Sohi et al., 2010), carbon sequestration (Lehmann et al., 2006), but also for cleantech and remediation technologies (Cao et al., 2010). This makes the biochar a commodity with increasing value.

The five types of traditional manure treatment technologies, complemented with the four innovative technologies, leads to nine types of technologies that are included in this analysis. These types are listed in Table 3-1.

Table 3-1: Manure treatment technologies

	Process name	**Maturity[1]**	**Fraction**
1	Reverse Osmosis	Experimental	Entire mass
2	Biology treatment	Mature	Liquid
3	Constructed wetland [2]	Experimental	Liquid
4	Drying	Experimental	Dry
5	Composting	Mature	Dry
6	Quicklime	Mature	Dry
7	Algae production [3]	Innovative	Liquid
8	Duckweed production	Innovative	Liquid
9	Pyrolysis + drying + RO	Innovative	Entire mass

[1]: Mature technologies are applied at this moment. Experimental technologies are installed in test pilots and experimental full-scale applications. Innovative technologies are still under development.
[2] : The constructed wetland is here an addition to a biology treatment
[3]: The algae production is an addition to a reverse osmosis filtration.

3.2 The manure treatment agent in the ABM

The manure treatment agents in the agent-based model (ABM) are set up as service providers to the agricultural sector. Each treatment company is specialised in one particular technology only, and develops and refines this technology over time. These treatment companies have other individual characteristics besides the specialisation in technology, such as a specific research strategy, and an amount of own capital at the launch of the company. A treatment company creates treatment projects. The treatment company is able to use personal funds and loans to finance a project for a manure treatment installation. This project is launched when the treatment company foresees a sufficient return on investment for these projects.

The result is a structure with two levels. There is a level of parent companies of different sizes, ages and specialisations. And there is a second level of manure treatment projects, each depending on one particular parent company, as illustrated in Figure 3-4.

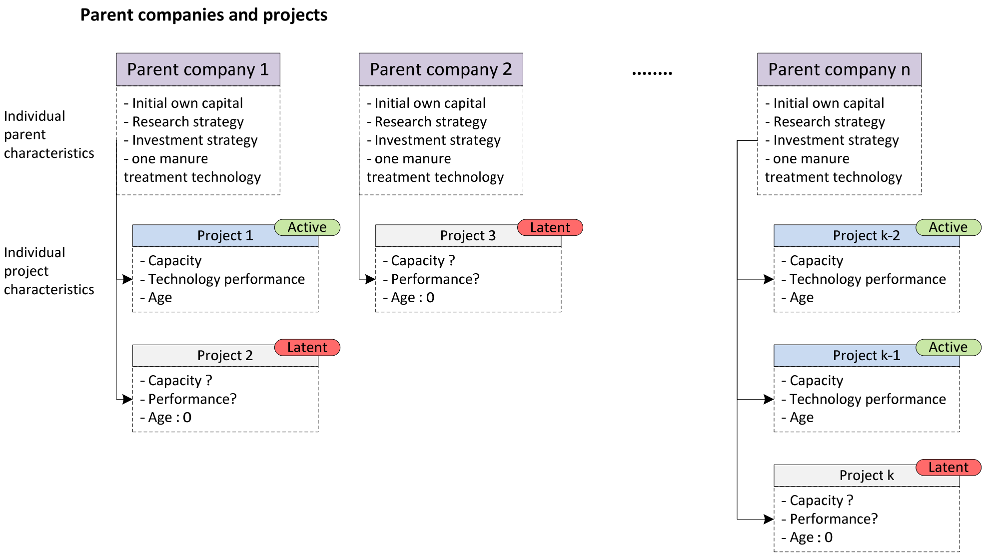


Figure 3-4 : Double-levelled structure of manure treatment parent companies and projects

The treatment projects are the active agents in the ABM that are responsible for the manure treatment. The project has a defined manure treatment capacity, and deals on the manure market to obtain its input. Each project is launched by one parent company only. At the moment of the launch, the treatment project obtains the most advantageous technology characteristics that the parent company can supply. The central unit for each treatment technology is the installed capacity, expressed in tons of manure annually treated. Because none of the discussed methods use combined agricultural waste flows, this capacity also determines the annual input of organic matter in the treatment centre. All other variables are related through economic or physical relations, as illustrated in Table 3-2.

The parent company starts without any active manure treatment project. The company continuously invests in research for technology improvement. When the market circumstances and technology characteristics allow, a manure treatment project is launched. Over time, a parent company can be leading several manure treatment projects simultaneously.

A parent company always keeps one project in a latent state. This latent project is not launched yet, the final capacity has not yet been decided, but its viability is constantly surveyed. When the project is foreseen to be profitable, it is launched at its optimal capacity, and a new latent project is created for the company.

3.2.1 Overall model structure

Figure 3-5 shows the different steps taken by the technology agents. Following the two-levelled structure between parent companies and technology projects, the model creates two simultaneous annual cycles, one for each level. At the start of the model, Parent company agents are created. These agents check for new investments, and initiate technology projects when the situation allows it.

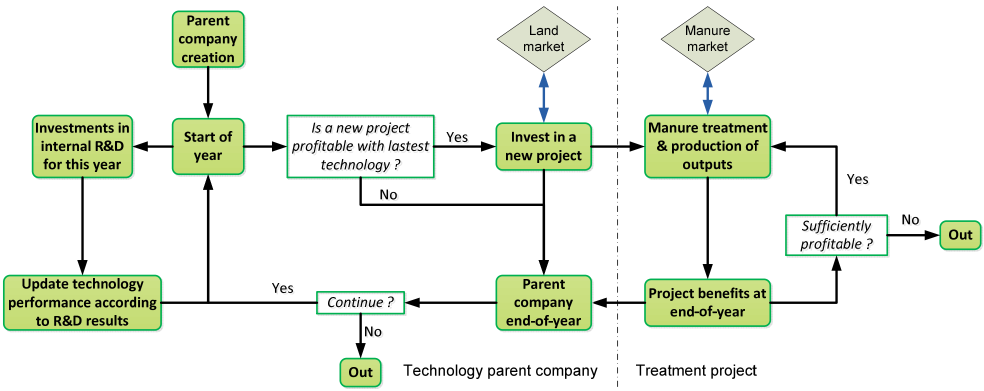


Figure 3-5 : Model steps for the technology agents

This initiation steps is actually the agent creation step for the technology project agents. Once these are created, they can start buying manure, and treating it. At the end of the year, the profitability is checked and it is decided whether the project continues.

At the same time, the annual balance and result of the parent company is calculated, incorporating the gains or losses from their technology projects. This leads to the continuation decision of the parent company, and launches the start of a new year.

3.2.2 Annual costs and benefits

Similar to the construction of the farm agent, the manure treatment agent in the ABM is based on a simplified accounting structure. This structure gathers costs and benefits, and determines the annual cash flow to determine the chance for survival. In the double levelled structure, costs and benefits are incurred both at the level of the parent company and at the level of the project. All costs and benefits from projects belong to the accounting structure of the parent company. There is no separate accounting for each project.

- Costs incurred at the level of the project :
    - Recurrent costs
        - Wages for labour
        - Annual costs (for maintenance, electricity etc...)
        - Transportation costs
        - Payment for inputs (especially manure, but also chemicals etc…)
    - Financial costs for the project loan
        - Interest payments
        - Capital reimbursements
- Benefits obtained at the level of the project :
    - Recurrent income
        - Sales of valuable outputs
        - Subsidies

The net benefit from the projects is directly transferred to the parent company.

- Costs incurred at the level of the parent company :
    - Recurrent costs
        - Wages for research and development
- Benefits obtained at the level of the parent company :
    - Recurrent income
        - Net benefits from all owned projects
        - Subsidies
    - Benefits from structural changes
        - Sales (+) or purchases (-) of farm acreage

The research efforts of the parent companies result in innovations and in gradually improving characteristics of the manure treatment technologies. The way to model these innovations is the most defining aspect of the evolution of the manure treatment sector.

3.2.1 Manure treatment technology characteristics

To simulate the activity of technological projects, estimation rules have to be set up for all costs and benefits at the level of the individual project. Each manure treatment project uses economic inputs, such as capital and labour, but also material inputs, such as manure, energy or agricultural waste streams. This leads to matter-based outputs, (fertilisers, feedstock, additives, fuels …) that simultaneously have a physical and economic value. Both dimensions will have to be followed during the evolution. The estimation rules for all costs and benefits are based on the central physical dimension of the technology project, being the maximum manure treatment capacity in tons per year (*Cap*).

The combination of both types of inputs, and more precisely the parallel modelling of the physical and economic dynamics, is regularly included in models of environmental economics, but rarely in evolutionary settings. However, this combination of physical limitations and economic dynamics can be helpful in improving the robustness of agent-based evolutionary models. The robustness of these models is challenged by the high quantity of degrees of freedom. But the inclusion of physical dimensions results in more relations and real-life physical restrictions that improve the overall robustness of the model (Faber et al., 2009).

The estimation rules are preliminary approximations of real costs and benefits. The high uncertainty is logical for an undeveloped sector. The primary interest at this stage is the distinct economic interactions of different groups of technologies. Five potential productive inputs are considered: capital, energy, manure, labour, and land. The technologies use these inputs in a very different way. Thermo-physical transformations of manure, such as drying or pyrolysis, entail mostly high investments and high energy costs. But they require relatively less labour and land. Traditional technologies such as composting are relatively labour intensive. The technologies that are based on the activity of photosynthesis require high land and labour inputs. This is the case for constructed wetlands, duckweed or algae. There are technologies with an optimal capacity at the initialisation of the model that is very large, such as pyrolysis, others have much smaller optimal treatment capacities, such as duckweed.

Finally, technologies that do not require land inputs in this case can be integrated in industrial areas, and do not increase pressure on agricultural land, such as pyrolysis or drying. So this diversity makes for a range of technologies that will also display a different behaviour under changing market circumstances.

Table 3-2 reports the relations between the capacity of the treatment facility and different required inputs. The central parameter for calculation is the manure treatment capacity of the project, *Cap*, expressed in tons per year. Costs for investments, maintenance, energy use, labour and land use are derived from *Cap*.

These figures are based on various preliminary estimations of future costs and benefits of these technologies. Some of the inputs are based on technical reports (de Hoop et al., 2011; Hoeksma et al., 2011a; Kimball et al., 2011; Lemmens et al., 2007). Others are based on techno-economic analysis of individual projects, being the only source of information at this moment; as large-scale sites do not exist yet. The tables illustrate an initial performance of the technology. Under current market circumstances without any financial support, most of these technologies are not profitable. Even if the manure achieves negative prices on the market, the innovative technologies are often unprofitable with the presented economic performances. The outputs of the different technologies are illustrated in Table 3-3 as weight percentages of the manure input.

Table 3-2: Characteristics of costs for manure treatment technologies

	Investment $I = a\ Cap^{\alpha}$ [EUR]		Horizon [year]	Annual cost[1] [EUR/y]	Energy use[2] [MWh/y]	Labour $L = a\ Cap^{\alpha}$ [FTE/y]		Land use $LU = a\ Cap^{\alpha}$ [m²]	
Process name	a	α		A	a	a	α	a	α
Reverse Osmosis	394	0.747	10	2.0	0.016	0.0151	0.3	0	0
Biology treatment	615	0.7	15	0.89	0.014	0	0.0	0.083	1
Constructed wetland [3]	650	0.7	15	2.40	0.014	0	0.0	0.458	1
Drying	794	0.7	20	6.4	0.018	0.0017	0.6	0	0
Composting	83	1	20	2.5	0.030	0.0009	0.8	0	0
Quicklime	2612	0.6	20	12.5	0.000	0.0039	0.6	6.5	0.6
Algae production [4]	793	0.7	20	2.5	0.042	0.0065	0.5	3.3	1
Duckweed production	623	0.7	20	1.0	0.042	0.0027	0.6	3.3	1
Pyrolysis + drying + RO	2999	0.7	20	3.2	0.059	0.0079	0.6	0	0

[1,2] : Annual costs and energy costs are proportionate to the capacity
[3] : The constructed wetland is here an addition to a biology treatment
[4]: The algae production is an addition to a reverse osmosis filtration.

Table 3-3 : Outputs as weight fractions of the input

Process names	Output 1		Output 2		Output 3		Output 4	
	Type	W%	Type	W%	Type	W%	Type	W%
Reverse Osmosis	Thick fraction	0.1753*	Permeate	0.4399	Distillate	0.3849		
Biology treatment	Digestate	0.6379*						
Constructed wetland								
Drying	Dried manure	0.4556*						
Composting	Compost	0.3000*						
Quicklime	Compost	0.5000*	Fertiliser	0.0500				
Algae production	Algae (in t DM)	0.0033*						
Duckweed production	Duckweed (in t DM)	0.0033*						
Pyrolysis + drying + RO	Char	0.0213*	Permeate	0.4399	Distillate	0.3849	Heavy oil	0.0243

* Primary output

The transportation cost has not been integrated in Table 3-2. This is the main cost counters the economies of scale. All the manure that is to be treated in the facility has to be transported to the gate. This assumes that the receiver has to pay for the manure transportation. In this case the transportation costs are approximated. Based on analysis of manure transport to regional biorefineries (Maes et al., 2015) it can be concluded that the transportation distance can be estimated in function of the total manure quantity. One can assume a relatively evenly distributed availability of manure in the region. The treatment facility transports then the total quantity of manure from within a circle around its location. The average distance to be travelled by the manure is a direct function of the total quantity required.

$$d = 0.0230\ Cap^{0.6}\ \text{[km]} \quad (14)$$

A perfectly levelled availability of manure over the entire region would result in a power factor equal to 0.5. Assuming that the facilities choose a favourable location within a local area with higher availability of manure, leads to slightly higher power factors, such as 0.6 in this case. The regional transport cost is estimated at 0.22 EUR/km.tonne.

3.2.2 Creation, effects and diffusion of innovations

Further technological development is necessary before the majority of the manure treatment technologies will be mature enough to deploy on the market. With innovation and improved application, these technologies can become profitable, and should then emerge on the market. This requires a continuous innovation in the sector of manure treatment.
Innovations in this sector can be created by small improvements, by additional extractions of new outputs, by advances in market creation and by radically new technologies. For instance, there is substantial research in the crystallisation struvite in manure, in order to recuperate phosphorous compounds (Münch et al., 2001; Shu et al., 2006). There is also a long tradition in the digestion of manure for the production of biogas (Amon et al., 2007; Weiland, 2010). Both processes do not result in the total treatment of the manure. The output is a digestate or modified composition of the manure that still requires a form of treatment before it can be disposed of. But these processes extract an additional valuable output from the manure, and can therefore be critical to ensure the overall profitability of the combined manure treatment. The combination with extraction processes is only one option. Many traditional and innovative manure technologies provide the potential to be combined in different structures. Pyrolysis for instance is already based on pre-treatments with reverse osmosis and drying. But also combined production of algae and duckweed is theoretically possible, or the use of composting in the pyrolysis chain. Numerous combinations are possible, and if additional new technologies enter the manure treatment sector, the number of potential combinations will only increase. The search for optimal technology combinations can provide several innovative breakthroughs.

In this sense, it is important to determine the points in the production model that are affected by innovations. Van den Bergh (1999) distinguishes between the potential effect on production efficiency in physical units and on the value of the output in economic terms. New production technologies can improve the yield of valuable materials, thereby increasing the efficiency. However the market value can be improved as well, by new technologies that improve output quality, or by advances in product marketing. In this specific case, a third important point has to be added. Most models of innovation and industrial change incorporate the innovation in the production process (Dosi et al., 2010; Fagiolo et al., 2003). But in this case, the technologies are also replicated in consecutive new projects. Over time, the manure treatment company can decide to invest in new projects applying the latest version of their technology. Therefore, the third point that is modified by innovation is the investment cost for new projects. New developments can markedly decrease the unit cost of the investment.

The literature on innovation and industrial change displays a large range of models (Dawid, 2006). The issue of innovation and its importance for economic growth has multiple aspects. Specific agent-based models have been applied to increase the understanding of these dynamics. The influence of networks has been simulated, for instance to investigate spill-over (Pyka et al., 2009) or network configurations (Schön et al., 2012). Also the negative effect of innovation on incumbent actors has been simulated (Beckenbach et al., 2011). Other studies analysed the effect or even the necessity of innovation for the creation of endogenous economic growth (Saviotti et al., 2004). Empirical research had shown the dilemma of companies confronted with the choice between innovation exploitation or the search for new innovations (Greve, 2007). This effect has also been investigated closer by means of an appropriate model (Fagiolo et al., 2003). In a related investigation, Dawid (2005) explores the effect of company strategies, depending on their focus on innovation, profit or growth. These models have shown to present more closely than neoclassical models some empirical features of innovation. Malerba (2001; 2008; 2002) even developed a strict modelling approach that allowed the replication of historical industry evolutions. But even if these analyses are very diverse, still more aspects are observed that are still to be integrated in new modelling approaches, such as the dynamics of company knowledge build-up for innovation, and the decay of innovation capacity with reducing rates of exploration (Greve, 2007).

Many of the intricate aspects of innovation have to be simplified in this case. The evolution under investigation has little empirical data, as it is a very new sector. So the simulated dynamics should present a general effect of innovation. Also the effect of creative accumulation, being the imitation of winning technologies by large incumbent firms (Bergek et al., 2013), is not applicable here, because there are no large incumbent firms in this emerging sector at the moment. The relationship between innovation in an industrial sector and university research can also be important to speed up the emergence of new solutions, especially because the collaboration increases the overall innovation capabilities of the actors (Ahrweiler et al., 2011). However, in an attempt to structure the main influences of innovation in this case, we can revert to the standard sector taxonomy of Pavitt (1984). According to this taxonomy, agriculture obtains most of its innovations through its suppliers, and the rate of internal innovation is low. The manure treatment sector is the supplier of innovation in this case, and this sector can be characterised as specialised, production–intensive suppliers of mechanical and instrument engineering. This particular group of companies produce innovations mostly internally, to be used in other sectors. This means that there can certainly be interactions between manure treatment companies and university research centres, but the main source of innovation is internal. In a first application it is not required to include the effect of external research.

The success in R&D depends strongly on the innovation models in the sector. The type of innovation varies in this sector. Empirical investigation shows that the growth of the biobased sector has singular characteristics. The origin of the biobased research is in health applications and this explains a strong prevalence for business models based on closed innovation such as patenting and research confidentiality, even if this is less common for applications outside of healthcare and if this makes the business less adaptive (Cooke, 2013). However, new business models are gradually created (Iles et al., 2013), and open innovation structures are also increasingly adopted (Fetterhoff et al., 2006; Gassmann et al., 2010; Vanhaverbeke et al., 2006). The research interest in open innovation has also grown during the last decade (Gassmann et al., 2010; Huizingh, 2011). The advantages of open innovation for individual firms have been highlighted (Laursen et al., 2006; Vanhaverbeke et al., 2008). Empirical studies show a rise in open innovation models in biotech sectors (Bianchi et al., 2011). Also increased knowledge sharing has been linked to higher absorption capacity of firms and higher innovation success rates (Liao et al., 2007).

Next to the innovation structure, the emergence of innovative technologies is also influenced by effective policies. Adapted policies and stimulation from public entities are important to enable the uptake of new biotech technologies in the economic structure. Many types of collaboration include public partners or gain support by means of public funding. Other aspects of innovation dynamics can be influenced by policies as well, such as competition policy, network creation, education strategies, or regulations and standards (De Jong et al., 2008). However, stimulation policies are always to some degree selective with respect to technologies (Azar et al., 2011). Policies can therefore unwillingly contribute to the creation of lock-in (Safarzyńska et al., 2010) as well as to its prevention (van der Vooren et al., 2012). Technological lock-in refers to a rigid state which keeps the economy dependent of a suboptimal technological system (Unruh, 2000). A diverse set of technologies increases the swift adaptability of the future economic structure, and avoids future this lock-in (Simmie et al., 2010).

3.2.3 Modelling the effects of innovation

The innovation model is required to include innovations in production efficiency, product value, and investment price. Also, both new internal innovation breakthroughs and diffusion of innovations from other agents should be accounted for. This will allow the model to simulate the effect of different stimulation policies on the innovation dynamics.

The most practical approach for this situation is to base the simulation on the classic model established by Nelson and Winter (1985). This model simulates a group of related companies, accounting for innovation and imitation in a competitive market environment. Market effects will also be integrated in the approach, as all the companies will be in relation with the markets for manure and land, established for the farm agents.

The agent for the manure treatment company simulates innovations at three locations: the physical production efficiency, the output value and the investment price for new projects. For each of these three variables, the value can evolve over the years.

If M_t is the total quantity of manure taken in by the manure treatment company, then the physical output is Q_{1t}, measured in tons:

$$Q_{1t} = f_{at} w_1 M_t \quad (15)$$

The increasing factor f_{at} captures the increasing physical production efficiency of the technology. The weight factor w_1 is the weight proportion of output 1 that is produced per ton of input, according to Table 3-3. In case of multiple outputs, Q_{1t} is the primary output, being the output that contributes most to the total turnover of the company, as indicated in Table 3-3. In case of production of multiple outputs, the corresponding production efficiency of the other outputs is reduced accordingly for output 1, in order to remain coherent with physical restrictions.

In economic values, the obtained sales price for the output can be changed as well:

$$p_{1t} = f_{bt} p_t^{Ind} \quad (16)$$

Here, p_t^{Ind} is the average market price for output 1. The factor f_{bt} presents the increase in output value compared to the average market price. It captures the benefit of the additional product quality that can be obtained with new production technology.

Finally, the investment price for new investments is

$$I_t = f_{ct} I_1 \quad (17)$$

I_1 is the investment price per unit capacity for the technology in year 1. The decreasing factor f_{ct} captures innovation in technology machinery that allow the same capacity to be treated with innovative and less expensive machinery.

The three factors f_{at}, f_{bt} and f_{ct} reflect the result of internal innovation and imitation from competitors simultaneously.

$$f_{it} = \max(f_{it-1}, g_{it}\widetilde{f_{it}}, h_{it}\, \mathrm{f}_{\mathrm{it-1}}^{\mathrm{max}}) \text{ for i : a and b} \quad (18)$$

$$f_{ct} = \min(f_{ct-1}, g_{ct}\widetilde{f_{ct}}, h_{ct}\, \mathrm{f}_{\mathrm{ct-1}}^{\mathrm{min}}) \quad (19)$$

The factor g_{it} is either 0 or 1, indicating a failure or success in innovation. The factor h_{it} is either 0 or 1, indicating a decision to purchase a license for the technology of competing company. The factor $\widetilde{f_{it}}$ is the effect from an innovation breakthrough at the individual firm. The factor $\mathrm{f}_{\mathrm{it}}^{\mathrm{max}}$ is the maximum effect over all firms which apply the same technology. When h_{it} is equal to unity, the firm buys a license to apply the top efficiency that is available for its technology. This decision is taken by comparing the license cost with the marginal benefit that can be derived from the new production efficiency. The factors g_{it} is based on a probability function dependent on the investment of the firm in their search for innovation.

$$Prob(g_{it} = 1) \sim \gamma K_t^L \quad (20)$$

Here, K_t^L is the total of liquid assets of the firm. The probabilities that g_{it} is equal to unity, is proportionate to γK_t^L, being the amount invested in innovation search. The investment is determined by the firm-specific value γ. This implies that the company invests a fixed percentage of its liquid assets in research and this is a fixed company strategy. The value is firm-specific, so this also indicates strategy diversity in the sector.

The innovation factor $\widetilde{f_t}$ is also firm-specific and drawn from a random walk with drift. The distribution of $\log(\widetilde{f_t})$ is $N(\mu + \delta C_n, \sigma)$. Here, C_n is the total accumulated amount that the company has invested in R&D over time. This amount is used here as a proxy for the accumulated R&D experience of the firm. The higher the R&D experience, the faster efficiency breakthroughs can be achieved. The variables determining this distribution, μ, δ and σ, are determined by each technology. Some technologies have a longer history of applications on the market and have reached maturity (ex. composting, chalking or to a lesser extent drying). Whereas other technologies (duckweed, algae, or pyrolysis) still present a large range of potential incremental improvements. This is reflected in the value of δ, where a higher δ indicates also faster increases technology improvement, as reported in Table 3-6.

It has to be noted that this application has some particular differences compared to the model of Nelson and Winter (1985). First, the probabilities of success in R&D depend here on K_t^L, the total of liquid assets of the firm. The original model bases this probability on the total capital stock. Many variables of the original model are based on the capital stock, such as the production or growth. In this case, the distinction with liquid assets has been made to reflect closer the real availability of funds for R&D. Actual investments of parent companies in treatment installation still account for the total capital stock, but as fixed assets, and as such these are no longer available to be invested in research. Also there is no direct reason in this case to assume proportionality between the total amount of capital, including fixed assets, and the total amount invested annually in R&D.

Secondly, the innovation factor $\widetilde{f_t}$ is here distributed as $\log(\widetilde{f_t}) = N(\mu + \delta C_n, \sigma)$. In the original model the distribution is $N(\mu + \delta t, \sigma)$. This means that the innovation speed is constant over time, and the potential for higher breakthrough efficiency grows linearly every year. It is more appropriate in this case to relate the speed of innovation to the accumulated knowledge that the firm has gathered over the years. This accumulated knowledge can best be approximated by the total amount that the firm has invested in R&D over the years, C_n. This particular difference also relates to the choice of assuming the majority of the innovations to be based on internal R&D in the sector, and not on continuous research outside of the sector.

Thirdly, the division between the parent companies and the projects gives a larger inertia to this model. In the original model, whenever an innovation was successful, the improved efficiency was applied in the production of the firm. In this case, existing treatment plants cannot automatically replicate new efficiencies obtained at the parent company. This is not possible in practice either. A parent company launches a treatment project, and continues to investigate and refine the technology. When new solutions are found, these cannot be applied directly to the existing treatment plants. This would require new investments, and would render the existing installations partly obsolete. In order to apply the new efficiencies in practice, a new treatment plant has to be created. The original model could be applied for instance to finance or service sectors, where fixed assets investments are not so preponderant for the practical application of new inventions. In this industrial sector, each treatment plant is based on specific machinery, and there are each time new investments in fixed assets necessary for the industrialisation of the new inventions.

Finally, the last difference is that the original model accounted for innovation and imitation simultaneously. In this case, both effects have been separated, and imitation of good practices is implemented with the possibility of licensing.

3.2.4 Starting variables

There are three elements that are unique for each individual parent company. The first is the variable γ that determines the proportion of the money invested in innovation and the innovation speed. The second unique element is its initial capital. The third individual determinant of the parent company is its judgment on the future manure prices. When considering investments, the parent company makes a forecast of the future benefits of the manure treatment project. Prices are kept fixed in this forecast, but the manure prices are expected to rise considerably over the coming years. This is a conservative, protective assumption. The companies differ in their optimism towards estimating this effect. The estimated manure price trend is distributed over all companies with a lognormal distribution N(15%, 0.075).

The exact values of the variables have to be assumed at the start. In order to remain traceable, there is only a distinction made between three types of technologies according to their maturity. The variable set [γ, δ_q, δ_P, δ_I] depends on the technology type. Parent companies with more mature technologies invest less in innovation, contrary to the companies specialised in more innovative technologies. At the same time, experimental and innovative technologies are not yet optimised that the moment, so there is a larger chance of finding new breakthroughs. This is reflected in higher values for each of these variables. The γ variables vary between different parent companies, and are normally distributed with the average given in the next table.

Table 3-4 : Assumption of the innovation random walks for different types of technology maturity

Technology type	Technologies	Proportion of R&D investment γ	Increase in production efficiency δ_q	Increase in quality δ_P	Decrease in investment cost δ_I
Mature	Biology, Chalking, Composting.	0.4%	0.5%	1%	-0.3%
Experimental	Constructed wetlands, reverse osmosis, drying	0.8%	2%	3%	-0.7%
Innovative	Algae production, Duckweed cultivation, Pyrolysis	1.6%	3%	5%	-1%

Table 3-5 : The different variables determining the characteristics of each individual parent company, according to the technology

		Research investment (as % of liquid assets) $\log(\gamma) = N(m, \nu)$				Initial capital $\log(Cap) = N(m, \nu)$			
		Av	Stdev	m	ν	Av	Stdev	m	ν
1	Reverse Osmosis	0.8%	0.004	-4.94	0.47	3 200 000	640 000	14.96	0.20
2	Biology treatment	0.4%	0.002	-5.63	0.47	3 200 000	640 000	14.96	0.20
3	Constructed wetland	0.8%	0.004	-4.94	0.47	3 200 000	640 000	14.96	0.20
4	Drying	0.8%	0.004	-4.94	0.47	3 200 000	640 000	14.96	0.20
5	Composting	0.4%	0.002	-5.63	0.47	3 200 000	640 000	14.96	0.20
6	Quicklime	0.4%	0.002	-5.63	0.47	3 200 000	640 000	14.96	0.20
7	Algae production	1.6%	0.008	-4.25	0.47	3 200 000	640 000	14.96	0.20
8	Duckweed production	1.6%	0.008	-4.25	0.47	3 200 000	640 000	14.96	0.20
9	Pyrolysis + drying + RO	1.6%	0.008	-4.25	0.47	3 200 000	640 000	14.96	0.20

Table 3-6 : Characteristics of innovation random walk, according to the technology.

		Initial average	Standard deviation	**Innovation characteristics,** $\log(\widetilde{f_t}) = N(\mu + \delta C_n, \sigma)$								
				Physical production efficiency			Quality increase			Investment cost		
		Av	Stdev	μ	δ	σ	μ	δ	σ	μ	δ	σ
1	Reverse Osmosis	1	0.2	1	0.020	0.197	1	0.030	0.194	1	-0.007	0.199
2	Biology treatment	1	0.2	1	0.005	0.197	1	0.010	0.196	1	-0.003	0.199
3	Constructed wetland	1	0.2	1	0.020	0.196	1	0.000	0.198	1	-0.007	0.200
4	Drying	1	0.2	1	0.020	0.197	1	0.030	0.194	1	-0.007	0.199
5	Composting	1	0.2	1	0.005	0.197	1	0.010	0.196	1	-0.003	0.199
6	Quicklime	1	0.2	1	0.005	0.197	1	0.010	0.196	1	-0.003	0.199
7	Algae production	1	0.2	1	0.030	0.195	1	0.050	0.192	1	-0.010	0.200
8	Duckweed production	1	0.2	1	0.030	0.195	1	0.050	0.192	1	-0.010	0.200
9	Pyrolysis + drying + RO	1	0.2	1	0.030	0.196	1	0.050	0.194	1	-0.010	0.200

At the initiation, not every technology is represented by active parent companies, exactly like in the real situation in Flanders, as illustrated in Table 3-7. These data are based on the annual sector questionnaire carried out by the manure treatment sector platform (VCM, 2012).The number of plants in the population equals the number of installations in reality for each technology. From the innovative technologies, only the constructed wetlands have been realised in a few occasions. Reverse osmosis has been installed in some 10 installations in the Netherlands, but has not yet emerged in Flanders. The other innovative technologies have not yet been applied in practice.

Table 3-7 : Initial population of manure treatment agents, compared with the real situation in 2011 (VCM, 2012)

	Total	Real Situation 2011	Number of parent companies	Number of plants	Capacities		
					Average	Min	Max
	[ton/y]	[ton/y]	#	#	[ton/y]	[ton/y]	[ton/y]
Reverse Osmosis	-	-	-	-	-	-	-
Biology treatment	1 732 900	1 725 146	42	81	21 394	12 300	46 900
Constructed wetland	10 150	10 152	2	3	3 383	3 150	3 500
Drying	36 600	35 775	6	6	6 100	3 600	8 400
Composting	590 000	599 042	8	12	49 167	30 000	70 000
Quicklime	160 000	158 426	3	3	53 333	5 000	80 000
Algae production	-	-	-	-	-	-	-
Duckweed production	-	-	-	-	-	-	-
Pyrolysis + drying	-	-	-	-	-	-	-

3.3 Separate evolution of the manure agents

In order to illustrate the dynamics of the modelled innovation, an evolution of the manure treatment sector is simulated separately from the agricultural sector. This evolution looks at the internal dynamics, without the interactions with the farm agents.

The effect of growing capacity for manure treatment has an influence on the price. The price-demand functions have been determined linearly with the characteristics reported in Table 3-8. The price is determined based on the total demand for manure, of which the demand of the manure treatment sector is only a fraction. The majority of the total manure is the quantity spread on the fields or exported in raw form. For the independent evolution, it is assumed that this other quantity for use on the fields remains unchanged. In this case, the prices only depend on the demand of the sector itself, Q_D. As a maximum, the manure prices are capped at the price of mineral fertilisers, as it is not expected that production companies will purchase manure at a higher price than the mineral equivalent per nitrate content. These market approximation are based on the current market prices (-15 EUR/ton for liquid, and -5 EUR/ton for dry manure). In the case there is no treatment available, the price drops to -25 EUR/ton, equivalent to the price of export.

Table 3-8 : Linear price-demand relations for the independent evolution simulation

$p = {(Q_D + Q_F)}/{E} + p_b$	**Elasticity** E [ton/EUR]	**Baseline** p_b [EUR]	**Fixed quantity** Q_F [ton/y]
Liquid manure	110 000	-109	8 400 000
Dry manure	55 000	-54	1 600 000

3.3.1 Policy scenarios for the manure treatment sector

The emergence of a new manure treatment sector is a small development within the growing bioeconomy. Several progress reports aim to create more precise visions for the bioeconomy. They point out barriers to the development, specify regional advantages and lead to recommendations for policy actions. At an international level, the OECD has been actively involved in policy guidance for the bioeconomy (Arundel et al., 2009) and for the use of biotech in the environment (OECD, 2013). The European Commission also developed a specific strategy to promote the bioeconomy (EC, 2012). National reviews of current developments have also been collected in order to present general directions for policy guidance (Langeveld et al., 2009). On a regional level, the same exercises have been conducted in the Netherlands (SER, 2010; van der Hoeven et al., 2012) and in Flanders (Carrez et al., 2012). Complementary structural analyses have been conducted on very detailed subjects, such as the development of a dynamic market for the trade of manure (Boosten et al., 2011).

The important difference of this type of reports is that they do not prepare long-term scenarios. Scenarios would imply choices in policy instruments coherent with the economic and institutional situation. A scenario is related to future expectations and results in a set of complementary policy instruments. These reports list all potential elements that could contribute to stimulate the bioeconomy, without making those choices. Therefore, the selection and combination into instrument sets has to be done in this dissertation. The general trends and market descriptions from the agricultural scenarios will serve as a guideline for the selection of policy instruments.

The large and diverse list of different instruments that are proposed in the different reports can be categorised in four groups:

- Legal adaptation: Legal adaptation to allow new biobased production processes, creating quality standards to structure markets for biobased products …
- Coordination of initiatives: the proposal reach from voluntary coordination through stakeholder meetings, official bioeconomy panels and observatories, to more strict coordination such as official biobased waste treatment through innovative public tenders, and prescribed contributions to public institutions for biowaste collection.
- Stimulation of private capital: Investment of private capital in new manure treatment can be stimulated through investment support or through public-private partnerships (PPP) in large treatment plants.
- Public support systems: Public support can take the most diverse forms, going from increased university support for targeted research, to subsidies for in-house

development in companies, co-financing of collaboration in international research projects, industrialisation subsidies or volume-based subsidies for sustainable manure treatment.

This leads to four different scenarios for the manure treatment sector that are simulated:

I. "The status quo" The first scenario is the reference to compare the subsequent results with. This scenario assumes no presence of innovative sustainable technologies. The technologies that are currently implemented are the only available technologies, and are listed in Table 3-7. These can benefit from marginal improvements over the years, but new developments are excluded. Specific support for manure treatment installations is equally non-existent. The available capital for new treatment companies is also limited, and financial stimulation is not available.

II. "The independent development": In the second scenario, all technologies are available. Innovation is possible within the technology companies themselves, and this may help to implement profitable installations. However, there is no support strategy from the authorities. The only support is the removal of legal barriers. This implies that new biobased products can be produced legally. But the other support actions – coordination of initiatives, stimulation of private capital, and public support systems – are not present. If the new technologies manage to conquer a share of the market, then this will be only due to internal developments. The most important difference with the reference scenario is the availability of private funds that are invested in new manure treatment companies.

III. "The quantity focus": This scenario is the first where active support of technologies is implemented. In this case, similar to the former scenario, all technologies are available. The authorities remove legal barriers to implementation. In order to promote sustainable production, the authorities stimulate active removal of excessive manure flows, by granting a subsidy per ton manure treated in a new sustainable production plant.

IV. "The innovation focus": This fourth and last scenario is similar to the third. The only difference resides in the type of subsidy granted by the authorities. The scenario "the quantity focus" provides a subsidy per ton manure treated. This scenario provides subsidy for increased R&D activities and industrialisation of new processes. This subsidy strategy is therefore a reimbursement of R&D expenditures at the parent company. It is not linked with actual production of biobased products.

The overview of the four scenarios is given in Table 3-9.

Each form of public financial support is limited in time. Subsidies are granted from 2010 to 2023 only. The strategic behaviour of the parent companies is also altered by the public support schemes. In scenario I and II, the regular strategy of the companies is followed. In scenario III, the focus is on production, so companies devote less to innovation in order to have more money at their disposition for new investments in treatment plants. In scenario IV, the focus is on innovation, so parent companies increase their expenditure in R&D accordingly. This speeds up the emergence of higher production efficiencies.

An important remark is that the behaviour of the manure treatment companies is influenced by the policies. It has been assumed that parent companies react and adapt their strategy according to the stimulation policy. In scenario I and II, no stimulation is available, so the parent companies display their usual behaviour. Their investment strategy in R&D is based on the percentage of available liquid assets that the company devotes to internal R&D. This percentage is unique for each company and remains unchanged over the years. The rest of the liquid assets can be supplemented with loans and invested in new treatment plants.

In scenario III and IV, parent companies change their strategy. In scenario III, because the stimulation policy gives a subsidy per ton of treated manure, the focus shifts to actual implementation of treatment plants and less to internal R&D. The companies reduce their R&D expenditures with 33%, in order to have more assets available to invest in new plants. In scenario IV, the opposite happens. Because the policy supports actual R&D expenditure, the parent companies increase their R&D expenditure with 150%. Even with this increase, they do not see higher expenses, because the total amount of R&D costs is reimbursement for 80%.

For both situation it is also the case that once the support in the policies is stopped, the companies return to their standard behaviour.

Table 3-9 : Differences between the baseline scenario, and the differences in manure treatment support

Affected variables	General trend	Scenarios: I. Status quo	II. Independent development	III. Quantity focus	IV. Innovation focus
Subsidies for agricultural activity	Gradually decreasing subsidies for all activity. All subsidies decline with 3% annually after accounting for inflation	X	X	X	X
Manure spreading regulations	Gradually decreasing limits of manure spreading on fields[2]. Manure spreading limits change every five years: -5% for N and P spreading, +2% for N from animal origin.	X	X	X	X
Availability of new biobased technologies	New technological innovations can be implemented by start-ups.		X	X	X
Legal adaptation for biobased innovations	Legal barriers are removed, and biobased products can be brought to the market.		X	X	X
Availability of private capital	Private funds are willing to invest in the creation of new parent companies		X	X	X
Coordination of initiatives and stimulation of private capital	Increased available private capital for technology start-ups.			X	X
Public support for biobased activity	For scenario "III. Quantity Focus " : Support of 2.65 EUR per ton of liquid manure treated, and 3.65 EUR per ton of dry manure.			X	
	For scenario "IV. Innovation Focus": Reimbursement of 80% of the amount spent on internal innovation at the parent company.				X

[2] The reducing limits for manure spreading apply to N and P limits. The limit of N of organic origin however, is assumed to be gradually increasing and then to be abolished. This is because of the growth of fertiliser products based on manure. With the increased variety of fertiliser products based on organic and fossil inputs, the origin of the fertiliser gets increasingly difficult to determine. The spreading limit on N from organic origin becomes therefore very difficult to control in a biobased economy.

This model is based on empirical data, in order to remain close to the real situation. The simulation starts from the current situation in Flanders, including all present manure treatment companies and technologies.

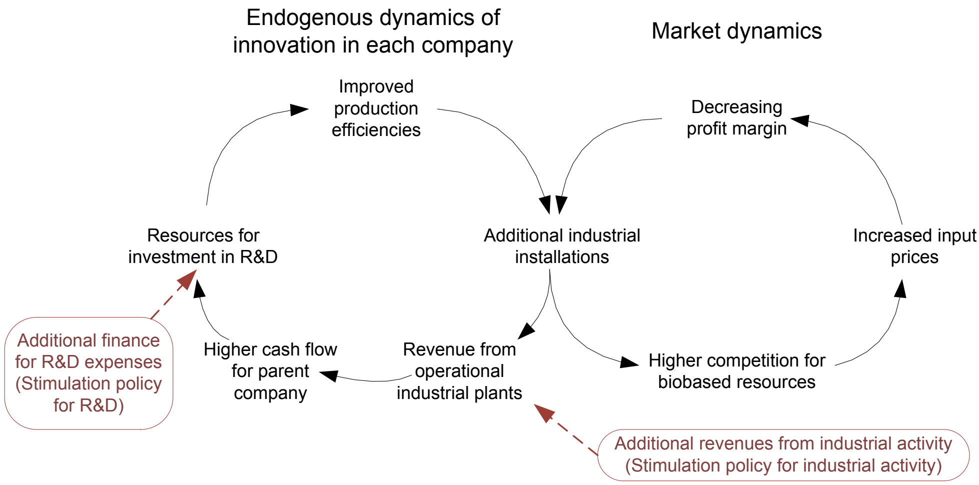


Figure 3-6 : Systemic representation of the innovation dynamics in the manure treatment sector

Figure 3-6 structures the dynamics that are investigated. A new technological sector requires large R&D efforts at the start. The crucial point for the emergence of innovative technologies is therefore available budgets spent on R&D, and their success rate. In this case, the focus is on the quantity of resources invested in internal R&D in each company. Increasing experience of companies with R&D increases the success rate for research as well. These funds are provided from revenues from operational industrial plants that the company already owns. Operational revenues are partly reserved for internal R&D, and increased R&D funds lead to higher chances of technological breakthroughs to improve the production efficiencies of new plants. New plants generate again additional income, and this closes the dynamics inside each parent company.

This movement is counterbalanced by the market dynamics, as additional industrial plants drive up the demand for biobased resources to operate on. This increase input prices and leads to lower profit margins for the plants. Figure 3-6 also indicates the entry points where the different scenarios bring modifications into these dynamics. The stimulation policy for industrial activity provides a subsidy for every ton of manure treated, and thus boosts revenues from all active industrial plants. The stimulation policy for R&D reduces the cost for internal R&D expenditure, which leads companies to increase their R&D efforts.

So the two entry points act to reinforce the dynamics that fuel internal R&D in each parent company. However, each technology has a historical situation. Traditional technologies already have several operational plants, and create revenues to fuel their internal R&D. Experimental or innovative technologies lack these incomes. At the start, they can only base their R&D on invested capital at the creation of the company, and subsidies. The experimental and innovative technologies have thus an important disadvantage in their competition with vested technologies at the start of the simulation. For them, further technological development is necessary before their manure treatment technologies will be mature enough to deploy on the market.

The reference situation is the sector structure without any policy intervention. Based on the structural description of the dynamics, the following impact might be expected of the policies. The policy for stimulation of industrial activity is expected to bring additional revenues to all operating plants. This can increase the innovation speed for all actors in the sector, but does not change the advantage of traditional technologies. The policy for stimulation of R&D however may be to the benefit of innovative technologies, because this increases the innovation speed, and may therefore allow innovative technologies to break through before the parent companies go bankrupt following a lack of operational income.

These hypotheses are based on a simplified structural description of the evolution of this sector. There are two aspects that may cause the evolution to divert from these expectations in practice. The first aspect is the heterogeneity of actors and technologies. The variety of innovation speeds, production efficiencies and actor strategies may very well lead to an uneven competition in the sector, and different outcomes than expected with a simplified homogenous group of companies. Secondly, the market dynamics remain important as well. The growth of the manure treatment sector is restrained by the availability of manure. The sector can grow if more added value can be created from manure, but the resource is limited. The inclusion of these relations and constraints requires the use of a detailed modelling approach.

3.3.2 Results

The general trends for the independent evolution are indicated in Figure 3-7 and Figure 3-8. These figures illustrate the total installed capacity for each technology. The first scenario does not include the arrival of new technologies. Of the technologies that are currently available, only three continue in the future. Composting and biology treatment both decline and disappear. By 2023, the entire sector is made up of constructed wetlands, drying and quicklime installations.

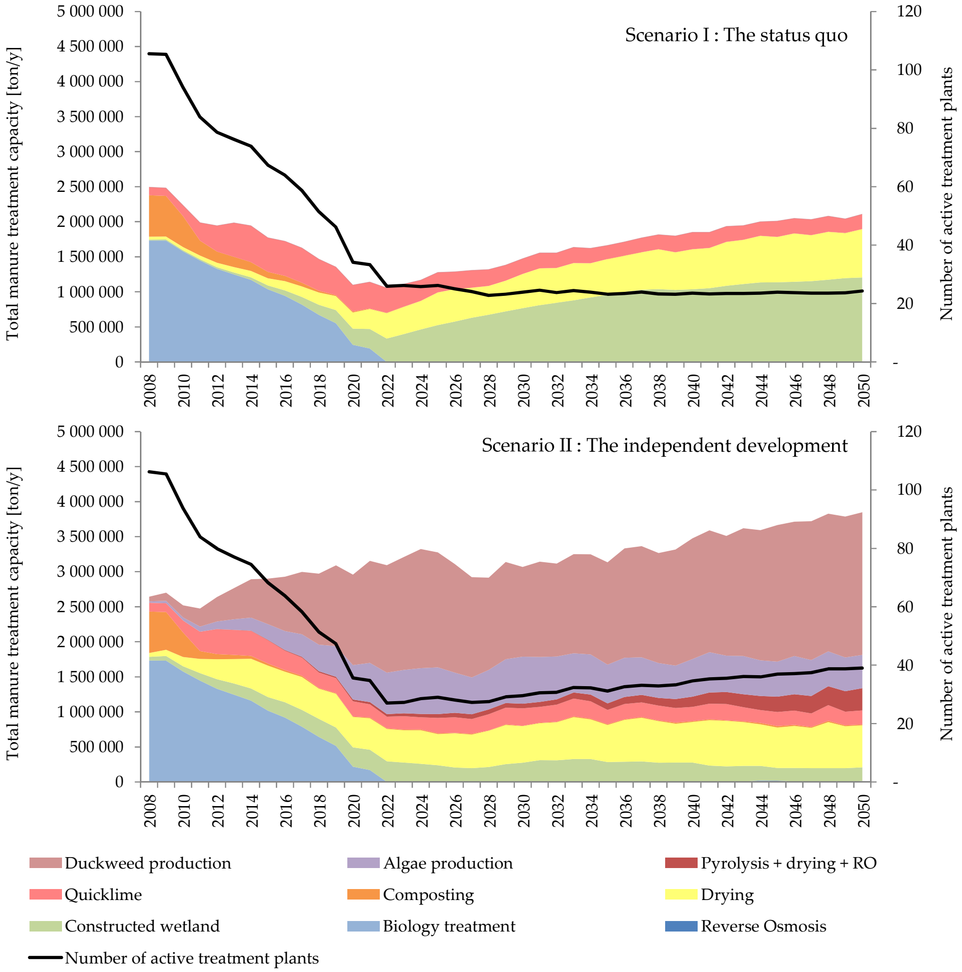


Figure 3-7 : Sector evolution in scenario I & II

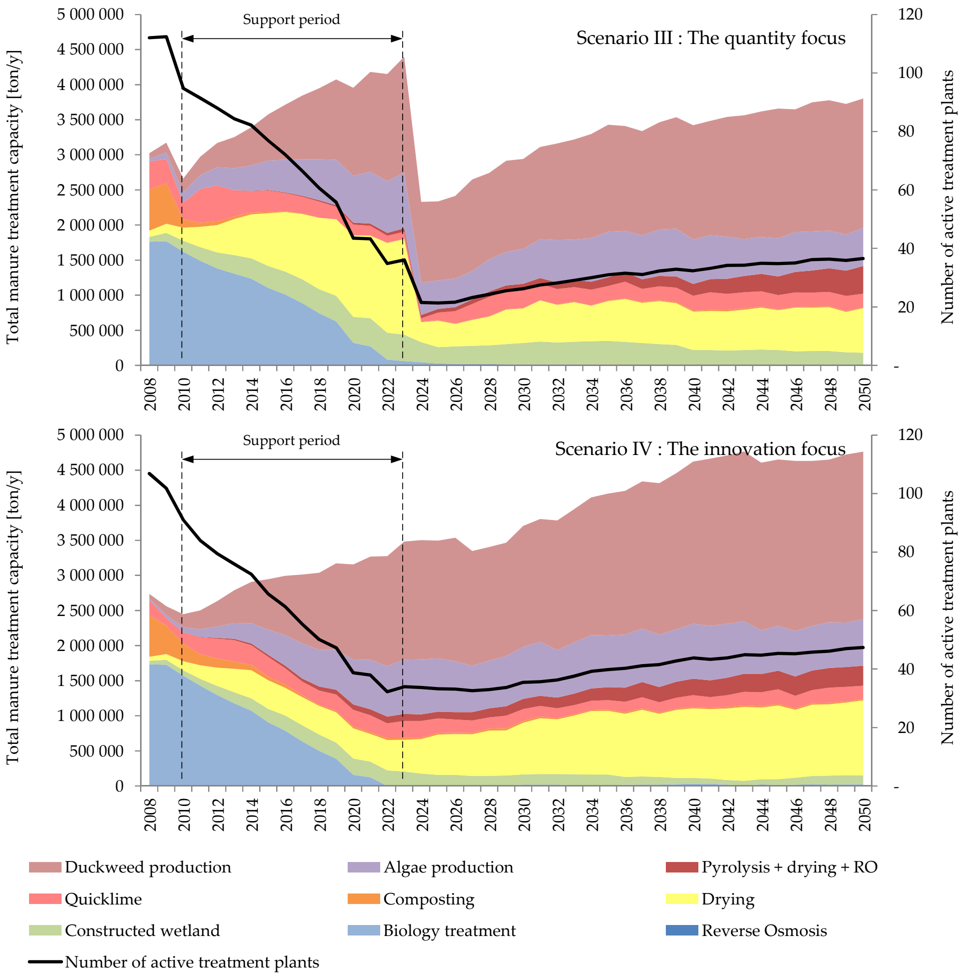


Figure 3-8 : Sector evolution in scenario III & IV

In the other three scenarios, the new technologies are available. Each of the scenarios presents a similar evolution in terms of technological renewal. The traditional technologies of composting and biology treatment phase out by 2023. The majority of the new treatments are based on algae or duckweed production.

The two stimulation policies have a significant impact on the sector evolution. The supporting policy for industrial activity leads to a fast sector growth at the start of the support period. But it leads equally to a collapse of the sector at the end of the support period, returning the sector to levels that are similar to the situation without support. This is also reflected in the manure prices that the sector is willing to pay to the farmers. During the support period, the prices are slightly higher, around -10 €/m³ compared to -12.6 €/m³ on average in scenario II.

But in the long term, this effect is annihilated, and the prices for manure return to the same level as the situation without support.

The stimulation of R&D has a different impact. During the support period, very little effect is visible in terms of sector growth or manure prices. The end of the support period has no direct effect on the sector size either. But the benefit from increased R&D between 2010 and 2023, continues to have effect and leads to significantly higher sector capacities in the long term. The technologies are capable of providing a higher added value per ton manure treated and this is translated in higher prices for manure in the long term as well: -4.6 €/m³ compared to -8 €/m³ for the other situations.

Table 3-10 : Average sector capacity, manure prices and sector structure for the different scenarios

	Scen I	**Scen II**	**Scen III**	**Scen IV**
Sector situation in the period 2041-2050	**Reference**	**Independent evolution**	**Industrial simulation**	**R&D stimulation**
Sector capacity [1 000 m³/year] (*)	2 006	3 688	3 657	4 681
Active parent companies (*)	8,5	14,9	14,2	19,6
Industrial plants per company (*)	2,9	2,7	2,6	2,4
Liquid manure price [€/m³] during support period (2010-2023)	-23,4	-12,6	-10,2	-11,9
Liquid manure price [€/m³] in the long term (2041-2050)	-22,2	-8,2	-8,1	-4,6
Total policy cost [M€]	0	0	168,6	26,9

(*): The figures relate to the sector situation in the long term, and show the sector average during the last decade of the simulation (2041-2050).

The evolution and the technological renewal of the sector are accompanied by a change in sector structure as well. This is already indicated by the number of active treatment plants in each of the scenarios. The total number at the start is very high, and quickly diminishes as the smaller biology treatment plants are being closed. Much larger industrial plants are opened, based on other technologies. This makes it possible that the absolute number of plants continues to decrease, while the total sector capacity stagnates or even increases. The average size of the industrial plants is larger than the average plant size at the initialisation of the model.

Between 2020 and 2025, a structural shift takes place, and the number of active plants stabilises or starts to increase again. The same timing is visible when looking at the average number of plants per parent company, as illustrated in Figure 3-9.

Figure 3-9 : Average number of treatment plants per parent company for each scenario

At the start, the traditional parent companies have less than 2 treatment plants each on average. The sector is dispersed, and the actual plants are small. The continuing decline in traditional technologies forces parent companies to close small plants during the first years. Between 2020 and 2025, a sudden increase is visible. At that point, most small parent companies have closed down, and only the largest parent companies with several active treatment plants can survive. This is also the point with the fewest active plants, and thus the highest concentration of the market during the evolution.

But also these are gradually replaced by new entrants. The new parent companies have been investing in innovative technologies. The number of active parent companies increases again. Starting with a few active innovative plants, they manage to outcompete the larger traditional parent companies. In the end the entire sector evolves to a new dispersed situation where the new parent companies have approximately 3 treatment plants each.

The total cost of the policy measures indicates the total amount of public support channelled to the parent companies between 2010 and 2023. It should be noted that the support is granted during the formative years of the new technologies, and it stops before large treatment capacities are actually installed, and just at the time when the traditional technologies are abandoned. In scenario I & II, there is no policy cost. The total cost for scenario III rises to 169 million EUR on average over the total period. But the sector does not show a large increase in capacity in the long term, despite this large support. The total cost for scenario IV reaches

27 million EUR over the same period, and this support is capable of increasing the sector capacity in the long term.

A more detailed look at the different technology efficiencies shows that even though the stimulation policy for R&D is successful, it is not fully effective. For every parent company, assets to conduct internal R&D are a percentage from the cash flow from the previous year. Internal R&D is required, because the innovative technologies are neither mature nor profitable at the start in 2010. In scenario II, the cash flow of the previous year is composed of income from previous investments, and a percentage of these are used for internal R&D the next year. In scenario III, even more resources for R&D are available, because the cash flows from the previous years are higher than in the other scenarios. The cash flow from the previous year consists of revenues from previous investments and is supplemented with a subsidy per treated ton. The companies invest faster in new treatment plants. However, when the support stops, several parent companies go bankrupt. The bankruptcy removes several companies from the sector, and their acquired knowledge and production efficiencies disappear as well. The overall effect of the stimulation policy for industrial activity is close to zero. In scenario IV fewer investments in actual treatment plants are being made. The parent companies focus on more internal R&D, as this is cheaper in this scenario. The cash flow from the previous year is mostly composed of R&D reimbursements. In the end, the efficiencies in scenario IV are only slightly higher than in scenario II. In scenario IV the internal R&D is financed by governmental support, whereas in scenario II it is financed by active manure treatment plants.

Still, despite the fact that R&D reimbursements replace internal funds, scenario IV leads to a larger sector capacity. This difference does not show during the first decades. However, the first decades are especially important, because this is the only period where support is granted. From 2024 on, the internal dynamics of the sector in scenario IV are exactly the same as in scenario II. The increased R&D efforts lead to a stronger innovation capacity that is only visible 10 years later. This shows the importance of the early investments in R&D and in treatment plants to generate early cash-flows, even if the technology still is being improved.

These results are very particularly suited to this situation. There are important limitations to further extrapolation of the results to other sectors or developments. The limitations are the origin of the private capital and constrained growth of this biobased sector, dependent on manure supply.

First, scenarios II, III, and IV all assume the same availability of private funds for the investment in new manure treatment companies. The high availability of funds can be defended in scenario III and IV. If a stimulation policy is installed, the average profitability of the sector is lifted and an interest for private investment follows. However, the availability of private funds is not logical in scenario II. The sector consists of immature technologies, and there is no stimulus foreseen to prevent early bankruptcy or to improve the general profitability of the sector. It is important to include scenario II with the same starting conditions for private capital, without policy support. This enables a distinct perception of the influence of public policies. But given the same availability of private capital in scenario II, this situation as such is not very likely at first sight. However, the situation becomes more likely if the investment funds are provided by authorities. The authorities can decide to support a development by taking part in new technology companies that do not give a high return in the short run. The discussion of public funds invested in private actors is not developed here, and therefore the results show no cost for public policy in scenario II. But this means that the comparison of the public costs for different policies should be interpreted with this limitation in mind.

Second, the limited availability of manure turns out to be an important limitation of the growth of the sector. This situation is particular to the development of the biobased economy, where new biobased technologies depend on the availability of large volumes of organic matter for successful industrialisation. In this simulation, parent companies are capable of importing manure from abroad to supplement local manure, but the price of imported manure is prohibitively high. This also shows that stimulation policies for industrial activity or internal R&D are not very helpful to overcome this limitation. In reality, parent companies will also consider the creation of industrial plants abroad, and this option is not included in the current simulation. The option of international expansion of the parent companies may bring to light other differences between the closed and the open innovation structure, but this investigation is beyond the scope of the current paper.

3.4 Robustness check

The emergence of innovations in the manure treatment sector depends on the innovation variables in Table 3-6. These values are assumed at the start, so the influence of these assumptions on the results has to be tested. The general set-up of the analysis is based on 100 statistically independent runs. This number is relatively small, and is motivated by resource constraints. The differences in outcome for the simulation of the manure treatment sector are large. The outcomes are determined by the assumed innovation characteristics of the technologies. The robustness analysis checks to what extent the distribution of outcomes is dependent on the initial assumptions.

The innovation values differ following the maturity of the technology. A sensitivity analysis is based on a random variation of the initial innovation parameters with a uniform distribution. The lower and upper limits of these distributions are indicated in Table 3-11.

Table 3-11 : Variable variation for the sensitivity analysis

Technology type	Proportion of R&D investment			Increase in production efficiency			Increase in quality			Decrease in investment cost		
	γ			δ_q			δ_p			δ_I		
	Ref.	Min	Max	Ref.	Min	Max	Ref.	Min	Max	Ref.	Min	Max
Mature	0.4%	0%	0.8%	0.5%	0%	1%	1%	0%	3%	-0.3%	0%	-0.7%
Experimental	0.8%	0.4%	1.2%	2%	1%	3%	3%	1%	5%	-0.7%	-0.3%	-1%
Innovative	1.6%	0.8%	2.4%	3%	2%	4%	5%	3%	7%	-1%	-0.7%	-1.3%

There are 2.000 sets of initial innovation parameters randomly chosen from these distributions. For each variable set, 100 independent simulation runs are executed. This leads to 200.000 observations of the sector development. The final installed capacities for each individual technology are retrieved, as well as the number of active projects and parent companies. Table 3-12 indicates the differences in outcome when comparing the reference situation with the sensitivity analysis. The reference situation is the group of simulations for the variables indicated in Table 3-6. The simulations have been executed according to scenario II, the independent development. The sensitivity analysis is the distribution of outcomes from all 200.000 simulations with varied values for the innovation variables.

The outcome is compared for the year 2025 and 2045. This shows that at both times during the simulated evolution, the results are quite similar and do not depend heavily on the exact variables that have been assumed for the emergence of innovations. Both the reference case as the results from the sensitivity analysis show similar installed capacities for each technology. If a difference is notable, it is that the sensitivity analysis arrives on average at higher installed capacities. For the larger capacities, this difference is about 10%. The model reacts non-linearly to increasing innovative speeds. The deviation between the simulated runs remains similar.

Table 3-12 : Difference between installed capacities during the sensitivity analysis

Technology type	Situation in 2025				Situation in 2045			
	Reference case		Sensitivity analysis		Reference case		Sensitivity analysis	
	Mean	*Std*	**Mean**	*Std*	**Mean**	*Std*	**Mean**	*Std*
Reverse Osmosis[1]	0	*0*	0	*1*	0	*0*	3	*30*
Biology treatment[1]	0	*0*	1	*8*	9	*38*	9	*38*
Constructed wetland[1]	259	*455*	226	*400*	140	*305*	153	*372*
Drying[1]	485	*442*	449	*427*	488	*431*	617	*813*
Composting[1]	6	*21*	15	*42*	9	*29*	20	*51*
Quicklime[1]	184	*292*	218	*294*	225	*305*	183	*279*
Algae production[1]	788	*991*	579	*943*	776	*1229*	674	*1239*
Duckweed production[1]	1589	*1261*	1702	*1322*	1965	*1618*	2155	*1730*
Pyrolysis + drying[1]	34	*62*	54	*96*	83	*281*	240	*730*
Number of projects	28	*9*	29	*11*	35	*11*	39	*12*
Parent companies	8	*2*	9	*3*	14	*5*	16	*5*
Total capacity	**3345**	*737*	**3243**	*1072*	**3695**	*1225*	**4054**	*1354*

[1] : Capacities are indicated in 1000 ton/year

A second conclusion is visible when looking at the distribution of the total sector capacities in 2025 and in 2045 in Figure 3-10. The variable of the sensitivity analysis are evenly distributed, but the outcome is highly skewed. Both in 2025 as in 2045 there are very few simulations that exceed a certain maximum sector capacity. For instance, for 2045, only 4% of the simulations exceed 5.6 Mton/year, and these outliers stretch over a very long range. The total sector capacity can only expand if the extracted value from manure rises sufficiently high. It turns out that it is very hard for the innovative process to achieve sufficiently high production efficiencies to expand beyond 5.6 Mton/year. This barrier corresponds to the market demand that sets the manure prices at equal level as the mineral fertilisers. Only in very few cases the treatment companies manage to produce such added value to allow them to purchase manure at higher prices than the mineral equivalent.

When looking at the original distribution of outcomes in the reference case, as illustrated in Figure 3-11, it is visible that the distribution is quite similar.

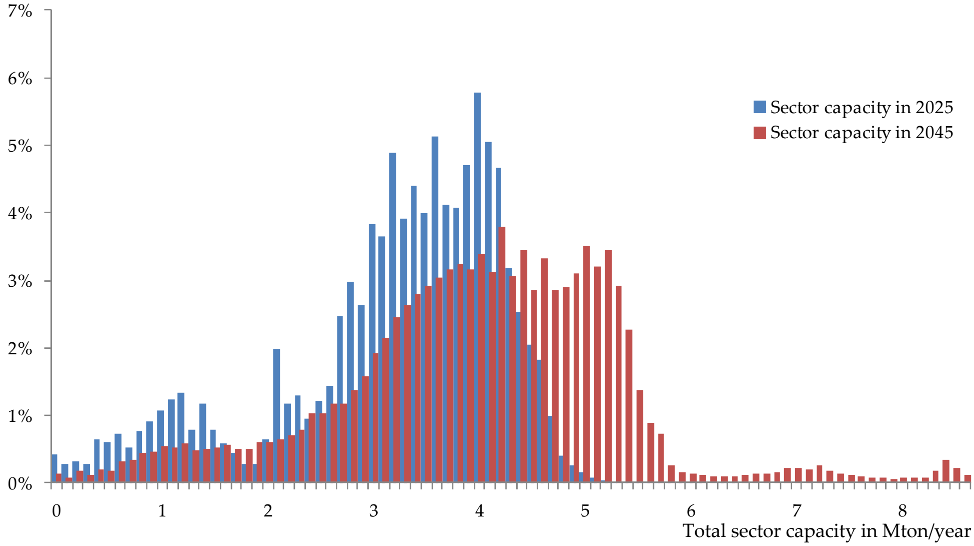


Figure 3-10 : Distribution of total capacities in 2025 and 2045 in the sensitivity analysis

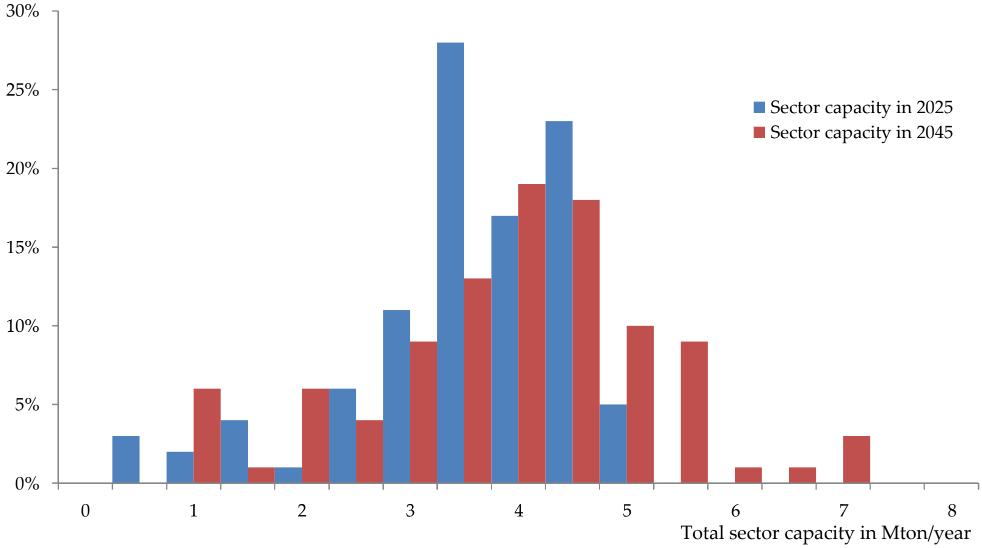


Figure 3-11 : Distribution of total capacities in 2025 and 2045 in the reference case

3.5 Conclusions

The sector of manure treatment companies is diverse and rapidly changing. The technologies differ widely in inputs, optimal scale, type of outputs and overall sustainability. Moreover, certain technologies are mature and already applied on a large scale, whereas others are still being developed and require several years of effort before they can be applied in practice. This results in a high diversity in the sector, in terms of both profitability and sustainability.

These dynamics are replicated in the sector model. This approach looks closely at the dynamics of internal innovation and its effect on sector growth. The model incorporates nine widely different technologies, with diversity in R&D strategy, prediction rules and capital. The solution opted for the distinction between parent companies and projects, in order to reflect closer the real situation. This distinction brings delay in the implementation of new innovations on the market, and provides that changes in R&D only reach their full effect on sector growth years after their discovery. The model is also initialised based on empirical data of the practical situation of the moment in Flanders.

This set-up has been used to look at the effect of four different policy scenarios, when considering an independent sector supplied from a fully efficient manure market. The results show large differences between the different policy effects. The investments in R&D are shown to bring the largest promises for sector growth in the long term. The evolution of the sector also shows a shift in technologies. In the first scenarios, not all technologies are available, and as a consequence, the sector does not reach high transformation capacities in the long run. The three other scenarios show a similar shift in technologies over the years. This is accompanied by a structural shift in parent companies and average project size.

The robustness check at the end of this chapter indicates the role of the innovation parameters. These innovation parameters have been assumed at the start. The initial values are important, but the robustness check shows that variations of the parameters lead to similar results, with a similar distribution in outcomes.

These result only relate to the independent evolution. The next objective is to review the evolution of the sector when it is directly coupled with the agricultural sector. The next chapter discusses the reference evolution of the sector, its influence on the evolution of the manure treatment sector, and the effect of policy scenarios in a combined model.

In our culture, talking about the future is sometimes a polite way of saying things about the present that would otherwise be rude or risky.

Benjamin Bratton (2013)

Chapter 4 Policy simulation and sector evolution

The former chapters discussed the construction of the model, and the calibration of the initial starting point with empirical data. This chapter applies the model for the simulation of future scenarios. The large quantity of variables and actors creates several entrance points where external variables can influence the outcomes of the simulation.

The chapter builds on scenarios that lead to coherent sets of external variables. The description of these scenarios requires choices in research aspects covered, and eliminates other future trends from the research spectrum. This chapter details the scenarios that are retained, and describes the indicators that are used to measure the outcome of the simulations. Finally, each scenario simulation is reported and discussed.

4.1 Policy scenarios

The former chapters discussed the construction and the calibration of the model. This set-up is now used to investigate different future evolutions. When looking at future evolutions, numerous variables can change compared to the present situation. In this model, the number of variables that can enter into play is extremely large. The model incorporates several markets with each a range of actors, prices, and external influences. Also the various types of agents, as well as large heterogeneity within each actor group make that there are many potential points where variable changes can influence the outcome of a simulation. Table 4-1 illustrates the different groups of variables that can be influenced in the future. Each of these variables has a significant influence on simulated outcome.

The simulations are therefore based on external scenarios. These scenarios have been elaborated in other projects. Scenarios can take contrasting forms (Höjer et al., 2008). In this case, the simulations are based on scenarios that describe future pathways of the evolution of agriculture and the related sectors. Scenarios present stories that are essential for research communication. Sustainability research is interdisciplinary, and this type of scenarios contribute to communication of this research across different scientific fields (Lang et al., 2012). The total set of scenarios covers then a full range of probable and improbable outcomes (Tonn, 2005).

The scenarios cover a much larger part of the economy than the model constructed in this project. They can therefore serve as a coherent source to value external trends. Scenarios also describe intuitively the effect of these external factors on agriculture. The external factors affect the course of future evolutions, and scenario exercises describes these evolutions based on holistic and intuitive understanding of the economic complexity. It is part of the research objectives to verify the described evolutions through simulation. The scenarios provide the external factors for the simulation, but the described evolution itself is not a starting point for the simulation. The comparison of predicted and simulated evolutions can contribute to insight in complex dynamics and interactions. This type of increased comprehension of the economic complexity adds to adaptability and reactivity confronted with large future uncertainties (Tschakert et al., 2010).

The focus in this case is on the development of a new technological sector, and its influence on the structure of agriculture. Table 4-1 shows multiple subjects that can be integrated in scenarios, such as changing diet patterns, sustainability in the animal breeding sector, international (and specifically extra-European) trade, environmental legislation, spatial planning, diversification in food products,….

The chosen scenarios here focus on the development of innovative manure treatment sector, and look specifically at support instruments and subsidies for this sector.

This research builds on former projects that have assembled very detailed and coherent visions for pathways of future development. The transition project by DP21 focussed on the future of agriculture in Flanders (Magiels, 2003). Others looked at the manure market (Boosten et al., 2011), and biobased processes and the bioeconomy (Carrez et al., 2012; Schaerlaekens et al., 2014). The scenarios led to future pathways and descriptions, but have these have not yet been quantified. The purpose of these exercises was to collect ideas from various stakeholders, and to compose visions in order to discuss actions and pathways to be chosen. These constructions follow a 'soft' constructivist system analysis (Reynolds et al., 2010). The approach reaches a holistic view by integrating multiple dimensions and relations, and it creates inspiring stories for the future, encouraging further discussions and actions. Specifically for the transition stories in agriculture, a multi-scale perspective was adopted, leading to very rich results (Biggs et al., 2007). The stories contain radical changes, affecting agriculture at various levels. The systemic effects make it difficult to foresee how agriculture will evolve. This is an area where simulation could bring more insight to support the present intuitive results (Gilbert et al., 2005).

Based on results from former projects, the scenarios are assembled. The descriptions of the future agricultural sector are taken as a basis to determine the overall external variables and large trends that underpin most change in the evolution of agriculture. These descriptions create the larger framework of external variables.

Table 4-1 : Different entry points for variable changes in the model.

Targeted model component	**Influence description**	**Changed variables**
Overall trends	Economic prosperity or low economic activity with reduced consumer spending?	Overall meat products demand in Flanders Price for meat products
	Increasing appeal of vegetarianism, and reduced meat consumption	Reduced meat products demand
	Market protection / openness to external competition	Arrival rate of new actors Availability of foreign meat products (lowering prices) Possibility for export (influencing total meat products demand from Flanders)
	Emergence of new disease epidemic for animals	Shock effect on productivity of one animal type, Less demand for one type of meat product, leading to a price differentiation between pork and beef products
Farm agents	Importance of sustainability criteria for products	Differentiation in output markets (Sustainable / non-sustainable) Creation of separate supply chains Value of price premium for sustainable products
Land market	Increase in hobby farming	Overall land availability for agriculture Upward pressure on land prices
Manure market	Further restriction for manure disposal	Restricted disposal norms on individual parcels.
	New construction of manure standards	New pathways to legally dispose of manure
Manure treatment agents	Availability of private capital	Arrival rate of new agents
	Availability of venture capital	Potential for faster growth
	Support regimes for biobased economy	Different levels of support and subsidies for various stages in project development for new manure treatment technologies.

4.1.1 Existing scenarios for agriculture

Interest in the application of transition thinking has grown in Flanders. Especially the regional authorities in Flanders have integrated this idea in regional policy texts. Currently, the Flemish regional policies actively stimulate a host of transitions on different economic topics, such as urban renewal, economic internationalisation, smart grids, healthcare, poverty reduction, and mobility. The fragmented approach does not ensure a thorough transition thinking approach for each issue. But there are several links and transversal policies, aiming for coherence between the different sectors. Particularly the fact that the policies state that structural change is essential in each evolution, indicates that the thought framework of transition thinking has been accepted and integrated at this level. This acceptance of transition thinking is a recent phenomenon. The acquaintance of policy makers with transition projects did grow over the last decade, especially as a result of two transition projects that were started around the start of the century.

The first two sectors that actively participated in a transition governance approach in Flanders were the recycling sector and the agricultural sector. In 2006, "Plan C" was launched, a Flemish transition network for sustainable management of materials. This ambitious project created a network of stakeholders for the recycling sector, and forged shared visions on how to transform the industrial tissue with reduced waste production and better reuse of materials. The sector's structure and its awareness to this transition changed markedly since the start of Plan C, and the organisation has to keep adapting to the new dynamics in order to maintain its central role in the transition process (Paredis, 2011).

Transition thinking has been applied as well in the agricultural sector. In 2001, a principle text was published outlining regional aspects of sustainability in agriculture (Reheul et al., 2001). The objective of this text was to start a sector discussion on the definition and implementation of sustainable agricultural practices. Starting in 2001, DP21, a non-governmental organisation was created to start a dialogue between farmers, agro-industrial sector federations and authorities. DP21 conducted a large project to define future scenarios through intensive interaction with multiple stakeholders in agriculture. The scenarios each described a different potential path for the future development of meat production and consumption in Flanders. Following general trends and specific crucial uncertainties, three central scenarios were elaborated:

- The race: This scenario assumes a low economic growth, limited consumer spending power, strict environmental regulations and an international fully freed trade for agricultural produce. Farms respond individually, by increasing specialisation, efficiency and scale. In this scenario, family farms gradually disappear, and large individual farms specialise in order to remain competitive against foreign imported food products.

- The European forum: This scenario assumes limitation to free trade based on environmental and social aspects of European agriculture. New export opportunities arise due to the EU enlargement and the collaboration between agriculture and agrifood actors intensifies. The farmers react more in cooperation, with emergence of niche productions and high-quality produce.
- The global bazaar: This scenario assumes a consumer concerned about quality and willing to pay for additional environmental values. International free trade allows the rapid growth of international consortia. Farmers respond individually with highly specialised niche production and flexible cooperation with other actors in the food chain. The market becomes highly dynamics with large international consortia, challenged in niche products and niche markets with small versatile highly-specialised producers.

These scenarios have been written and multiple social and economic aspects of their development were elaborated in stories. The project raised the awareness within the sector of the future challenges of agriculture and the importance of scenarios in this respect. The participatory process of DP21 involved a large variety of stakeholders, and it started a dialogue within the sector (Magiels, 2003; 2004). The transition project has also contributed to further research in sustainable agriculture. Building on this development, a Flemish policy research centre for sustainable agriculture (Stedula) was created (Nevens et al., 2008). Stedula continued the participatory approach for vision creation in a transition thinking setting and developed multiple sustainability measurement methods (Meul et al., 2008; Van Passel et al., 2007). Further research led to a holistic system analysis of the ongoing transitions in agriculture (VMM, 2012). These highlighted the links between niche-development in different scenarios and crucial issues that accelerate or hamper the emergence of more sustainable agricultural practices.

But the effects on agriculture remain small. Despite these early successes, the transition projects did not enable a corresponding transformation of the agricultural sector. The developed ideas and visions have become commonly known, but the actual evolution of the agricultural sector does not seem to take its lessons into account.

One reference scenario has been chosen to clarify for the internal dynamics of the agricultural sector. The reference scenario follows the trends outlined for the case of an economic recession. The corresponding transition scenario where a continuing economic recession puts pressure on prices and demand accompanied by little availability of government funds for support, is integrated in the scenario 'the race'. In this context, future prices for agricultural products are under pressure, and this is accompanied by declining consumer expenditure and little willingness to pay for internalisation of externalities linked with food production. The scenario "The race" defines the external variables and their evolution during the reference situation. The evolution of the external variables is described in Table 4-2.

Table 4-2 : General tendencies for external variables for the agricultural sector

Affected variables	General tendency
Meat demand	The local demand for meat products declines, due to growing acceptance of vegetarian diet, and low consumer spending. However, increased international trade connects the Flemish market to the increasing meat demand overseas.
Meat price	The price for meat products remains at the same levels. High prices are excluded due to the possibility of import of low price substitutes.
Other products	Declining prices for other agricultural products
Wages	Wages struggle to keep up with general inflation
Energy prices	Energy prices increase beyond inflation.
Feedstock prices	Feedstock prices reduce following unrestricted import.

These effects now have to be translated in input figures for external variables. The first assumption is that each variable follows a gradual evolution from 2008 to 2050, with a fixed percentage change each year. This annual growth or decline of the value is fixed on top of the inflation. The overall inflation is set at 2%. The list of change percentages for external prices and demands is illustrated in Table 4-3.

A specific clarification is needed for the estimation of the meat consumption. Meat consumption is decreasing since a few years in Flanders, reflecting changes in food patterns. The beef consumption is declining rapidly, with an average of 3.1% per year, whereas the pork consumption remains steadier (ADSEI, 2013), showing an annual decrease of 0.86% over the long term. This evolution is assumed to continue in the near future. However, the percentages of decreasing will probably evolve towards each other, as to a certain degree pork and beef are substitutable. However, the scenario 'the race' is based on the assumption of a growing internationalisation of the meat industry. This implies that the industry will be increasingly connected to the growing international demand for meat products. On the other hand, this implies also that the industry will be a price-taker on an international level. So regardless of the declining local demand for meat products, this leads to a possibility for growing meat demand for the sector. However, this will be accompanied with stagnating or decreasing price levels.

Table 4-3 : Changes for different variables according to the scenarios

Animal products price and quantity evolutions			
	Milk products	Beef	Pork
Meat product prices	0%*	0%*	0%*
Meat and dairy demand	+1.5%	+1.5%	-+1.5%
Other input and output price evolutions			
Variable	Evolution	Remarks	
Agricultural production			
Crop price index	-2%*		
Horticulture	-1%*		
Cattle feedstock	-1%*		
Pig feedstock	-1%*		
Wages	0%*		
Energy price index	2%*		
Nitrate Fertiliser	2%*	Nitrate fertiliser is aligned to the energy price evolution.	
Phosphate Fertiliser	3%*	Phosphate fertiliser reflects the growing scarcity of mined phosphate.	
*: All price evolutions are real evolutions and are indicated on top of a general inflation level of 2%. For instance, the nominal change percentage for the beef price is +1%.			

This situation of the agricultural sector is simulated for different evolutions of the manure treatment sector. The aim is to investigate how innovation affects the co-evolution between the two sectors. More specifically, the dissertation looks at the presence of available innovative technologies and two different strategies to stimulate the implementation of technology.

4.2 Input data and interaction between the different agents

The combined evolution of the farm agents and the technology companies obliges a synchronised evolution of the two groups. The annual cycle of the farm agent is illustrated in Figure 2-4. The equivalent cycle for the technology parent companies, and their technology projects, is illustrated in Figure 3-5. The combined evolution is scheduled to allow both agents to interfere simultaneously on the land market and on the manure market. This ensures a direct interaction between the two groups.

The combined annual cycle is illustrated in Figure 4-1. The model is initialised in a preliminary phase. This phase builds up the starting populations of both agent types, and loads all data. Further details on all data that are added in the simulation can be found in Annex I (page 275).

A second phase starts the annual cycle with the production of the farm agents. This leads to the excess manure presented on the market. The active technology projects present simultaneously an offer to purchase manure. After the combination of bids and offers, the technology projects can produce. At the end of the year, both parties sell their productive outputs on their respective markets.

In a third phase, the annual results are calculated for each agent. Farm agent finalise their annual accounting based on the return for their products. Technology parent companies calculate their benefit for the end of the year, based on the sales of their own projects.

In a fourth phase, agents of all types follow their adaptation procedure, following their behaviours and objectives. During the adaptation, both can interact on the land market. Farm agents can buy or sell to readjust their acreage. Parent companies can buy land if they launch new industrial installations.

In the end, new agents join the population, and the annual cycle can start over again. Each simulation is run in annual time steps. The starting conditions are based on the situation in 2008, and the simulation is run until 2050 included.

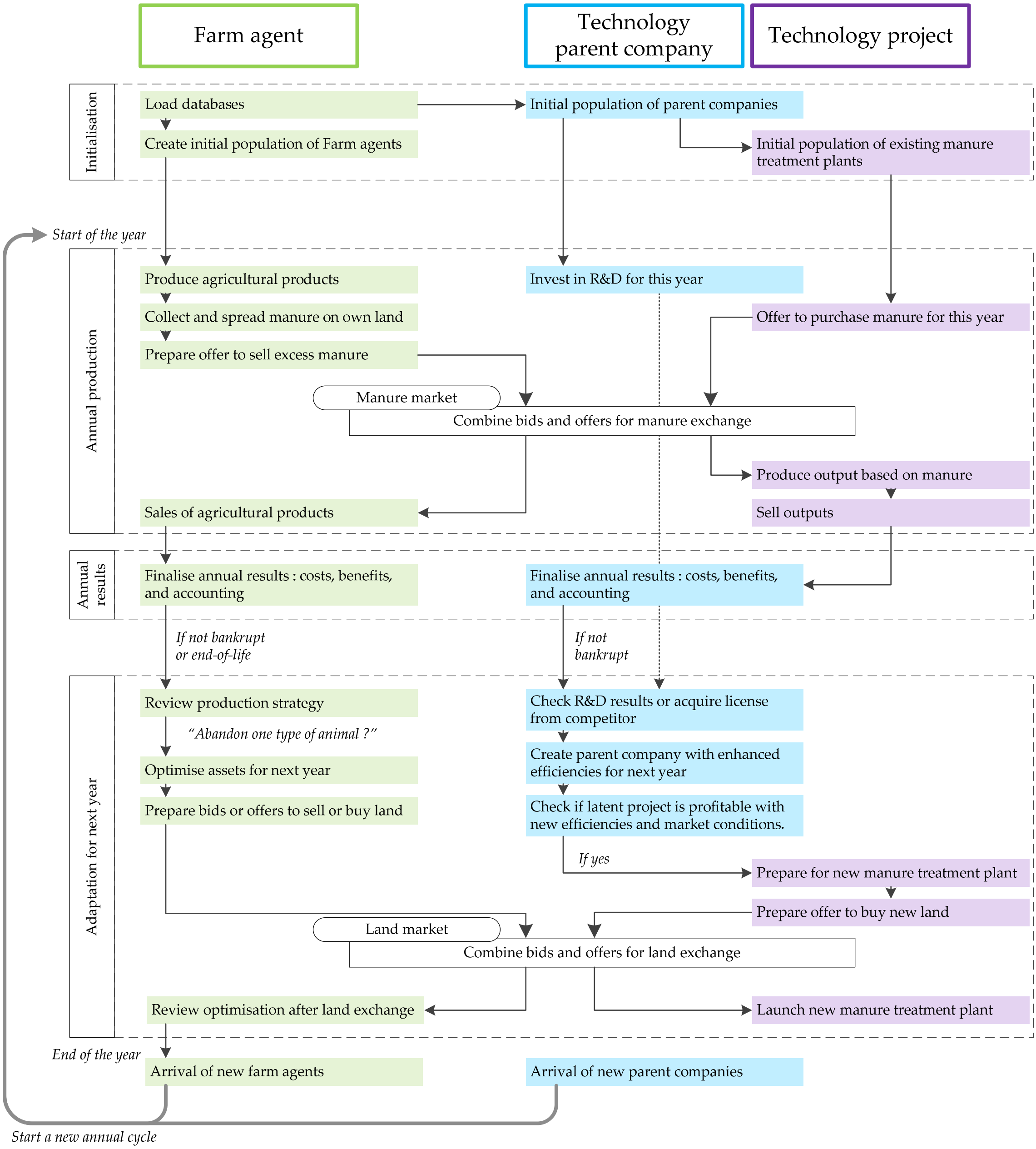


Figure 4-1 : Synchronisation of all steps in annual cycles to simulate the co-evolution between the farm agents and the technology agents

4.3 General trends in the agricultural sector

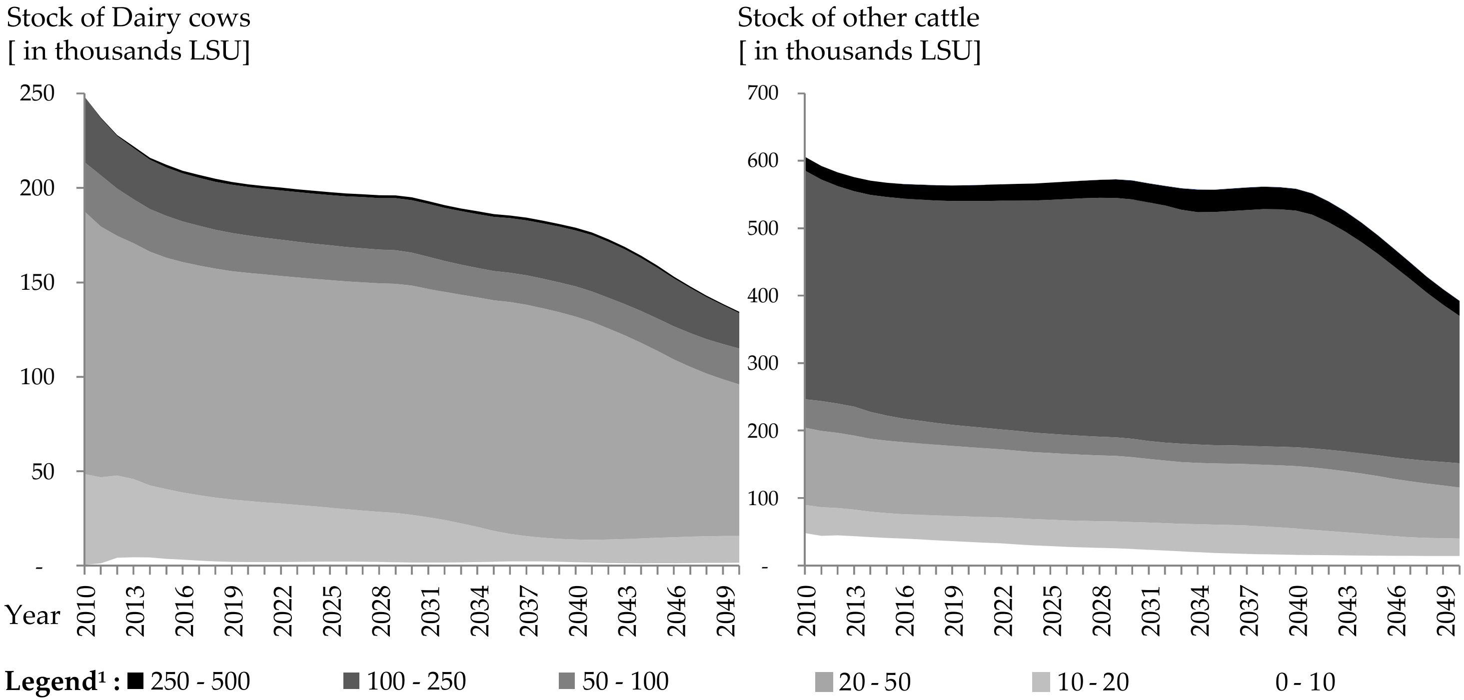
The review of the simulation results starts from the general trends in the agricultural sector. The different scenarios of the manure treatment sector interfere only slightly with these trends. The simulated agriculture evolution remains steady regardless of the growth of the manure treatment sector. Divergence from these trends will be indicated when discussing the evolution of the manure treatment sector in the next section.

The general trends outlining the evolution of the agricultural sector are based on the scenario ‘the race’. The exogenous variables have been set according to the previsions of this scenario. The simulated changes within the agricultural sector show a lot of similarities with the evolutions that have been predicted intuitively. The simulations provide further details and show relations between different underlying trends of internal dynamics.

The evolution of the cattle-related activities is indicated by Figure 4-2. This figure shows the total stock of cattle in active farms in Flanders during the next decades. The stocks are split between dairy cows and other cattle. Both show a short decline of the total stock until approximately 2015, and a stable period afterwards. The total stock of dairy cows in Flanders in 2030 is reduced to 70% of the initial population in 2008. The cattle stock is reduced to 80% of the initial population in 2030.

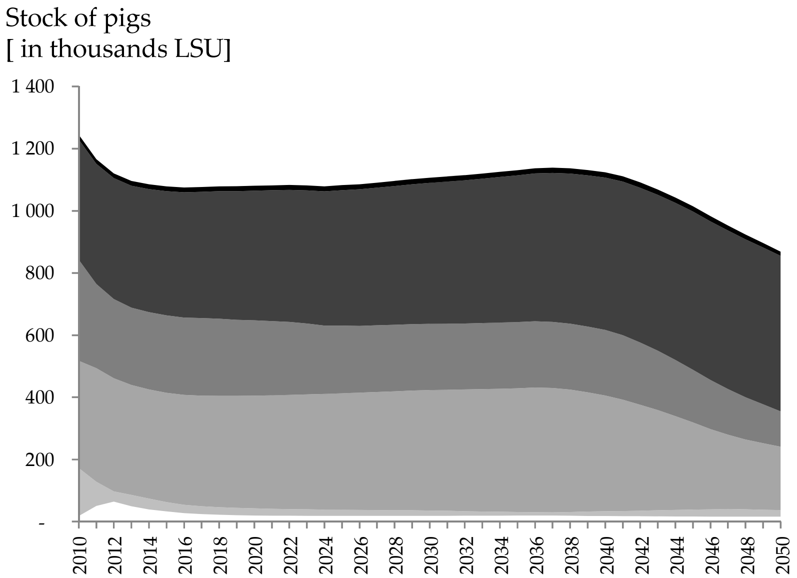
For the dairy cows, the distribution according to the size of the farm shows that especially the smaller farms account for this reduction, this is with less than 50 LSU. The number of larger farms, with over 50 LSU of dairy cows, quickly stabilises and even shows a growing trend after 2030. Economies of scale contribute to the higher survival rate of this group. However, the very large farms, over 100 LSU, fail to break through and remain a small part of the sector. This is because the growth of a farm stock is related to a minimum acreage required for the cattle. The rigidities in the land market severely hamper the growth of farms looking for these large land plots.

The evolution of the rest of the cattle stock is similar. While the number of smaller farms continues to decline, the stock sizes of the large (> 100 LSU) and very large farms (> 250 LSU) increases again after 2025. And the largest category of farms fails to break through. There is no farm agent that starts with these large animal stocks. The active farm agents have to be able to grow to reach an animal stock over 500 LSU. But it is not possible in this structure. This is again related with the rigidity of the land market, effectively barring farms from growing quickly.



[1] : Farm stock sizes are given in LSU/farm, separated between dairy cows and other cattle

Figure 4-2 : The total stock of cattle in Flanders, distributed according to the stock size of animals at the farm



Legend[1] : >500 250 - 500 100 - 250 50 - 100 20 - 50 10 - 20 0 - 10

[1] : Farm stock sizes are given in LSU/farm

Figure 4-3 : Evolution of the pig farming illustrated by the distribution of the pig stocks in Flanders

The evolution in the pig sector has some similarities. The overall trend also shows a decline in the total stock of animals in the short run. In 2030, the total stock is 71% of the stock in 2008. After the initial decline, the animal stock slowly starts an upwards trend. This trend is carried mostly by the growth of farm with 250- 500 LSU pigs. The larger farms do not appear in the pig sector either.

This decline in stocks leads to a parallel decline in production of animal products. It also shows the shift in production assets from livestock production to crop farming in general. Next to the structural changes, these trends are also accompanied by a shift in the composition of the agricultural sector as illustrated in Figure 4-4. This figure illustrates the number of active farms for each farm agent's behaviour type. It shows that the proportion of the behaviours changes significantly during the years.

In a first period, between now and 2035, the number of growing family farms drops from 14 623 to a minimum of 3 795. The number of stable family farms is reduced from 13 112 in 2008 to 4 592 in 2035. Only the number of elderly farmers increases during this period to a maximum of 9 961. In a second period, the number of elderly farmers declines. But the number of other farmers does not grow sufficiently to counter this trend. The number of stable farmers further declines to 2 574 in 2050. The number of growing family farms shows a slight growth to 4 932. Over the entire period, the proportion of innovator and industrial farms remains very small.

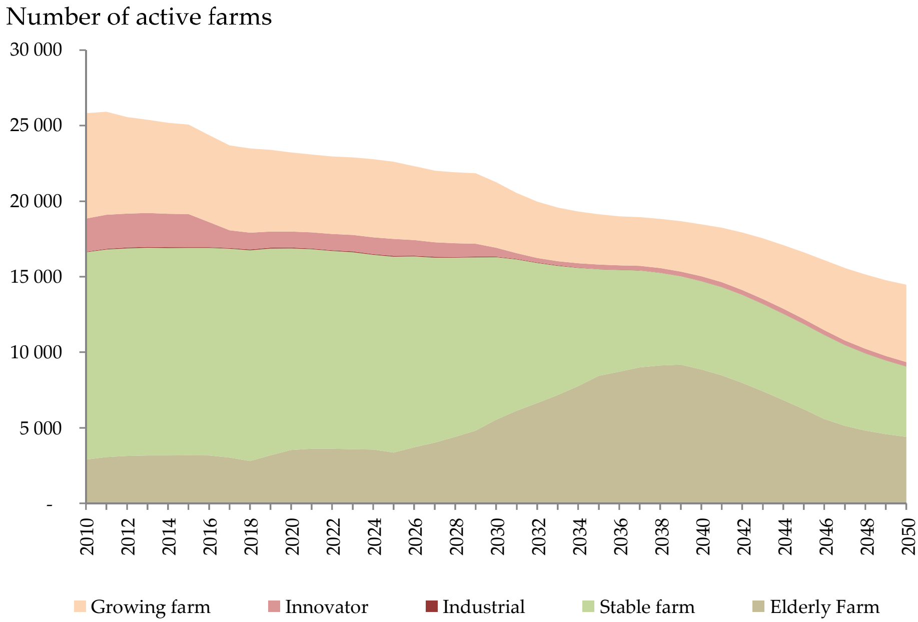


Figure 4-4 : Evolution of the total number of farms in Flanders, distributed according to behaviour type

This evolution quantifies the story behind the scenario of 'The race'. The growing family farms are the first group to adapt to unfavourable market circumstances and this group gradually leaves livestock production. The stable family farms are much less adaptive and remain longer in this sector. Their position is stable for as long as bankruptcy or old age does not drive them out. Their survival is only possible because this type of farms accepts a lower profitability. Their average profitability before deduction of the household income in the period between 2010 and 2035 is only 12% for stable farms compared to 21% for the growing family farms.

This shows a sector that is predominated by less adaptive farms with very low incomes, accompanied by a growing population of retired farmers who remain active. This image suits the intuitive scenario description of 'The race'. The growing proportion of elderly farmers is a direct consequence of the age pyramid of the farm sector, but their presence adds to the rigidity of the sector, as the elderly farmers do not adapt any longer during their final years.

Only after 2040 the situation starts to improve, when production has decreased so much that the prices for agricultural produce start to rise again, and when the evolution in the age pyramid reduces the impact of the retired farmers. It is also remarkable that in the last decade, when the large proportion of elderly farmers is reducing, the growing adaptive farmers are again rising in numbers. They are the first to react to the positive market circumstances.

Table 4-4 : Overview of Stock decreases and reduction in active farms between 2010 and 2050

	2010	2020	2030	2040	2050
Stock of Dairy cows (in total LSU)					
in farms < 50 LSU	187 602	155 016	148 268	131 895	95 977
in farms between 50 - 250 LSU	60 701	45 517	45 204	45 624	37 786
in farms > 250 LSU	66	1 398	1 581	1 391	626
Total	**248 369**	**201 932**	**195 052**	**178 911**	**134 389**
Stock of other cattle (in total LSU)					
in farms < 50 LSU	204 215	175 441	160 576	147 370	115 648
in farms between 50 - 250 LSU	381 118	364 899	382 221	378 749	254 178
in farms > 250 LSU	20 566	23 320	27 915	32 245	22 398
Total	**605 899**	**563 661**	**570 712**	**558 364**	**392 224**
Stock of Pigs (in total LSU)					
in farms < 50 LSU	172 872	42 716	35 854	33 370	37 094
in farms between 50 - 250 LSU	670 075	604 914	600 436	583 404	318 009
in farms > 250 LSU	386 858	417 491	453 888	490 389	500 063
Total	**1 229 806**	**1 065 121**	**1 090 178**	**1 107 164**	**855 166**
Active farm agents' behaviour (in number of farms)					
Growing farm	6 972	5 241	4 332	3 441	5 128
Industrial	35,6	47,25	39	5,1	6
Innovator	2 189	1 062	590	320	283
Stable farm	13 723	13 352	10 754	5 840	4 657
Elderly Farm	2 898	3 524	5 535	8 864	4 399
Total	**25 819**	**23 226**	**21 250**	**18 469**	**14 473**

4.4 Simulated evolutions of the manure treatment sector

Exactly as in the independent simulation of the manure treatment sectors, four policy scenarios have been investigated in the combined model. The first reference scenario excludes any type of support ("I : the status quo"). The three other scenarios distinguish the support according to its type and origin:

- Private funds for investment are available ("II : the independent development")
- Private funds + subsidies per ton manure treated ("III : the quantity focus")
- Private funds + reimbursement of R&D expenditure ("IV : the innovation focus")

The discussion of the results treats first the general trends, then the differences between the scenarios. Finally, it looks at the co-evolution between the manure treatment sector and agriculture.

The general trends are illustrated in Figure 4-5 and Figure 4-6. These figures indicate the total installed capacity of manure treatment for each technology.

The situation without any support, in scenario I, leads to a swift erase of the entire sector. Installed plants continue to function, but very few new plants are constructed. Ultimately, the total treatment capacity drops to almost zero in 2023. Whenever support or financial funds are available, the evolution is quite different. The three other scenarios present a very similar phase-out for the traditional technologies. The new technologies slowly take over and from 2023 onwards the sector capacity is made up only of new technologies. When looking at the technology choice, all three scenarios lead to a similar technology use in 2050. The bulk of the installations are based on duckweed and algae production. A small proportion uses drying or pyrolysis. The particular exemption is the case of drying, a traditional technology that continues to remain in application beyond 2023.

The three scenarios show a very remarkable similarity in the overall evolution. The impact of the different policies is much lower here than in the independent simulation. The independent simulation showed a steep rise in sector capacity in Scenario III, and again a steep decline when the support in scenario III stopped. These predictions no longer seem to hold when the manure market is coupled with the evolution of the farm agents.

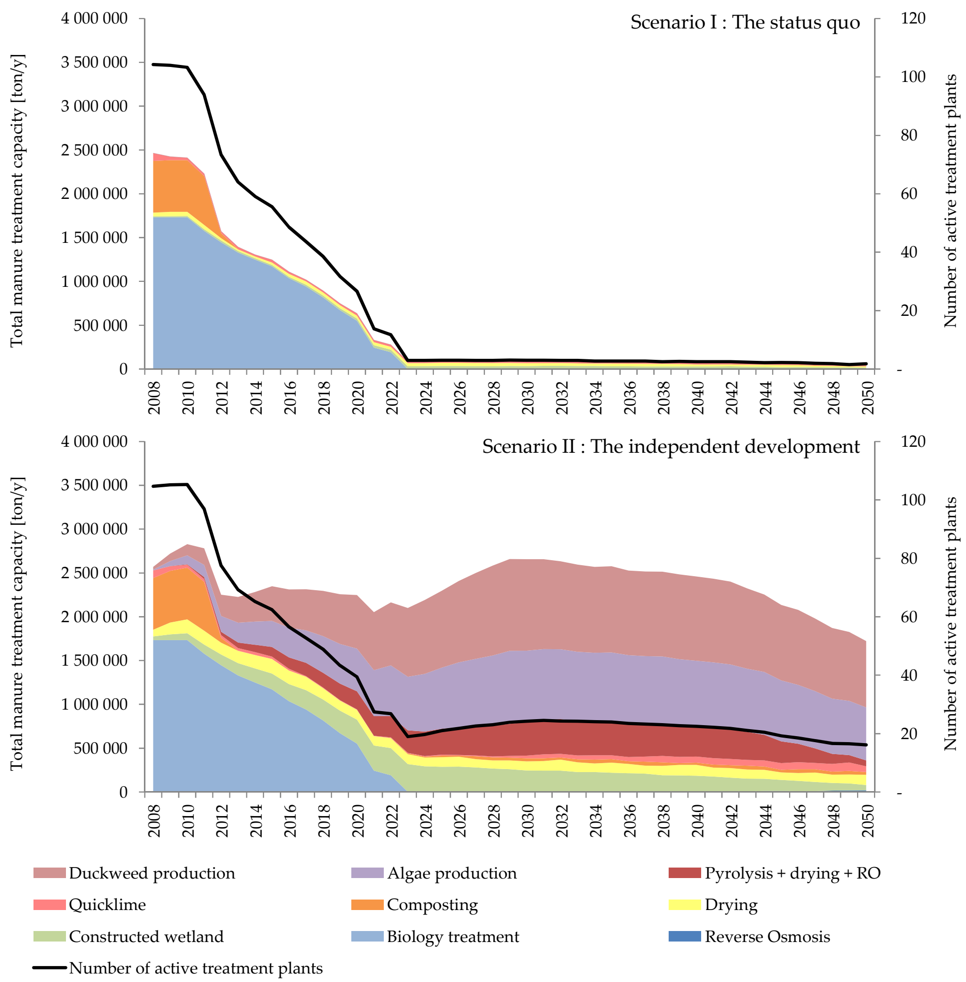


Figure 4-5 : The average evolution of the manure treatment sector in scenarios I & II

Scenario II an IV show almost an identical evolution Scenario III has some smaller differences. During the support period, the sector grows markedly faster. But after the support period has ended, the sector capacity declines faster as well. This leads ultimately to a lower sector capacity than in the other scenarios. Each scenario has been executed for 100 independent runs. The variation in total sector capacity varies strongly between these runs, as is illustrated in Figure 4-7 showing a boxplot of the average sector capacities between 2041 and 2050. Even with this diversity between parallel runs, the overall result is that the sector is less developed in the long term in scenario III than in II and IV.

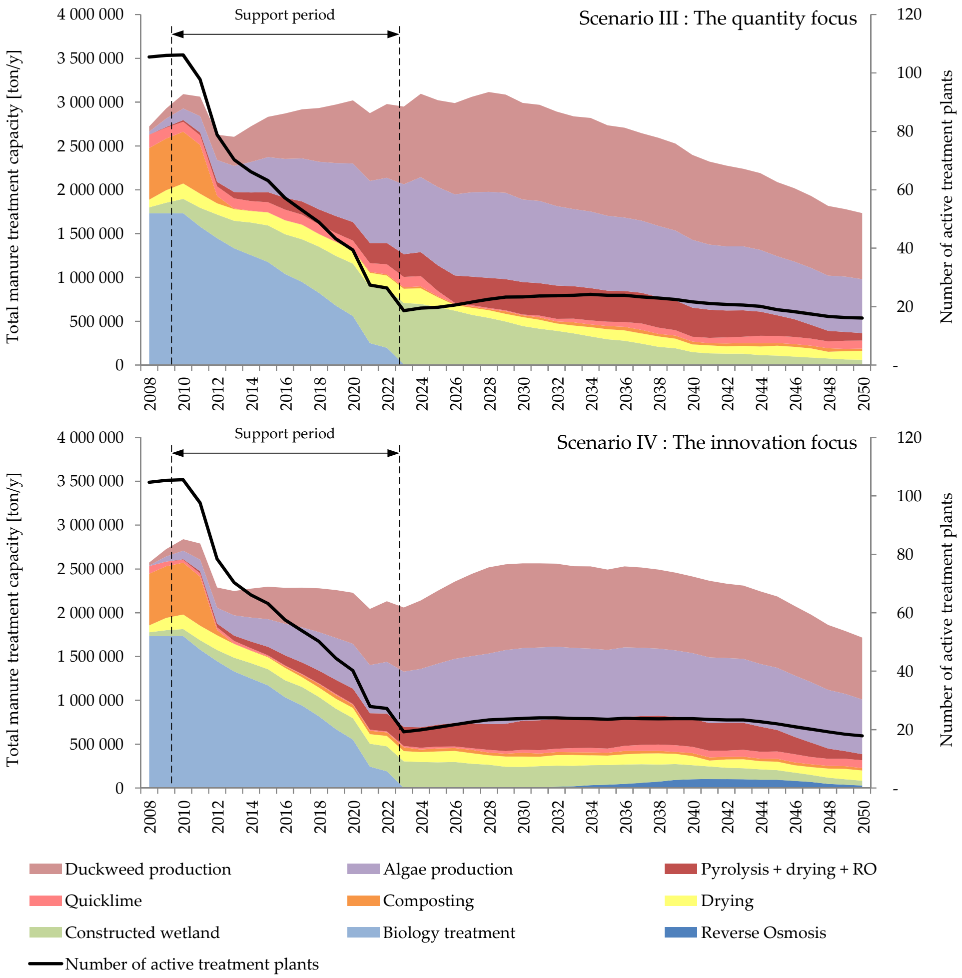


Figure 4-6 : The average evolution of the manure treatment sector in scenarios III & IV

Table 4-5 : Average sector capacity, manure prices and sector structure for the different scenarios

	Scen I	**Scen II**	**Scen III**	**Scen IV**
Sector situation in 2025				
Sector capacity [1 000 m³/year]	92	2 252	2 963	2 207
Active parent companies	2,9	19,6	19,2	19,8
Industrial plants per company	1,1	1,1	1,0	1,1
Total policy cost [M€]	0	0	107.4	39.0
Sector situation in the period 2041-2050				
Sector capacity [1 000 m³/year] (*)	77	2 135	2 072	2 116
Active parent companies (*)	2,2	19,0	18,6	20,9
Industrial plants per company (*)	1,0	1,0	1,0	1,0

(*) : The figures relate to the sector situation in the long term, and show the sector average during the last decade of the simulation (2041-2050).

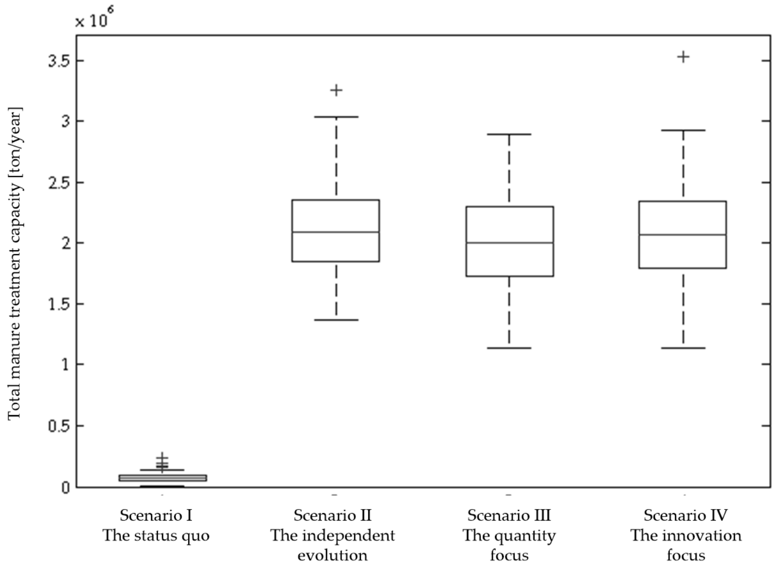


Figure 4-7 : Distribution of the sector average treatment capacity in between 2041 and 2050

In the independent simulations of the manure treatment sector, the impact of the stimulation policies is not related to the cost of the policy. In the combined simulation, the policy impact is even less clear. The policy costs are comparable to the costs found in the independent situation. But there is hardly any effect on the long-term growth of the sector.

In scenario II, there is no policy cost. The total cost for scenario III rises to 107.4 million EUR on average over the total period. The total cost for scenario IV reaches 39 million EUR over the same period. These expenditures are not in relation with the outcome of the final use of innovative technologies in the sector.

4.5 Discussion

The former sections present a simulated evolution of the agricultural sector between 2008 and 2050. The simulations are based on a large number of assumptions and imposed external variables. Only few of these factors have an important influence on the simulated outcome.

4.5.1 Evolution of the cattle and pig sector

The simulated evolution of the cattle and pig sector does not seem influenced by any variable. Random factors interfere in the simulation runs, and change the distribution of farm types of the individual farm agents, they allow for short-term price variations, and cause divergent technological developments. But despite these differences, the simulated outcome of animal stocks is always very similar. The variation of results is very small. Table 4-6 shows the differences in average animal stocks of scenario II, III and IV, when compared to the reference, scenario I. Both the average and maximum differences remain extremely small, given the large number of variables that interfere in the total simulation. It shows that the model initialisation was very determining for the future evolution of the sector, but the variables varied in the scenarios were not. This shows for instance that short-term price variations for live animals are not sufficient to keep the size of the animal sector at today's level. Significant and structural price increases for live animals are required to avoid the decline in animal stocks.

Table 4-6 : Maximum and average differences in total animal stocks between scenario I and the other scenarios

		Scen II	Scen III	Scen IV
Dairy	Max	0,78%	1,21%	0,78%
	Average	-0,34%	-0,59%	-0,34%
Cattle	Max	1,23%	2,88%	1,47%
	Average	0,60%	1,38%	0,80%
Pig	Max	0,43%	0,60%	0,49%
	Average	-0,03%	-0,10%	0,02%

This research has based its simulations on the scenario of an economic downturn, "The Race". An alternative scenario, "Forum Europeanum", provides a more promising economic climate with gradually increasing prices. But even these increasing prices are not sufficient to stop the trend of stock decline. Gradually increasing prices only make a significant difference after ten years, and the largest stock reductions have already taken place by then.

An important restriction of this research has to be noted. This research set out to investigate the evolution of the economic structure in agriculture under different influences. This objective has been followed, and the current approach allows farm agents to adapt their farm structure over time. By aggregation, this clarifies the structural change in the sector as a whole. The reference scenario of "The Race" is also based on individual farmers that adapt their structure to cope with unfavourable economic conditions.

However, if the prices for live animals do not change significantly over the short run, the farm agent has to do more than adapting his farm structure; he has to adapt his business model. This implies for instance new cooperation with colleagues or strategic partnerships in his supply chain. These actions are much more pervasive for the sector structure and are part of the other reference scenarios "Forum Europeanum" and "Global Bazaar". But the current research approach does not account for new business models for farmers. It does not integrate new networks or types of cooperation. The model and the reference scenario follow individual farm agents. Therefore, the current outcome illustrates the evolution of agriculture where innovations in business models for agriculture are absent. This is an important limitation that should be kept in mind for the interpretation of the results. The other way around, these results show that many influences that are expected to improve market conditions for farmers are not sufficient. Price variations, increased manure prices or further mechanisation in farms do not halt the decline in cattle stock. It is possible that new business models for farmers are more powerful in this respect, but this falls beyond the scope of this dissertation.

The model has integrated several sources of rigidity and resistance to adaptation. There is the presence of a segment of non-adaptive farmers, consisting of stable famers and elderly farmers. There is also the rigidity in the land market, which restricts the access to new land. Growing cattle farms have to deal with both effects. These two sources have been calibrated to empirical data in Chapter 2. It has shown that land access is rather low. A levelled cattle stock requires growing individual farms to counter the stock reduction from elderly farmers closing down. An individual farm that needs to grow requires more access to land than what the calibration provides for.

In general the stability of the agricultural evolution is explained by rigidity determined by (i) the farm agents' age pyramid, (ii) by simplified behaviour assumptions and (iii) by the market rules for animal prices

First, the age pyramid turns out to be very important in the explanation of the sector's rigidity. The proportion of the elderly farm reaches a peak in 2035, and declines afterwards. It is remarkable that several important changes in the sector structure accompany this decline in elderly farms during the last decade. For instance, after a period of relatively stable animal stocks, the departure of elderly farms also leads to a faster decline in animal stocks. This leads to new market conditions and improves the situation for growing family farms. The decline in elderly farms enables a rising number of adaptive growing family farms for the first time during the entire simulation period.

It has to be noted that the calibration of the initial farm agent population did not include all elderly farmers from the start. It has been discussed at the calibration in chapter 2 that especially the large group of elderly farmers with very small acreages was underrepresented in the calibration, and thus not included in the model. This indicates that the rigidity resulting from the age pyramid appears strongly in the results, but it is still underestimated in the model.

The second reason for rigidity is in the division between stable and growing farm agents. The majority of the active farm agents are stable family farms. At the start, only 40% of the remaining active agents are assumed to be growing farm agents. This is a very small group, and the only group that reacts according to price signals. As the simulation proceeds, the adaptive proportion is also the first to leave, because the initial market conditions are not favourable. This leads to a model with very few farm agents that are reactive to the price.

There is therefore a direct link with the third reason, the prices for live animals on the markets. The prices for live animals are determined by a market model for slaughterhouses, and the prices are capped by international price trends as well. The model calibration learned that overproduction is definitely a possibility to explain why prices for live animals remain at the current low levels. According to the resulting price formulas, prices will become interesting again when the animal production is significantly lowered. The calibrations leave very few farm agents that actually consider lowering their animal stock in response to the low prices. So the total animal production did not diminish sufficiently to make prices interesting again. Without profitable prices, there is no feedback effect between the farm agents and the live animals market, and thus no complex effect in the evolution.

It turns out that the calibration results are in this case so determining that the scenario variables hardly interfere with the evolution of the agricultural sector.

A principle aim of this dissertation is to investigate in detail the co-evolution between agriculture and an emerging biobased sector. In this specific context, co-evolution can be defined as a mutual influence of two connected sectors during their development trajectory. The current results show that there is no sign such of mutual effects. The evolution clearly has an impact on the development of the manure treatment sector, as discussed in the previous section. But the reverse, an effect of the growing manure treatment sector on agriculture, is almost non-existent.

This lack of influence can be explained by the high level of rigidity in the simulation. The future scenario of 'The Race', established by a transition project of DP21, estimated the future decrease in livestock much higher. The scenarios estimated intuitively the reduction of the animal stock within 20 years to -35%, -70%, and -50% for dairy cows, cattle and pigs respectively. The results from the simulations reach -30%, -20% and -30% only. The simulated rigidity of the sector prevented a larger decline of the animal stock.

It is now required to assess to what extent the rigidity is related to the assumptions of the simulation and to what extent it reflects the real situation.

The rigidity in behaviour is the main cause for the stability of the evolution. It first reduces the flexibility of the sector under changing market conditions. And secondly, it keeps prices at low levels, which drives the few adaptive farm agents away. The actual behaviour of farmers is certainly more nuanced. Far more behaviour types are necessary, with more detailed heuristics, to catch the dynamics of the sector in detail. Still, the current behaviour types have been calibrated to empirical data. So it is likely that more diverse behaviour types will result in similar levels of sector rigidity.

The second source of stability is the market for live animals. As long as the estimated production levels are maintained, the prices remain low, and this does not encourage adaptation in the sector. The model assumes general levelled prices for animals, and for dairy. This makes the development of diversified products or niche markets impossible. It remains possible that a simulation allowing diversified prices leads to new interesting agricultural subsectors that can ultimately affect the overall evolution. The first source of rigidity, the existence of non-adaptive behaviour, is checked with empirical data. The second source, the imposed standardisation of animal prices, has not been controlled to the same extent.

4.5.2 Evolution of the manure treatment sector

The evolution of the manure treatment sector is subjected to four different policy scenarios. The first scenario foresees no support and only limited private capital for investment, and this situation leads to a total phase-out of the sector. The other three scenarios present an uneven but very similar growth pattern and a shift in technology.

The first conclusion is that the availability of start-up and investment capital is very important. However the additional subsidies for industrial activity or for the reimbursements of internal R&D, do not give any additional benefits. In the case of additional subsidies for industrial activity, the sector growth is even less when compared to scenario II.

It is most interesting to compare these results with the results from the independent sector evolution in Chapter 3, section 3.3.2. The independent evolution showed a clear difference between the four scenarios, indicating a significant effect of the policies. Secondly, the overall sector capacities were much larger, the number of active parent companies higher, and these parent companies owned on average more active treatment plants as well. In general the sector presented a much stronger growth in the independent simulation.

From the point of view of the manure treatment companies, the main difference between the two simulations lies in the manure market. The independent simulation is based on a standard linear price-demand function, described in Table 3-8. This leads to immediate and coherent reactions between changes in demand and changes in price. The price also follows the evolution of the sector gradually. Moreover, the set-up guarantees a single and common market price for all participants.

The combined model does not provide the same market conditions. The manure market in the combined model is totally different, and this has important consequences for the manure treatment sector. The differences concern the supply of manure, the diversity in prices between different transactions and between different years.

The combined model connects supply and demand. Especially the supply is overestimated in the independent simulation. During the first years, the agricultural sector sees a short decline in animal stocks, and this reduces the availability of excess manure. The reduced amount of available manure affects the development of the new technologies during the first years. As discussed in the independent simulation, the first formative year are decisive for the further development trajectory of the technologies. Investments and breakthroughs during the first years allow the first development of active treatment plants, and these supply again income for further R&D. A smaller availability of manure leads therefore indirectly to less available funds for R&D and to a delay in innovative breakthroughs.

The second difference is the variability in manure prices. The auction market allows for differences in prices between transactions. Manure treatment agents insert their shadow price for manure in their purchase offer, and farm agents set their bid price according to their own sales history. So the prices of the successful transactions vary. There is also a variation in manure prices over the years, as manure treatment companies are not connected to the same farm agent in the long term. So their manure purchase price depends on the party they exchange with every year. This has an influence on the subsequent investment decisions. The manure treatment agent investigates the profitability of a new plant by calculating the total revenue of the plant over the entire lifetime of 15 years. This revenue takes a gradually increasing manure price into account. The starting point is based on the past manure transactions that the manure treatment company has done. If the agent has bought manure during the last year for a very advantageous price, the estimated profitability for a second treatment plant will be high. Inversely, if the agent was less fortunate and had to pay an expensive price for manure, the profitability of the new plant will be estimated very conservatively.

A better estimation would require the manure treatment agent to do in-depth market research, by comparing prices of different transactions, and by estimating the future price trend more precisely. This would allow the manure treatment agent to judge the risks and determine the plausible future benefits better. But the current simulated agents are not equipped with such an elaborate instrument to determine prices. Within the scope of these simulations, it is not sure if this extension would be opportune either. However, the effect on the sector evolution is that new manure treatment plants are launched taking either too much risk or too little. The treatment plants taking too much risk perish quickly. The manure treatment plants taking too little risk are based on conservative estimations, and are reduced in capacity. Both effects lower the total treatment capacity of the sector.

This effect may also explain the relative indifference between scenario II and scenario III. After several years, the sector consists of treatment plants that are more robust to market risks than the sector simulated in the independent model. This explains why a sudden decrease in subsidies for industrial activity does not cause the same number of bankruptcies as in the independent simulation, but a more gradual decline. The more robust plants do not fail immediately when the subsidies are stopped. They fold after a few years, surviving on the reserves built up during the years when subsidies were available.

The difference in market conditions causes large impacts on the sector evolution and on the influence of policies. The independent simulation showed a significant impact of the policies to support the development of an innovative manure treatment sector. Still the effectiveness of the different policies could be questioned, and this has been discussed in chapter 3. In the combined model, the impact of the policies is almost non-existing and sometimes even negative. It is important to note that the innovation dynamics and the behaviour of the companies are exactly the same for both situations. The difference in policy impact is an indirect effect of different market conditions. This poses a particularly difficult problem for policy makers. When a fully efficient and reactive market is assumed, as in the independent simulation, the policies bring results. When a market is assumed with diversified and volatile prices is assumed, subjected to the evolution of the agricultural sector, the policies no longer seem to have an impact.

The real market conditions and the real composition of the manure treatment sector probably lies between these two extremes. The fact is that the sector is dealing with market characteristics that are recurrent for biobased matter. Because manure transport costs are relatively high, regional and local price differences will exist. Manure is also an agricultural waste product, and large market mechanisms for effective price determinations do not exist yet, so negotiations between farmers and manure treatment companies may lead to price differences between individual transactions and between consecutive years. In order to reduce risks, the manure treatment companies may enter into partnerships with individual farmers or with cooperatives of farmers. This may lead to more stable prices and better predictions of future benefits. But the construction of these partnerships carries large transactions costs. In reality, manure treatment companies may also use better tools to estimate the risk they expose themselves to. So even if the market conditions in reality may be close to the market conditions simulated in the combined model, the behaviour of the manure treatment companies may result in a sector that is less conservative.

From the point of view of policy makers, it is important to have a more precise view on the market conditions, and on the heuristics that companies use to base their investment decisions on. The standard market representation with a price-demand elasticity leads to overly optimistic estimations of future policy impact.

There is always an easy solution to every human problem—neat, plausible, and wrong.

H. L. Mencken (1920)

Chapter 5 Conclusions

This chapter gathers the conclusions and reviews the added value of the chosen approach. The results indicate major points that require further analysis, and these avenues for future research are outlined as well.

5.1 Lessons learned

The general results are categorised under three headings, depending whether they are most relevant to the co-evolution of the two sectors, to the added value of the methodology or indicate the potential use of the model in different sectors and regions.

5.1.1 The co-evolution of the livestock production and the manure treatment sector

This dissertation has built a multi-disciplinary model to simulate the future evolution of livestock production in Flanders, and the related manure treatment sector. Qualitative descriptions of this evolution have been created in transition projects of the agricultural sector. The main trends of these descriptions are confirmed by the modelled results. The model followed the scenario of 'The Race'. This scenario relates to an agricultural sector during an economic downturn and subjected to free international markets for agricultural in- and outputs. The scenario describes the evolution of the sector with a growing part of impoverished and elderly farmers, accompanied by a declining animal stock. These results are confirmed by the simulated results. The total number of active farmers diminishes markedly from about 25.819 in 2010 to 21.250 in 2030. The proportion of elderly farmers grows from 11.2% in 2010 to 26.0% in 2030. The younger farmers that remain in animal breeding, are mostly farmers that see no alternative to their current farm structure. Due to lack of alternatives, they maintain their cattle and pig stocks, and obtain this way a reduced farm income. The animal stock is reduced with approximately 20 to 30% in 2030.

The simulation of this scenario enables a distinction between major and minor effects. Two major influences for the future evolution are the prices for live animals and the proportion of stable farm agents in the total agent population. The prices for live animals are determined by the scenario assumption on meat demand and prices for meat products. It takes until after 2035, that is until the peak of retired farmers starts to diminish, that positive market conditions are again noted.

The proportion of stable family farms is also highly influential. A proportion of 60% of stable and non-adaptive farmers is required to explain the historical production levels of live animals between 2000 and 2011. The same proportion determines the size of the animal stock between 2020 and 2040, where a relatively stable level is obtained, after the initial decline of the animal stock. A high proportion of stable family farms leads to a similarly high stable level, because at that point the farm agent population is mostly composed of stable and elderly farmers.

The simulation incorporates several effects that do not influence the outcome. Temporary price changes are integrated, but these are not sufficient to keep the current production levels. Also the creation of a more innovative manure treatment sector, that can produce outputs with higher added value from manure, does not change markedly the evolution of the sector.

The calibration of the model to empirical data has given specific insights in individual aspects of this economic sector. The calibration of the live animals market revealed significant market powers for the farmers producing live animals. One potential interpretation of this market power is connected to regional overproduction of live animals. This can be a result of reduced adaptability of the sector to changing market conditions. The calibration of the farm agent behaviour has revealed two of these rigidities: the rigidity in the land market and the presence of a significant group of farmers that do not adapt their farm structure according to the prevailing market prices. These rigidities are important concepts to clarify the evolution of the sector, and they are essential to explain the production levels of live animals during the last ten years. The same factors can be coherent with the existence of an overly large animal stock, and are very important factors that determine the speed of the evolution in the agricultural sector in the future. The results present an image of a sector where prices for agricultural in- and outputs only have a limited influence on the sector evolution. Other factors, such as alternative business models or the evolution of the farmers age pyramid are equally important. Future policies to guide the transition of agriculture have to take market and behaviour rigidities into account. The current approximation is only based on a coarse distinction between adaptive and non-adaptive farmers. Future research is required to get a more detailed view on these dynamics.

The manure treatment sector is also simulated, starting from the current technological composition. Gradually new innovative technologies appear on the market. The simulations show that new technologies are capable of taking over the entire sector, if this is accompanied by sufficient available capital for investment in new treatment plants. Without investments, the sector quickly decreases its overall capacity, and disappears in 2025. The sector is also subjected to different policies intended to stimulate the emergence of new biobased and sustainable manure treatment technologies. The simulated results show that the effectiveness of the policies depend strongly on the market conditions for manure. If the market is not fully efficient and presents high volatility and high risk, the impact of the policies is severely diminished.

The comparison between the disconnected evolution of the manure treatment sector, and the simulation with the full model, reveals that the emergence of the manure treatment sector is highly dependent on the manure market dynamics. The full model shows a smaller treatment capacity over time, due to growing scarcity of manure and to high volatility of the price on the increasingly thinner manure market. In most cases, the sector remains limited in capacity. The physical scarcity of manure does not drive up the price, but prevents the growth of the treatment sector. This results in a very limited impact of the evolution of the manure sector on agriculture.

5.1.2 Review of the methodology

This dissertation simulates the evolution of the agricultural sector, influenced by emerging innovations in the manure treatment sector. This evolution contains multiple aspects, and requires the integration of several scientific fields, such as engineering, sustainability science, evolutionary modelling, industrial economics, agricultural economics, and behaviour models. The combination of all these elements is innovative. But this elaborate approach makes uncomplicated and straightforward communication of the results very challenging. Communication is a common barrier for the valorisation of results from Agent based models, as it is also in this case.

Despite these disadvantages, the approach has provided valuable results. The research approach is set up to investigate the future evolution of agriculture including complexity effects. Qualitative scenarios for this evolution have been created, based on transition thinking. The model has clearly been able to add new insights to the general results of the qualitative scenarios. It also added a lot of precision to the scenarios and provided several alternative pathways for future research on the agricultural sector. Several aspects of importance in transition thinking have also been included in the current simulation method, and these aspects have provided added value:

- Complexity and endogenous markets: The principal reason to start with an agent-based approach was to allow the model to replicate the complexity inherent in transitions. The complexity has been simulated by connecting different groups of actors through endogenous markets. The results display the advantages of this approach. The separate simulations of the manure sector shows very different results, as many aspects of the evolution are not accounted for in a disconnected simulation. The fact that the interaction between the two sectors produced only a smaller effect for agriculture in this case is one of the major conclusions of the dissertation.
- Endogenous innovation: The appearance of new innovations has been shown to depend on the evolution of agriculture as well. The endogenous appearance of

innovations was the only approach that could make this dependence possible in simulations.

- Diversity and models of behaviour: This part turned out to be a crucial element of the approach. The calibration of the diversified behaviour clarified the existence of internal barriers for change in the agricultural sector. These barriers have strongly influenced the final simulations of the future evolution. The structural diversity of the actors has also influenced the results.
- Integration of physical dimensions: Both the internal markets are based on physical quantities, tons of manure and agricultural land. The definition of these exchanges based on the physical dimensions permitted the inclusion of real constraints, such as the limited quantity of total agricultural land in Flanders and the limited quantity of manure that can be disposed of per unit land. Also the analysis of the sustainability of the treatment technologies was enabled by the relation with the physical quantities for in- and outputs.

The main novelty of the approach has been the combination of these multiple elements, and each of these elements has enriched the results. Through the combination, it is possible to detail the evolution of agriculture and its related sectors, and to weigh the importance of very diverse aspects against each other. The results respect the interconnections between different aspects and are therefore more balanced.

5.1.3 Potential for alternative application

The current model has been built to approximate Flemish agriculture in detail. A lot of effort has been put in the detailed calibration of different parts, leading to a very specific model suited for a very particular application. The same model and approach can be applied in different contexts, for different regions or for alternative scenarios. The modifications that are required depend on the alternative use of the model. The most direct adaptation of the model is the analysis of a similar dynamics in a different region. In a very similar region, the adaptation would only require new calibration efforts. The largest effort is in this case the collection of appropriate data and the recalibration of the starting population of agents. After these steps, the same model can be readily applied for the analysis of future scenarios.

When the model is adapted to a different region, the differences in the structure of the agricultural sector have to be considered. When the structure is similar, recalibration can be sufficient. But the appearance of new types of farms may very well require the adaptation of the model itself. This can for instance be the case when different types of livestock, that are of lesser importance in Flanders, are prominent in another region, such as goats or sheep. In that case, an additional column of animal types has to be added. This modification is easily feasible, but requires a precise change in the program.

A second difference may appear when standard crops are being replaced by perennial cultures, such as grapes, olives or orchards. This can change the cost structure of the farm, and – more importantly - the adaptability of the individual farm. When the model is adapted to a region with a large proportion of perennial cultures, these modifications has to be programmed.

Larger adaptations are needed when the model is applied to a region where more informal markets are regular. This can include region where animals are slaughtered and meat is prepared at the farm. This change is quite easily feasible in the model, but it requires a diversification of the type of products that a farm can produce. On the other hand, when a large part of the farm's production is destined for personal consumption, the model adaptations become more important. Other models, such as MP-MAS, have integrated very detailed dynamics that simulate the relation between the household's nutritional habits and adaptations, and the farm's production. These dynamics are not present in the current model.

The sector of manure treatment agents can be adapted to represent various types of sectors with technological diversity and a structure based on industrial plants. The main restriction is that the current model is based on technologies that use a physical input. The production function is thus bound by a mass balance. In this case, two different inputs are implemented – liquid and dry manure – and up to four different outputs are possible with one technology. This structure can be sufficient for multiple industries. It is also possible to extend the number of different in- and outputs with small software adaptations. This makes the model applicable to investigate the innovation dynamics in several sectors. Multiple sectors can also be simulated in parallel, so co-evolution is very well possible in this set-up.

More far-reaching adaptation are required if the industry is more information-driven and less based on the transformation of physical matter. In principle, this adaptation can be easily included, by changing the production functions for the different technologies. But the innovation dynamics as such may very well differ from the described dynamics here. Also the model is based on the assumption that industrial installation cannot improve drastically their production efficiency when new technologies are available. This is much less the case in information-driven industries.

5.2 Options for further research

The results are based on diverse assumptions and model limitations. These have been imposed in order to keep the practical development of this research within a realistic timeframe. The results indicate the largest influences in the modelled evolution, and the points that are most important to look into during further research.

5.2.1 The development of the biobased economy

The technological advances of the biobased economy will reach the stadium of pre-industrialisation and may soon be practically applied. This dissertation looks at a very limited sample of these technological advances. The entire range of new developments can influence agriculture and the related sectors much more. A first step to gain more insight in this evolution is therefore to extend this research into crop farming and forestry. The proposed innovations of the biobased economy rely strongly on the cultivation of new crops or on innovative use of forestry residues. This development can induce important land use changes. But limitations to the available biomass may create a barrier to the development of the biobased economy as well. In this case, it showed that reduced availability of manure presented an important barrier to the development of the biobased sector. Without additional private or public funds, the sector will entirely disappear. In this case, it has also been shown that there is no explicit co-evolution between the two sectors. The evolution of agriculture is not influenced by the rise of the manure treatment sector. This is because this biobased sector does not alter significantly the prices for manure.

The biobased economy is larger and contains a vastly more diverse technology set than the subsector of the manure treatment technologies. The biobased economy equally needs an adapted biomass supply in order to emerge. This requires crop substitution and changes in agricultural practice. A crucial point in this respect is then to see if a co-evolution is indeed possible. This implies first research on evolutions of biomass markets. What are the factors that determine the actual prices, and will prices be affected by the new evolutions? The second part is then to see if the price changes are sufficient for agriculture to adapt fast enough to ensure the minimal biomass availability to launch new biobased innovations. This combination determines the minimal adaptation speed of agriculture to enable the biobased economy.

A specific part of these investigations can make use of the present results on the emergence of the manure treatment sector. Small technological niche sectors cannot immediately influence market prices for biomass. A sizeable sector can be influential for market prices, but this sector does not develop if the biomass is not available. Inversely, unchanged prices do not induce market-based crop substitutions from farmers, leading to a lock-in.

This leads to two focussed options for this interaction. The first option regards the independent evolution of agriculture as given and investigates the potential emergence of the biobased industry following that availability of biomass. In the end, a combined model can clarify to what extent the initial assumption of lack of co-evolution has influenced the results.

The second option investigates alternative collaboration models between the industry and farmers. Alternative collaboration models can motivate adaptation and crop substitution for individual farmers, while increasing certainty on the availability of biomass a specific price level. This could allow the production and exchange of biomass separate from the general market; thereby avoiding the lock-in.

5.2.2 Ecological impact and ecosystem services

This dissertation has focused on technological innovation and its coevolution with agriculture. The same approach is possible for further investigation of the relation between agriculture and its surrounding ecosystems. A large scientific field is specialised in this relation. In an evolutionary approach, the relation between agriculture and regional ecosystems can be developed. Advances are still possible on new instruments that aim to account for the value that ecosystem services provide for agriculture. These instruments, such as payment for ecosystem services (PES) schemes, can influence the evolution of agriculture. Two aspects that have not been integrated here will have to be added in this case. First, the focus on ecosystem services requires more detail in the biological relations of the farm activity with its land, and with the surrounding area. Secondly, the investigation of regional ecosystems requires the entire model to be defined with geographical characteristics as well. This is a substantial expansion that will require also additional large efforts.

5.2.3 Adaptation in behaviour and new business models

The results indicate that the adoption of innovative business models for farmers may be unique in its capacity to influence the future evolution of agriculture. Modified business models have been shown to be powerful at the level of the individual farm, when solutions such as farm shops, community supported agriculture, organic and agro-ecological agriculture, small cooperatives or partnerships have drastically changed the financial structure of the farm.

Further analyses can clarify the potential for the entire sector. This requires a more detailed look at the relations between farmers, and the relations of farmers with their customers and suppliers. To investigate the potential of new business models for farming, the investigation has to combine work on innovative case studies with a network analysis of the farming sector and their regional clients.

The dissertation has used a model with diversified behaviour. The discussion stated that this current definition of behaviour heuristics is only a first approximation. The behaviour heuristics have shown to be extremely important in the definition of sector rigidity, and in the simulation of the future evolution of livestock production.

Given its importance, more insight in the actual behaviour types will provide much more precise results and will also provide avenues for new policy interventions. If behaviour is not entirely driven by financial motives, then policy interventions must take the other motives into account in order to be efficient. Especially the behaviour of elderly farmers deserves further detail in this respect.

A research project to detail and model these behaviours has to start from field work. Different options are available, such as questionnaires, discussion groups or role-playing games. A second part models these heuristics in order to estimate the adaptation speed of the agricultural sector more precisely. A specific link with the option for business model innovation is important here. The calibrations in this dissertation indicated that many farm agents do not adapt their farm structure under price constraints. What will then be the willingness of farmers to adapt their business model? Changes in business model can be much more disruptive, and even though several individual success stories exist, it is not sure how capable the sector is to adopt these innovations universally. A further research into the behaviour heuristics of farmers should therefore include the willingness to adapt both the farm structure and the farm business model.

5.2.4 Market research and price rules

The simulated results have illustrated the large dependence of the sector evolution on the market prices and market conditions. Also the impact of the policies to support new biobased processes was highly influenced by the assumed market rules.

Market prices are essential sources of information. The manure market is in this case a representation of various markets for biobased materials. The market has price variability between actors, between transactions, and over time. Many markets for organic matter and agricultural waste streams are under development, because with the interest in the bioeconomy, new actors are emerging and new pathways for the transformation of biomass are being created. The evolution of new biobased sectors and agriculture will both be influenced by the exact market conditions and price determination rules. Policies to stimulate a successful bioeconomy as well as policies for a sustainable agriculture will both require more research into the exact market mechanisms and their effect on the evolution each sector.

Prices for live animals are equally essential sources of information that steer the future evolution of the agricultural sector. There is a lot of research in the price rules and power balances in the markets for agricultural products. It is important to continue and refine this work to include price differentiation and different types of partnerships in the supply chain. A more detailed view on the prices for agricultural produce will also enable a better insight in the evolution of the agricultural sector.

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Annex A Regressions for production

Table A. 1 : Weighed non-linear regression results to determine the individual labour need

		α_I	β_I
Dairy cows		0.00813***	0.947 ***
Other Cattle		0.399***	0.201***
Pigs		0.0177***	0.669***
Crops		0.0455***	0.675***
Horticulture		0.591***	0.108***
Forage		0.151***	0.241***
R^2	0.908	Adj. R2	0.908
Obs.	466	Weighed Obs.	1,472,118

Table A. 2 : Total fodder need (in tons) regression per animal type

	Cow fodder need		Pig fodder need
# of animals	Dairy cows	1.304***	2.329***
	Other cattle	1.091***	
Weighed obs.	1,225,857		611,968
R^2	0.821		0.873
Adj. R^2	0.821		0.873

Table A. 3 : Annual costs regression per animal type

	Dairy cows	**Other cattle**	**Pigs**
# of animals	129.5***	89.5***	64.6***
Weighed obs.	1,472,118		
R^2	0.795		
Adj. R^2	0.795		

Table A. 4 : Average annual costs

Surface		**Other crops**	**Horticulture**	**Forage**	**Grassland**
Symbol [unit]		A_C [ha]	A_H [ha]	A_F [ha]	A_C [ha]
Annual costs	Average	634***	2716***	405***	185***
Weighed obs.	1,472,118				
R^2	0.893				
Adj. R^2	0.893				

Table A. 5 : Initial subsidy relations

Variable	Regression coefficient
Fixed assets	0.0224***
Dairy cows	156***
Other Cattle	162***
Pigs	-14.2***
Crop acreage	875**
Horticulture acreage	-237***
Forage acreage	612***
Grassland acreage	426***
Observations	466
Weighed Observations	1,472,118
R^2	0.928

Table A. 6 : Regressions for predictions of animal production

	Crops	**Horti-culture**	**Forage**	**Milk products**	**Cattle products**	**Pig products**
α_I	1,211***	3,636 ***	0.230***	5.70***	0.200 ***	1.015***
β_I	1.132***	1.237***	1.317***	1.093***	1.199***	1.091***
Weighed obs.	1,203,921	287,624	1,177,806	699,736	915,037	611,968
R^2	0.812	0.665	0.306	0.967	0. 829	0.864
Adj. R^2	0.812	0.665	0.306	0.967	0. 829	0.864

Annex B ODD-protocol description & technical implementation

The final model is implemented in Matlab code, with the following technical characteristics :

- Software version : Matlab/R2012b © 1994-2015 The MathWorks, Inc.
- 59 modules, and 23 data input matrices.
- Random generation based on a random seed database

Each is represented in the model as a matrix, containing all data relative to the agent during the course of one year. The construction gathers all agents in a similar structure, and the agent matrix is renewed every year. Each agent type has a different structure. The farm agent structure is illustrated in Table B.1. The structures for the technology parent company and the technology project are shown in Table B.2 and B.3 respectively.

Table B. 1 : Schematic structure of all variables for the farm agent

		1	2	3	4	5	6	7
1	**General Data**	Farm ID	Age	Initial risk factor (RF_0)	Age-adapted risk factor (RF)	Farmer Type[3]		
2	**Structure**	# of working persons in the household	Total used land (ha)	Rented land (ha)	Owned land leased to others (ha)	Dry manure percentage	Nitrate reduction due low emission nutrition	Will be taken over[4]
Production categories		Crops	Horticulture	Forage	Grassland	Dairy cows	Cattle	Pigs
3	**Production efficiency**	f_{Crt}	f_{Hot}	f_{Fot}		f_{Dt}	f_{Ct}	f_{Pt}
4	**Predicted prices**							
5	**Area (ha) or # (LSU)**	A_{Cr}	A_{Ho}	A_{Fo}	A_{Gr}	An_D	An_C	An_P
6	**Fodder input (Tons)**							
7	**Production (Qty)**							
8	**Annual costs (EUR)**							
9	**Labour demand (FTE)**							

[3] There are 6 different farm types, according to behaviour types : 1 : Industrial, 2 : Innovator, 3 : Growing Family farm, 4 : Elderly farm, 5 : Out, 6 : Stable farm
[4] Takeover situation : No successor = 1; Will be Taken over = 0

		1	2	3	4	5	6	7	
10	**Manure production data**	Total dry manure production [m³]	Dry manure N-content [kg/ton]	Dry manure P-content [kg/ton]	Dry manure Total N from animals [kg]	Mineral fertiliser need N in kg	Ideal acreage [5]	Ideal Dairy stock[5]	**Ideal farm data for Stable Family Farms**
11		Total liquid manure production [m³]	Liquid manure N-content [kg/ton]	Liquid manure P-content [kg/ton]	Liquid manure Total N from animals [kg]	Mineral fertiliser need P in kg	Ideal Cattle stock[5]	Ideal Pig stock[5]	
12	**Manure spreading by grazing**	Effective N-Content [kg]	P-Content [kg]	Animal N content [kg]	Ideal requested sales price	Requested sales price	Sold land surface	Final sales price	**Land sales data**
13		Total Qty [m³]	Out 1 Used [m³]	Out 1 sold [m³]	Ideal requested purchase price	Requested purchase price	Purchased land surface	Final purchase price	**Land purchase data**
14	**Liquid Manure spreading**	Effective N-Content [kg]	P-Content [kg]	Animal N content [kg]	Last year's sale price	Ideal requested price			**Liquid manure sales**
15		Total Qty [m³]	Out 1 Used [m³]	Out 1 sold [m³]	Request price	Sales price			
16	**Dry Manure spreading**	Effective N-Content [kg]	P-Content [kg]	Animal N content [kg]	Last year's sale price	Ideal requested price			**Dry manure sales**
17		Total Qty [m³]	Out 1 Used [m³]	Out 1 sold [m³]	Request price	Sales price			
18	**Secondary manure flow spreading (digestate)**	Effective N-Content [kg]	P-Content [kg]	Animal N content [kg]	Ideal requested sales price	Requested sales price	Sold land surface	Final sales price	**Land sales data**
19		Total Qty [m³]	Out 1 Used [m³]	Out 1 sold [m³]	Ideal requested purchase price	Requested purchase price	Purchased land surface	Final purchase price	**Land purchase data**

[5] Only for stable family farms

20	**Financial data Before investment decision**	Overhead percentage	Depreciation percentage	Total fixed assets (No land)	Total Fixed Assets (Land only)	Total assets	Total Cash At start of year	Efficiency investments	
21		Total liabilities	Loan interest percentage (%)	Total land rent	Average land rent price	Annual capital reim-bursement	Annual interest payment	Total land lease	
22	**End-of-year results**	Total Income	Total cash at the end of the year	Out ? Out = 1 Not out = 0	Out by retirement ? No = 0 Retiring = 1	Retirement mode ? Sells farm = 0 Successor = 1	Broke ? Not broke = 0 Broke = 1	Animal farm ? Still animals = 0 No Animals = 1	**Continuation result**
	Production categories	Crops	Horticulture	Forage	Grassland	Dairy cows	Cattle	Pigs	
23	**Farm structure changes next year**	Surface addition or reduction	Surface addition or reduction	Surface addition or reduction	Surface addition or reduction	Stock Change (%)	Stock Change (%)	Stock Change (%)	
24	**Sales prices**								
25	**Decisions for farm growth**	Total income division FFI	Total income division Investments	Total income division Liquid assets	Estimated need for land surface to sell this year	Estimated need for land surface to rent this year	Estimated need for land surface to lease this year	Optimal loan horizon	
26	**Financial data After investment decision**	Overhead percentage	Depreciation percentage	Total fixed assets (No land)	Total Fixed Assets (Land only)	Total assets	Total Cash At start of year	Efficiency investments	
27		Total liabilities	Loan interest percentage (%)	Total land rent	Average land rent price	Annual capital reimbursem ent	Annual interest payment	Total land lease	

Table B. 2 : Structure of the technology parent company

Row	Column n°		1	2	3	4
1	**General Data**		Parent ID	Strategy		Strategy
				γ		Manure price trend
2			Initial capital	Invested in projects	Liquid assets	Tech type
3			Invested in R&D		Active ?	Investment lever
4	**Innovation factors**	**Qty**	R&D success	Available alternative	New factor from internal R&D	Available alternative
			g_{it}	f_1w_1 (if licensed)	$\tilde{f}_t$	Parent ID
5		**Price**	R&D success	Available alternative	New factor from internal R&D	Available alternative
			g_{it}	f_{qual} (if licensed)	$\tilde{f}_t$	Parent ID
6		**Investment**	R&D success	Available alternative	New factor from internal R&D	Available alternative
			g_{it}	f_{Inv} (if licensed)	$\tilde{f}_t$	Parent ID
7	**Production**	**Efficiencies**	f_1w_1	$f_2\ w_2$	$f_3\ w_3$	$f_4\ w_4$
8			f_{qual} (price)	f_{Inv}		
9			Subsidies	License income	License cost	
10	**Results**		Total benefit	Next year's Liquid Assets	Total surface of land in projects	Cumulative amount of R&D investment
11	**Owned Projects**					
12			ID	Benefit	Capacity Liquid	Capacity Dry
13			ID	Benefit	Capacity Liquid	Capacity Dry
15			ID	Benefit	Capacity Liquid	Capacity Dry
16			ID	Benefit	Capacity Liquid	Capacity Dry
…			…	…	…	…

Table B. 3 : Structure of the technology project

Row	Column n°	1	2	3	4
1	**General**	Project ID	Age	Owner ID	Initial investment

2	**Data**	Technology type	Remaining lifetime	Active? (0 : Latent, 1 : Active, 2 : Out)	Manure price trend
3	**Structure**	Total used land surface (ha)	Project is going to trade land (0 : No, 1 : Yes)	Capacity liquid manure	Capacity dry manure
4 5	**Production efficiency**	Output 1 % from parent company f_{qual} (price)	Output 2 % from parent company f_{Inv} (investments)	Output 3 % from parent company	Output 4 % from parent company
6 7	**Production**	Product 1 [EUR]	Product 2 [EUR]	Product 3 [EUR]	Product 4 [EUR]
8	**Income**	Turnover	Subsidies		
9	**Land market interactions**	Land sale Ideal requested price	Land sale This year's request price	Sold land surface	Land sale This year's sale price
10		Land purchase Ideal requested price	Land purchase This year's request price	Purchased land surface	Land purchase This year's purchase price
11 12 13 14	**Costs**	Annual Costs [EUR] Energy Costs [EUR]* Labour cost [EUR] Transportation costs [EUR]*	Remaining loan Interest paid Capital reimbursed Manure costs		
15	**Result**	Net Benefit	Continuation result Out = 1/Not out = 0		
16	**Manure market interactions**		Liquid manure Last year's purchase price	Liquid manure Ideal requested price	
17		Liquid fraction bought [m³]	Liquid manure this year's request price	Liquid fraction bought [m³]	Liquid manure this year's obtained price
18			Dry manure Last year's Purchase price	Dry manure Ideal requested price	
19		Dry fraction bought [m³]	Dry manure this year's request price	Dry fraction bought [m³]	Dry manure this year's obtained price

Table B. 4: Description of the ABM model based on the ODD protocol (Grimm et al., 2010)

Overview

1. **Purpose**: The purpose of this agent-based model is to simulate the effects on manure treatment evolutions on the Flemish agricultural sector. Shocks can be exerted by new policies for manure disposal, or innovative technologies for manure treatment. The effects on farm activity, land prices, or market prices are investigated. The aim is to advise policy makers on optimal measures to stimulate the introduction of new sustainable manure treatment technologies, taking into account the adaptation of the agricultural sector.
2. **Entities, state variables and scales**: Farms are the main entities in the program. These are simulated as independent agents with both technical and behavioural characteristics. Technical data include the farm acreage with different types and ownership, the stock of dairy cows, other cattle and pigs, as well as financial balance data. Behavioural characteristics include financial risk aversion, and farm optimisation preferences.
   A second group of agents are the technology parent companies. These specialised in distinct technologies for manure treatment, and build industrial plants for manure treatment over time.
3. **Process overview and scheduling**: The model works in annual steps.

Design concepts

4. **Basic principles**: The model investigates the appearance of new manure treatment technologies, during a technological transition in the agricultural sector. This appearance of new actors happens due to a continuous non-equilibrium of the manure market. Because these new technologies also require land, and produce feedstock or other valuable outputs for agriculture, they have simultaneous effects in multiple agricultural markets. The model looks particularly at these complex relations.
5. **Emergence**: New actors and entrepreneurs or are introduced annually, or are latently present and activated when necessary conditions are present. Creation of new agents or entities by existing agents is not present.
   A particular feature is the emergence of innovations in the manure treatment sector. Following the innovation dynamics and R&D successes of the technology companies, new innovative solutions can emerge and can subsequently be applied in an industrial plant.
6. **Adaptation and objectives**: Farms adapt themselves according to their personal objectives. They have the capacity to increase or reduce to a limited extent the number of animals in

their stock, as well as the rented and owned surface of land. The model assumes behavioural diversity, and this leads to different objective functions for different types of farm agents. The technology companies are not implemented with this diversity, and are all profit-maximising entities.

7. **Learning**: Learning capacity is implemented through efficiency investments and transaction costs for any change that the farmer executes.
8. **Prediction**: Farms decide future investments and adaptation based on price predictions for inputs and produced outputs. These predictions are based on past experiences of sales and purchases, as well as on the general market information of the past years.
   The technology companies decide on future investments, taking a conservative evolution of the manure price into account. All other prices for their prediction are based on current market situations.
9. **Sensing and interaction**: The agents sense information through market interaction. Markets for land, manure and outputs not only publish average transaction prices, but also quantities of products unsold during regular market activity. The higher the unsold quantity, the lower the farmer sets his expectation on a good bargain price for next year's transaction.
10. **Stochasticity**: Stochasticity is present in the annual production. Annual farm production varies stochastically around the theoretical production based on the farm's assets. The stochasticity of one individual farm's production is unrelated with others.

11. **Initialisation**: The model is initialised by a group of reference farms, selected from the FADN database and calibrated to represent the Flemish agricultural sector both in production as in technical characteristics.
12. **Input Data**: The input data is collected in Annex I .
13. **Submodels**: One submodel determines the price of live animals at the slaughterhouses, based on an econometric analysis of slaughterhouse market power.

Annex C Slaughterhouse market analysis

In order to achieve a structural model of the live animals market, the dissertation includes a detailed market power analysis of one of the central actors in the meat supply chain: the slaughterhouses. After a short review of the market structure, an appropriate market power model is chosen in relation with the literature on this subject, and is built for this specific case.

Market description

The slaughterhouse sector in Belgium is highly diverse and contains a large number of independent entities. Whereas more than 200 slaughterhouses were active around 1995, only approximately 90 large active sites remained in 2011. Still, this number remains sufficiently high to allow a diverse sector that - at the first sight - does not show signs of excessive concentration. Table C. 1 reports the numbers of active slaughterhouses for cattle and pigs, based on official data from the Federal Agency for Safety of the Food Chain (FAVV). The smallest entities, with less than 10 animals per year, were excluded because they are related to artisanal butchers and local actors that rely on a personal supply chain. Also note that a limited number of mixed slaughterhouses are active in the production of both beef and pork and are present in both sides of the Table. The Herfindahl-Hirschman index (Hirschman, 1964), which is reported for each subsector, indicates a slow and gradual consolidation for pig slaughterhouses but not for cattle slaughterhouses.

Table C. 1: The number of active slaughterhouses for pigs and cattle and their market concentration.

	Cattle slaughtering				Pig slaughtering			
Year	Number of active entities	Average intake of live animals	Maximum intake of live animals	HHI[6]	Number of active entities	Average intake of live animals	Maximum intake of live animals	HHI[5]
2006	63	10,174	51,567	413	64	171,055	1,140,604	563
2007	61	10,375	50,708	411	61	189,092	1,155,094	570
2008	62	10,315	48,214	428	64	182,134	1,189 932	610
2009	54	11,536	66,753	503	60	199,469	1,350,932	681
2010	50	12,754	55,107	475	55	219,371	1,364,651	627
2011	50	13,245	51,626	440	51	232,532	1,476,973	680

The role of slaughterhouses is pivotal in the meat supply chain. Unlike the situation in other countries (Hayenga et al., 2000; Schulze et al., 2006), finding strong vertical integration in Belgium is not common. The largest slaughterhouses are independent factories, producing beef and pork carcasses with multiple clients and suppliers. The further transformation of the carcasses to meat products happens upstream in the supply chain.

Table C. 2: Average data on farms raising cattle and pigs in Belgium

	Cattle		Pigs	
Year	Number of farms	Average livestock size	Number of farms	Average livestock size
2000	38,370	79	10,230	720
2003	33,610	83	8,650	756
2005	30,840	88	7,720	818
2007	28,460	93	6,990	895

The price setting in market of live animals is based on the interaction between the slaughterhouses and the individual farmers who present their animals. In principle, this leads to different prices for each transaction. Certainly during the last decade, price differences for live cattle and pigs have diminished and the price became increasingly levelled across the sector. Several trends contribute to this evolution.

First, slaughterhouses publish their weekly purchase prices. Farmers are very well informed of price movements and tendencies. Pig prices are determined by local market situations and

[6] HHI = $\sum S_i^2$, where S_i is the market share of slaughterhouse i in percentage points. HHI ranges from $10\,000/n$ in a perfectly competitive market (*n*: number of slaughterhouses) to 10,000 in a perfect monopoly.

the published purchase prices in Germany (Schleswig-Holstein) and the Netherlands. The various governmental efforts to introduce transparency into the meat production chain resulted in the largest pig slaughterhouses publishing their purchase prices for live pigs on a weekly basis. These data are also collected by government institutions and farmers' associations. Individual farmers hold discussions to within a small variation of the published price depending on the quality of their animals. VEVA, the cooperation of Flemish pig farmers, collects the weekly net prices that farmers received after negotiation. These prices differ little from the published prices and closely follow the average prices throughout the year. Table C. 3 reports the average annual input prices for live cows and live pigs. The cattle prices for all types of cattle are averaged by weighting them by the number of heads for each type and represent the net prices received by farmers for their animals.

Table C. 3: Yearly average nominal prices for live animals [EUR]

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Cows	1,188	849	933	1,137	1,005	1,076	1,350	1,292	1,340	1,400	1,411	1,421
Pigs	135	161	131	117	135	133	138	127	144	133	127	137

Secondly, the slaughterhouses stress that negotiations with farmers are always critical. Significant effort is required from the slaughterhouses to obtain a sufficient amount of live animals, and competition for live animals among slaughterhouses is fierce.

Thirdly, for live cattle, cattle diversity is an additional factor. Sales of steers or bulls, heifers, old dairy cows, or calves all provide very different prices. Within the types, very different body qualifications are possible. Historically, the cattle supply chain contained one intermediary player between the farmers and the slaughterhouses: the negotiator. This person bought live cattle at the farms, and then negotiated a better price at the slaughterhouse for his lot. These negotiators maintained a profitable activity because the correct qualification of cattle value required significant experience. Because of advantages of scale, they were also able to exploit a better negotiation position against the slaughterhouse. However, during the last years, cattle qualification procedures became increasingly standardized and negotiators' added value was reduced to just transport.

Table C. 4: Number of slaughtered animals and net export during the last decade.

	Cattle			Pigs		
	Slaughtering	Net export of live animals		Slaughtering	Net export of live animals	
Year	thousands of LSU	thousands of LSU	%	thousands of heads	thousands of heads	%
2001	695.6	82.4	11.9%	11,314.9	–260.1	–2.3%
2002	749.2	110.6	14.8%	11,175.7	–159.7	–1.4%
2003	669.9	79.7	11.9%	11,234.0	–65.1	–0.6%
2004	667.5	80.0	12.0%	11,117.2	–256.6	–2.3%
2005	636.9	68.7	10.8%	10,903.5	–173.2	–1.6%
2006	627.8	30.1	4.8%	10,740.8	–154.8	–1.4%
2007	626.2	24.2	3.9%	11,223.0	–419.1	–3.7%
2008	626.5	7.6	1.2%	11,157.4	–371.8	–3.3%
2009	593.0	–15.9	–2.7%	11,161.3	–525.1	–4.7%

Figures from Eurostat and VLAM (Flemish agricultural marketing agency). Totals for cattle include adult animals, young animals, and calves and were combined using FADN livestock unit (LSU) factors.

Finally, the interaction with markets in neighbouring countries is also an important influence for the price setting. As illustrated in Table C. 4, slaughterings in the beef sector have slowly decreased since 2001. Yet, net exports gradually turned into net imports during the last decade. In 2001, cattle production capacity exceeded slaughterhouse capacity. However, this situation reversed in 2009, obliging slaughterhouses to import live animals from neighbouring countries. The situation is not the same for the pork sector, which has always experienced a net import of live pigs – a trend that slightly increased during the last decade. The overall slaughterhouse intake of live pigs remained at approximately 11,000,000 animals per year, whereas the produced quantity in Belgium decreased.

Table C. 5: The proportion of the Belgian carcass production destined for export.

	Unprocessed Beef			Unprocessed Pork		
Year	Total production	Net export		Total production	Net export	
	[tons]	[tons]	%	[tons]	[tons]	%
2005	271,133	64,545	23.8%	1,014,623	508,870	50.2%
2006	268,917	57,301	21.3%	1,008,037	524,935	52.1%
2007	272,863	59,118	21.7%	1,063,278	569,098	53.5%
2008	267,288	64,913	24.3%	1,056,169	578,539	54.8%
2009	254,918	53,357	20.9%	1,082,036	615,255	56.9%
2010	263,145	66,232	25.2%	1,123,767	619,443	55.1%
2011	272,282	73,620	27.0%	1,108,254	605.229	54.6%

On the output side of the slaughterhouses, the clients vary from meat distributors to retailers. For pork, 142 companies are active in the meat production and meat processing sector (FOD Economie, 2010), of which only two are integrated from the slaughterhouse to the meat product sales market. A similar image of a highly diverse and distributed sector exists for beef carcasses.

Although exports had limited influence in the market for live animals, this influence is much larger for the market of carcasses. As Table C. 5 illustrates, most pig and cattle carcasses are destined for export. The openness of the output markets obliges the slaughterhouses to take into account international price trends.

A market review of the relationship between farmers and slaughterhouses provided mixed signals in terms of the power balance. On the one hand, some factors may tend to expect market power from the slaughterhouses. The negotiation leverage induced by scale might provide a power advantage to slaughterhouses over individual farmers when discussing sales prices for live animals. Active slaughterhouses in Belgium are also decreasing in number, and pig slaughterhouses show a particular trend toward market concentration.

On the other hand, farmers also seem to maintain their ground. Sales prices are levelled across the sector. Slaughterhouses are also increasingly obliged to seek live animals abroad, incurring higher transportation costs. Finally, on the output side, slaughterhouses are obliged to account for international meat prices because of the large proportion of meat products destined for export.

Because a prevalent indication of market power is lacking, the model construction must be sufficiently flexible to allow for different types of market structures. The existence of levelled prices enables the option to model competition or collusion on a quantity basis.

For this study, a unique database of panel data on different types of information was assembled. The final panel data set contains 452 observations between 2002 and 2011 with combined slaughter data and financial data on 69 slaughterhouses. This database includes most of the sector's activity in Belgium. In this study, two slaughterhouse categories are considered: specialized cattle and specialized pig slaughterhouses. Mixed slaughterhouses for cattle and pigs and specialized poultry slaughterhouses are excluded from the scope of this study.

Market models for live animals and meat products

There are several approaches to estimate market power, such as conduct-performance models, industrial structure analysis or dynamic games (Perloff et al., 2007). A specific strand of industrial structure used this approach extensively, and has been grouped under the name "new empirical industrial organization" (NEIO) (Bresnahan, 1989). The NEIO approach frequently measures market power by estimating conjectural variations (Iwata, 1974). The conjectural variation is based on one strategic output of a firm (most often price or quantity) and indicates whether firms regulate their strategic output as a consequence of their competitors' change in output. When non-negligible interaction is measured, the conjectural variation reveals different types of non-competitive market behaviour, such as collusion or price arrangements between competitors (Appelbaum, 1982). The conjectural variation may also be directly linked to a price wedge and to standard price mark-ups, such as the Lerner index.

In this case, the model needs to include the potential for both oligopoly and oligopsony in the slaughterhouse sector. In this case, the NEIO approach is appropriate because its flexibility allows for modelling of various different market configurations. Depending on the range of conjectural variations, different types of collusion or market leadership by a predominant actor may be discovered (Roy et al., 2006). Because of the contradictory signals of the role of slaughterhouses, predicting the most appropriate type of market distortion is not possible. The NEIO approach allows for this freedom and maintains a reasonably simple model structure on the basis of a single parameter per market (Sexton, 2000).

The single-sided use of conjectural variation in only the input or the output market has frequently been applied in agricultural markets (Myers et al., 2010) and most regularly in the beef packing industry in the United States (Sheldon et al., 2003). Lloyd et al. (2006) used the market shock created by the crisis sparked by the Mad-cow disease in the United Kingdom to investigate market powers in the U.K. beef market. Applications also looked at mark-ups in Australia (Chung et al., 2009) or the Ukraine (Perekhozhuk et al., 2011), among others. This single-sided analysis was further refined to account for input substitution (Azzam et al., 1990), regional consolidation (Azzam et al., 1991), and relations' regional and national indications of oligopsony (Perekhozhuk et al., 2014). Whereas these studies mostly looked at the power structure at the sector level, further detailed analysis could use data at the firm level. Therefore, an increasing number of studies combined the effect of market power and firm efficiency (Delis et al., 2009; Kutlu et al., 2012; Lopez et al., 2002).

The double-sided investigation of input and output markets, which leads to approximations of oligopolic and oligopsonic behaviours, is equally possible. Schroeter (1988) set up the first application of both mark-ups in output and markdowns to investigate the evolution of market powers in the U.S. beef packing industry. For instance, other applications showed the evolution of both mark-ups and markdowns in the U.S. pulp and paper industry (Mei et al., 2008). In France, an important study uncovered significant market powers in the retail of dairy and meat products (Gohin et al., 2000). Additionally, a link between welfare loss and imperfect markets was established (Mérel, 2011). Further elaboration of the models led to methods to quantify imperfect price transmission between different actors in the value chain, in both theory (McCorriston et al., 2001; Weldegebriel, 2004) and in practice (Gonzales et al., 2002).

Because the model is based on the single parameter of conjectural variation, Morrison Paul (2001) called for caution when interpreting the results because other effects that are not related to active market collusion can also influence this single parameter, such as large efficiency differences in the sector or missing inputs. Other criticisms of this approach indicated that the results of these models provide only modest departures from perfect competition, and that the figures are difficult to precisely define. However, this notion is also related to the limited availability of precise data to which the early NEIO models were applied (Myers et al., 2010).

Notwithstanding these concerns, when compared with other models NEIO methods were found to be simple yet effective for the different types of collusion in two-firm competitions (Roy et al., 2006). In each case, the results are useful starting points for more detailed analyses, subsequently modelling a specific market configuration.

Model construction

The market for live animals is characterized by market-level prices. Hence, the model investigates quantity-based collusion. Given the uncertain role of slaughterhouses, a NEIO approach is adopted that allows for many different collusion configurations in both the input and the output markets.

Several ways exist to translate the conjectural variations to equations that match inputs and outputs. Commonly, the relation between the conjectural variations and the sector output is derived from profit maximization based on the strategic output. The full estimation of the parameters requires further choices as to constraints in markets or the imposition of functional forms. A profit function can be specified on the basis of production by using quantity optimizing. The corresponding input demands are then based on Hotelling's lemma. Alternatively, using a cost minimizing approach, the relation to the inputs is given through Shephard's lemma (Mei et al., 2008).

Another approach related to market power in both the input and the output markets is to assume a strict quantity relation between input and output (Huang et al., 1996; Schroeter, 1988). Finally, the work of Diewert and Fox (2008) can be used to estimate the total scale elasticity using index numbers for the approximation of market power factors (Vancauteren et al., 2011).

This investigation models the dynamics at the firm level and is based on the total scale elasticity, which draws from the analysis of Van Cauteren and de Frahan (2011) that estimated mark-ups in the Dutch food processing industry. This section extends this method to account for oligopsonic behaviour.

Robustness is controlled by comparing the results with those of a second derivation based on the standard model developed by Schroeter (1988). Because this standard model was based on an analysis of aggregated sector data, it is extended to include firm-level inefficiencies for application to firm-level data. The annex describes the entire robustness check, including the model construction and the results.

The slaughterhouse sector consists of n firms, $n \in [1,..,N]$. Firm output, y_{nt}, is defined as the total production created by firm *n* in year *t*. The output is a function of *I* inputs, x_{nit}, with $i : 1...I$. The inputs are capital and labour, and live animals of various types. ω_{nt} is the production efficiency of the firm.

$$y_{nt} = F(x_{n1t},...,x_{nIt})e^{\omega_{nt}} \tag{21}$$

We establish p_{nt} and w_{nit} as the prices for the output and input *I*, respectively. Firm n is assumed to maximize its profit in year t :

$$\pi_{nt} = p_{nt} y_{nt} - \sum_{i=1}^{I} w_{nit} x_{nit} \tag{22}$$

with $Y_t = \sum^{n} y_{nt}$, the total output of the sector, the conjectural variation of firm *n* in the output market η_{nt}, and the sector output price elasticity ε_t are defined as:

$$\eta_{nt} = \frac{y_{nt}}{Y_t} \frac{\partial Y_t}{\partial y_{nt}} \tag{23}$$

$$\varepsilon_{nt} = \frac{p_{nt}}{Y_t} \frac{\partial Y_t}{\partial p_{nt}} \tag{24}$$

For the market power dynamic in the input markets, a similar derivation is set up. When $X_{it} = \sum^{n} x_{nit}$ is the total input *i* for the entire sector, the conjectural variation ν_{nit} at the firm level for each input market *i* and the input price elasticity ξ_{it} are defined as:

$$\nu_{nit} = \frac{x_{nit}}{X_{it}} \frac{\partial X_{it}}{\partial x_{nit}} \tag{25}$$

$$\xi_{it} = \frac{w_{it}}{X_{it}} \frac{\partial X_{it}}{\partial w_{it}} \tag{26}$$

When profit equation 2 is maximized with respect to the input x_{nit} , we obtain:

$$p_{nt} \frac{\partial y_{nt}}{\partial x_{nit}} (1 + \frac{y_{nt}}{p_t} \frac{\partial p_{nt}}{\partial y_{nt}}) = w_{nit} (1 + \frac{x_{nit}}{w_{nit}} \frac{\partial w_{nit}}{\partial x_{nit}}) \tag{27}$$

This equation can be rewritten to show the relation between the conjectural variations in the input and output markets.

$$\left(1+\frac{\eta_{nt}}{\varepsilon_{nt}}\right)\frac{p_{nt}}{w_{nit}}\frac{\partial y_{nt}}{\partial x_{nit}}=1+\frac{\nu_{nit}}{\xi_{it}} \tag{28}$$

Both conjectural variations indicate collusion in their respective markets. Collusion in the output market is measured as the dependence of the total market quantity on the output of firm n. In a perfectly competitive environment, this indicator equals the market share of the firm n. If the conjectural variation is lower than the market share, it indicates that competitors reduce their output in a reaction to an output increase of firm n, which is a signal of quantity-based collusion in the market. If the conjectural variation is higher than the market share, it indicates that competitors increase their output in a reaction to an output increase of firm n. This signals the existence of a dominating firm in the market, aiming to maintain or increase market share. The interpretation of the conjectural variation in the input market is analogous. If perfect competition is present in the market, and the total number of firms is sufficiently high to make the individual market shares negligible, these parameters equal zero.

Parameter interpretation

The conjectural variations η_{nt} and ν_{nit} are interpreted as conduct parameters in a quantity-setting game (Bhuyan et al., 1998; Gohin et al., 2000). A Cournot conduct is revealed through a conjectural variation equal to the Herfindahl index at the sector level (Sckokai et al., 2013).

This concept is illustrated by rewriting the conjectural variations as mark-ups in the output and input markets, respectively μ_{nt} and σ_{nit}. In the output market, the mark-up μ_{nt} is a price wedge between the market price and the marginal cost of the product. Likewise, in the input markets, the mark-ups σ_{nit} are the price wedges between the input market prices and the shadow value for factor input *i* in firm *n* (Morrison Paul, 2001). The focus on mark-ups rather than on conjectural variations is also a methodological choice. The former equations for conjectural variations depend on the estimation of the price elasticities in both the input and output markets. Some studies are based on fixed estimates for price elasticities (Azzam et al., 1990; Mei et al., 2008; Morrison Paul, 2001). This model adopts an alternative solution and estimates the ratio of the elasticity and the conjectural variation in one variable as the price mark-up. The price mark-up on the output price is defined as μ_{nt} :

$$\mu_{nt}\equiv\frac{p_{nt}}{MC_{nt}} \tag{29}$$

The relation with the conjectural variation is established when maximizing profit π_{nt} with respect to the output, leading to the following first-order equation.

$$p_{nt} + y_{nt} \frac{\partial p_{nt}}{\partial y_{nt}} = MC_{nt} \tag{30}$$

Rewriting this equation and comparing it with the definitions of η_{nt} and ε_{nt} provides:

$$\frac{1}{\mu_{nt}} = 1 + \frac{y_{nt}}{p_{nt}} \frac{\partial p_{nt}}{\partial y_{nt}} = 1 + \frac{\eta_{nt}}{\varepsilon_{nt}} \tag{31}$$

The mark-up on the input prices is defined as σ_{nit} based on an analogue relation with the conjectural variations of firm *n* in the input market:

$$\frac{1}{\sigma_{nit}} \equiv 1 + \frac{\nu_{nit}}{\xi_{it}} \tag{32}$$

The traditional Lerner index in the output market is $L_{nt}^{O} = (p_{nt} - MC_{nt})/p_{nt}$. This definition sets a similar range of possible values for L_{nt}^{O}, from 0 (perfect competition) to $1/\varepsilon_{nt}$ (profit optimization in a monopoly). The equality $1/\mu_{nt} = 1 + L_{nt}^{O}$ sets a range for μ_{nt} from 1 to $\varepsilon_{nt}/(\varepsilon_{nt} + 1)$.

When defining a Lerner index for input *i* as L_{nit}^{I}, the relations with the markups on the input prices are similar: $1/\sigma_{nit} = 1 + L_{nit}^{I}$, leading to a range of values for σ_{nit} from 1 to $\xi_{nt}/(\xi_{nt} + 1)$.

This strict view limits the range of the conjectural variations and the corresponding interpretation of market structure. However, Kadiyali et al. (2001) showed that a firm's conduct when in competition can lead to conjectural variations that exceed the range previously outlined. First, such conduct is possible when markets contain differentiated products. Second, when firms lower prices to gain market share, the related mark-up may decline, even to less than 1. If a mark-up of less than 1 is observed in the output market, then products are sold at a loss. This observation indicates strong market power from purchasers or a temporary strategic behaviour to increase market share.

The interpretation of an extended range of values for σ_{nit} in the input market *i* is similar. A value of σ_{nit} that equals unity indicates perfect competition. A value of σ_{nit} that falls below unity indicates a firm's effective market power in decreasing its input prices. A value of σ_{nit} larger than one indicates the purchase of input materials at a price higher than the marginal shadow price for the firm. This phenomenon may result from the strong market power of the input sellers or from a firm behaving strategically to increase its' market share in the input market.

Estimation using index numbers

To estimate the conjectural variations using empirical data, the formulas are transformed to include the input cost shares. Substituting equations 11 and 12 into equation 8 gives:

$$\frac{\partial y_{nt}}{\partial x_{nit}} = \frac{w_{nit}}{p_{nt}} \frac{\mu_{nt}}{\sigma_{nit}} \tag{33}$$

Multiplying both sides of this result by x_{nit} / y_{nt} leads to:

$$\theta_{nit} = s_{nit} \frac{\mu_{nt}}{\sigma_{nit}} \tag{34}$$

For firm n, this equation provides the relation among θ_{nit}, the input elasticity of the production function to input *i*, and the input cost share s_{nit}. Then, the total scale elasticity θ^C of the output is:

$$\theta^C = \sum_{i=1}^{I} \theta_{ni} \tag{35}$$

$$\theta^C = \sum_{i=1}^{I} s_{nit} \frac{\mu_{nt}}{\sigma_{nit}} + u_{nit}^{\theta} \tag{36}$$

The input shares are difficult to observe directly. However, total turnover is observed for each individual firm. This turnover can be separated from the input shares and is related to the total scale elasticity. The total scale elasticity is assumed to be a reflection of technology and is constant in the sector, or $\theta_{nt} = \theta^C$, as in related investigations of mark-ups (De Loecker et al., 2009; Diewert et al., 2008)

Individual differences in efficiency cause firms to deviate from this average elasticity at the sector level. Because an analysis of slaughterhouse efficiencies is beyond the scope of this paper, the efficiency is absorbed in the error term of this approximation u_{nit}^{yp} .

This model does not account for market power in each input market. In a similar setting, Dobbelaere and Mairesse (2013) investigated the interaction between market powers in the labour input market and the output market and based their analysis on the assumption that firms act as price takers in other input markets. In this case, market power is assumed to exist only in the animal input market and not in the capital or labour markets. Slaughterhouses attract capital and labour from the regional capital and labour markets that are not restricted to their own sector. Given that the slaughterhouse sector in itself is rather small, slaughterhouses are unable to influence capital and labour prices at this regional level. Therefore, $\sigma_{n1t} = \sigma_{n2t} = 0$.

When equation (16) is split between capital (*K*) and labour (*L*) inputs on the one hand and live animals on the other hand, this equation can determine the market power indicator at constant returns to scale μ_{nt} / θ^C , and the separate market powers in the input markets σ_{nit} .

$$y_{nt} p_{nt} = \frac{\mu_{nt}}{\theta^C} \sum_{K,L} w_{nit} x_{nit} + \sum_{i=3}^{I} w_{nit} x_{nit} \frac{\mu_{nt}}{\theta^C \sigma_{nit}} + u_{nit}^{yp} \tag{37}$$

To extract μ_{nt} individually, the total scale elasticity θ^C is required, which can be determined by looking at the annual growth of the firm, following Diewert and Fox (2008):

$$\Delta ln y_{nt} = tc_{nt} + \theta^C ln Q^T (w_{nit-1}, w_{nit}, x_{nit-1}, x_{nit}) + u_{nt}^T \tag{38}$$

with:

- tc_{nt} : technical change of firm *n* in year *t*;
- θ^C : total input scale elasticity of the technology in subsector C; and,
- u_{nt}^T: stochastic error term.
- Q^T is the Törnqvist input index for firm *n* for years *t*–1 and *t*, inputs *x*, and prices *w*:

$$Q^T(w_{nit-1}, w_{nit}, x_{nit-1}, x_{nit}) = \prod_{i=1}^{4} \left(\frac{x_{nit}}{x_{nit-1}} \right)^{\frac{1}{2}\left[\frac{w_{nit-1}x_{nit-1}}{\sum_{j=1}^{4} w_{njt-1}x_{njt-1}} + \frac{w_{nit}x_{nit}}{\sum_{j=1}^{4} w_{njt}x_{njt}} \right]} \quad (39)$$

This approach implies the approximation of the actual production function using a translog function. A direct regression using a translog function implies fifteen degrees of freedom. The derivation through the Törnqvist index allows a more robust approach with only two degrees of freedom.

Animal price estimation for future scenarios

Equation 17 is also the basis for the estimation of future prices, based on scenarios of future meat demand (y_{nt}) and prices (p_{nt}). A simplification is made by assuming steady proportions between the input of capital and labour (K,L) and cows and pigs (C,P) for the coming years :

$$\lambda_{SL} = \frac{w_{nKt}\,x_{nKt} + w_{nLt}\,x_{nLt}}{w_{nKt}\,x_{nKt} + w_{nLt}\,x_{nLt} + w_{nCt}\,x_{nCt} + w_{nPt}\,x_{nPt}} \quad (40)$$

This way, the difference between two subsequent years in prices for live animals, can be approximated, by summing up over all slaughterhouses n, for I = C, P.

$$w_{it} = \frac{\dfrac{\theta}{\mu_t}\dfrac{p_t Y_t}{X_{it}}}{\dfrac{\lambda_{SL}}{(1-\lambda_{SL})} + \dfrac{1}{\sigma_{it}}} \quad (41)$$

This last equation describes the relation between the downstream side of the supply chain – the live animals – and the upstream side – the turnover of meat products. This equation allows an estimation of the average sales price for live animals based on the variables that are defined in the future scenarios:

- p_t : Price index of the meat products. In the scenarios, this index follows indices of consumer spending, and openness of markets to international trade;
- Y_t : The total quantity of meat products sold, is estimated in the scenarios following assumptions on consumer spending, and reducing importance of meat in the average food basket.
- X_{it} : The total quantity of produced animals is a result of the modelled actions of the farm agents.

Equation (21) can therefore make the link between consumption of meat products, and meat prices, with the actual price the farm agents receive for their animals. This equation simulates the working of the slaugtherhouse market in the model. The produced quantities of all farms are collected, and all other variables are defined by exogenous factors fixed in the scenarios of 0

Calibration of market powers with input scale elasticity

The first calibration determines the market power factors for the live animals market, following the market model set up in 0.

The model proceeds in two steps. The first step approximates the input scale elasticity using Törnqvist index numbers. The second step approximates equation (37) (page 227) and derives separate mark-ups for the input and the output markets. The regression differentiates between the slaughterhouse types, as reported in Table C. 6.

Table C. 6: Total input elasticities and annual technical change for different types of slaughterhouses.

Slaughterhouse type	Specialized Cattle	Specialized Pig
θ^C Expected value	0.936***	1.045***
θ^C Standard deviation	0.038	0.037
Tech. Change	–0.55%	–2.9% ***
Obs.	166	122
Prob > F	0.00	0.00
Adj. R^2	0.784	0.870
Legend: * p<.05; ** p<.01; *** p<.001		

The second step relates mark-ups to the scale elasticity on the basis of equation 17. Table C. 7 reports the market power factors and their respective confidence interval.

Table C. 7: Average market power estimations for input and output markets.

Slaughterhouse type		Expected value	StDev	95% conf interval	
Specialized Cattle	μ_C	1.10	0.071	0.963	1.245
	σ_{C3}	1.18	0.035	1.109	1.248
Specialized Pig	μ_P	1.15	0.049	1.055	1.249
	σ_{P4}	1.10	0.014	1.071	1.126

The market power indicators were determined with relatively high precision. The cattle subsector seems to impose a 10 percent mark-up on its products. However, this result cannot be fully guaranteed. The 95 percent confidence interval is large and a situation in which the actual mark-up is 0 percent is still probable. However, what can be guaranteed is that the cattle slaughterhouses are obliged to buy live animals at a mark-up of approximately 18 percent. This result implies that cattle farmers can exert considerable market power on cattle slaughterhouses. Retailers are capable of purchasing the products at a lower mark-up than the slaughterhouse has on the inputs. As a result, this subsector seems pressed between strong farmers and strong retailers.

The situation for the pig slaughterhouses is different. The average mark-up on the output can be statistically guaranteed and is expected to be approximately 15 percent. The pig slaughterhouses also pay a mark-up on their live pigs, but a smaller one at approximately 10 percent. This result illustrates the higher firm benefits that allow the rapid consolidation and industrialization of the subsector. In the opposite direction, consolidation helps the subsector achieve better negotiation leverage and, thus, a large mark-up on the outputs when confronted with powerful retailers. Consolidation also helps achieve overall positive market power. Therefore, both effects are closely linked and reinforce each other.

This derivation assumed stable market power during the entire period. The sensitivity of the results of this assumption is illustrated through annual calculations. Table C. 8 shows the same results of the derivation executed separately for each consecutive year between 2002 and 2011. All significant results are reported. The market power estimates for a 95 percent confidence interval that are entirely larger than unity are marked and indicate imperfect competition. The variation in market power is large and shows no clear trend. The conclusions from the previous results are reinforced. For the cattle slaughterhouses, the market power in the output market is systematically smaller than in the input market. The pig slaughterhouses reveal the opposite situation.

Table C. 8: Market power estimates show large differences during the last decade.

Slaughterhouse type		**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Specialized Cattle	μ_C	1.00	1.21	1.10	**1.16**	1.20	1.17	1.01	**1.22**	0.93	1.18
	σ_{C3}	1.06	1.29	**1.17**	**1.25**	**1.29**	**1.25**	1.08	**1.32**	0.99	1.25
Specialized Pig	μ_P	**1.13**	**1.22**	**1.26**	**1.22**	**1.15**	1.08	1.14	1.15	**1.20**	1.00
	σ_{P4}	**1.08**	**1.17**	**1.21**	**1.17**	**1.10**	1.03	1.09	**1.09**	**1.15**	0.93

Results in bold are significant at the 0.001 level and their 95 percent confidence interval is completely larger than unity.

The results lead to the conclusion that both cattle and pig farmers benefit from market power during price negotiations, thereby, pressing cattle slaughterhouses between strong farmers and strong retailers. Pig slaughterhouses are in a better position and seem capable of transmitting the cost mark-up on their inputs to their clients.

Interpretation

The interpretation of these results is not straightforward because several elements in firms' behaviour contribute to the same indication of market power. A comparison of these results with insights from the market situation outlines four different elements: slaughterhouses maximizing their turnover, farmers' unions, dependence on export, and overproduction of meat products. The present results do not allow for a distinction among these elements; thus, the exact origin of market power in the sector cannot be detailed using this model alone.

The first potential element of market power may be related to the behaviour of slaughterhouses. In the short run slaughterhouses can maximize their turnover rather than their profits. In fact, this type of strategic conduct is a principle deviation from the initial model assumption of firm profit maximization and may be rational in a competitive market environment. When live animals are in short supply, slaughterhouses may prefer to buy more animals than is optimal for maximizing profit. Purchasing more animals allows for full capacity utilization of the slaughterhouse and is detrimental to competitors. This behaviour also leads to increased prices for live animals.

A second potential element of market power is the collected action of farmers' unions and cooperatives. These cooperatives represent and defend the interests of their members in negotiations with other partners in the food production chain. The wide and direct distribution of price information to all farmers also reinforces this situation. For a few years, the entire production chain reached agreement on the beef price index. However, even before this agreement, cattle producers benefitted from higher market power relative to pig producers.

To a certain extent, the international market for live animals provides a third explanation for farmers' power. The growing slaughterhouse sector requires an increasing number of animals to sustain its growth. Animals must be imported; however, transport of live animals over large distances is costly, giving local farmers a strong negotiation argument.

The situation remains counterintuitive because even a selling price for an animal that is 10 percent or 18 percent higher than the perfectly competitive price still does not guarantee sufficient income for farmers. A perfectly competitive market would significantly worsen farmers' situation. The fourth potential explanation might be that this market power results from regional overproduction of beef and pork products. Theoretical market dynamics call for overproduction to reduce the price far below viable minimum prices for farmers and slaughterhouses. The theoretical ensuing bankruptcy of several farmers reduces production and increases prices again. However, in reality, the cost structure of cattle and pig farms is intensively studied. Companies higher up in the meat production chain also know the production costs of live animals based on feed and land prices. Within a fiercely competitive sector, such as the slaughterhouse sector, paying a farmer far below the production cost of the living animals is not in the long-term interest of any party in the meat supply chain. Bankruptcy results in the loss of long-term supply partners, which may be an additional source of farmers' market power because the slaughterhouses clearly understand that reducing the price far below the equivalent of a minimum income is not viable. However, the result is that the income of farmers who depend primarily on the benefits from live animals, remain around or below this minimum income as long as overproduction exists in the region.

There are also implications for policies in this sector. The results show a market power in favour of the animal farmers. Policy actions intended to increase levels of competitiveness in the meat supply chain are thus not expected to result in higher prices for live animals. The current policy actions for price index agreements along the entire production chain are indeed better suited to this type of situation. This price index can provide price levels for every actor in the chain that are closer to the actual production costs. However, the underlying problem is situation of capacity imbalance, and the price index does not affect this structural problem. The results can be related to two potential capacity imbalances. They can indicate an imbalance between the actual demand for meat products and the production capacity of the slaughterhouses. Or the results indicate an imbalance between a growing slaughterhouse capacity and a declining national production of live animals. In either case, structural policy interventions to improve this situation should be based on closer investigations of these imbalances.

This NEIO approach must be stressed as flexible enough to indicate very different market structures. However, the resulting market power factors represent various simultaneous effects that make a univocal interpretation difficult. The main purpose of this exercise is to provide initial insights into the power structures in this market. Based on these results, more precise models tailored to this specific market structure should be applied to reinforce insights into real market dynamics.

Robustness check

The results of the previous derivation are compared with the results of a different approach. The original model developed by Schroeter (1988) is appropriate because it is built for a similar market and contains assumptions that are specifically tailored to the meat processing industry. A first important assumption is the link between produced output y_{nt} and the input of the corresponding live animal x_{nt}. These two quantities have a strict linear relation, $y_{nt} = x_{nt} S_{eff}$, given by slaughter efficiency, S_{eff} , which is defined as the quantity of valuable kilograms of carcass that can be produced per kilogram of living animal. With this relation in mind, the benefit can be defined as:

$$\pi_{nt} = p_{nt} y_{nt} - \hat{w}_{nt} y_{nt} - C^n(x_{nt}, w_K, w_L) \tag{42}$$

In this equation, $C^n(x_{nt}, w)$ is the cost function for labour and capital depending on the input of live animals x_{nt} and the input prices for labour and capital, w , with $\hat{w}_{nt} = w_{nt} / S_{eff}$. This model specifically calls for firms that specialize in only one type of animal. The first-order condition of this profit expression with respect to output leads to the introduction of the conjectural variations.

$$p_{nt}(1 + \frac{\eta_{nt}}{\varepsilon_{nt}}) = w_{nt}(1 + \frac{\nu_{nt}}{\xi_{nt}}) + \frac{\partial C^n}{\partial y_{nt}} \tag{43}$$

The relations with the mark-ups allow the equation to be simplified to the first equation of the model:

$$\frac{p_{nt}}{\mu_{nt}} = \frac{w_{nt}}{\sigma_{nt}} + \frac{\partial C^n}{\partial y_{nt}} \tag{44}$$

The two other equations look at the optimal inputs for capital (*K*) and labour (*L*) using Shephard's lemma for $i = K, L$:

$$x_{nit} = \frac{\partial C^n}{\partial w_{nit}} \tag{45}$$

To allow deviations from the sector average, the cost function is implemented in this case as a generalized Leontief complemented by an efficiency term. The first part represents the sector's average response and the last part captures temporal and structural inefficiencies at the firm level.

$$C^n(x_{nt}, w_{Kt}, w_{Lt}) = x_{nt}(b_{LL} w_{Lt} + 2b_{KL}\sqrt{w_{Kt} w_{Lt}} + b_{KK} w_{Kt}) + F_{nt} x_{nt} \quad (46)$$

The relationship with firms' individual efficiencies is beyond the scope of this paper; therefore, F_{nt} is assumed to be normally distributed across the sector. Given this definition, the set of equations is gathered on the basis of 16 and 17.

$$x_{nKt} = x_{nt}(b_{KK} + b_{KL}\sqrt{\frac{w_{Lt}}{w_{Kt}}}) + u_{1nt} \quad (47)$$

$$x_{nLt} = x_{nt}(b_{LL} + b_{KL}\sqrt{\frac{w_{Kt}}{w_{Lt}}}) + u_{2nt} \quad (48)$$

$$\frac{p_{nt}}{\mu_{nt}} = \frac{w_{nt}}{\sigma_{nt}} + (b_{LL}w_{Lt} + 2b_{KL}\sqrt{w_{Kt}w_{Lt}} + b_{KK}w_{Kt}) + u_{3nt}^{m} \quad (49)$$

The three error terms are, respectively, u_{1nt}, u_{2nt}, and u_{3nt}. The term in the last equation is modified to $u_{3nt}^{m} = F_{nt} + u_{3nt}$. This model is solved as a simultaneous set of non-linear equations given the non-linearity of the constraints on the different parameters.

The results from the estimation based on the adapted model from Schroeter are reported in Table C. 9 and Table C. 10

Table C. 9: Market power estimates for cattle slaughterhouses using the Schroeter model.

Variable	Expected value	StDev	95% Confidence interval	
b_{KK}	–19.5	19.5	–57.8	18.7
b_{KL}	46.5**	8.2	30.5	62.6
b_{LL}	18.0**	4.2	9.79	26.3
μ_C	1.88***	0.74	0.44	3.33
σ_{C3}	1.23***	0.50	0.24	2.22
Equation	**Obs.**	**R^2**		
25	195	0.459		
26	195	0.644		
27	195	0.997		

*: p < 0.05; **: p < 0.01; ***: p < 0.001

Table C. 10: Market power estimates for pig slaughterhouses using the Schroeter model.

Variable	Expected value	StDev	95% Confidence interval	
b_{KK}	–4.86***	0.80	–6.42	–3.30
b_{KL}	5.11***	0.36	4.40	5.82
b_{LL}	5.26***	0.59	4.10	6.42
μ_P	2.09***	0.46	1.20	2.99
σ_{P4}	1.54***	0.34	0.88	2.20
Equation	**Obs.**	**R^2**		
25	145	0.765		
26	145	0.528		
27	145	0.996		

*: p < 0.05; **: p < 0.01; ***: p < 0.001

The results of interest are primarily the market indicators that were determined for the cattle and pig subsectors with high significance but low precision. The large standard deviations of the results make secure conclusions difficult to develop. The expected values of the market indicators are much higher than the former results. Yet, the market power indicators reflect market structures similar to those calculated using the former model. In this sense, the Schroeter model corroborates with the former results.

For the cattle subsector, the former results are very probable within the 95 percent confidence interval of Table C. 7. The high estimates of the Schroeter model are a modest confirmation of the nature of the mark-ups: positive on the output and on the input. However, confirming the size of the mark-ups with this outcome is not possible because of the significant imprecision.

For the pig subsector, the results of the Schroeter model are also much higher than the former results. The results from the former model are less probable according to these figures and are estimated too low. The mark-up on the input side is undetermined. Again, at the least, the nature of the mark-up of the former results is reflected in the figures of Table C. 7 and these should be regarded cautiously. The main purpose is to compare the performances of both models. The overall low precision proscribes the use of these figures to contradict the former results. Although the general nature is similar, the sizes of the mark-ups predicted by the Schroeter model are too imprecise to follow.

The low precision of this outcome is remarkable, even with the considerable similarity of the two models applied to the same database. One potential but albeit limited explanation is based on the assumption in the Schroeter model that the output is linearly related to the input. This link is slaughter efficiency and was determined for the cattle sector as 66.3 percent and 80.0 percent for pigs. Cattle slaughter efficiency is a weighted average of all types of cows slaughtered in Belgium during one year. For instance, the average efficiencies vary between 61 percent for old dairy cows to 70 percent for Belgian Blue bulls. Although these figures are stable, the average may vary considerably among slaughterhouses because different firms specialize in different types of cows, such as calves, old dairy cows, or Belgian Blue. This difference significantly affects the overall slaughter efficiency of the firm. A related remark on the matter is that the cost structure of slaughterhouses has long reflected this efficiency. The costs of the intermediate goods—the live animals—can surpass 90 percent of the total costs of the slaughterhouse. Capital and labour costs are relatively small. In the past, the added value of the produced carcasses allowed for reimbursement of the animal purchase. Labour and capital costs can largely be covered by the sale of slaughter waste, such as the intestines, the hide, or blood. These sources of additional income were rather stable and linearly related to the input. However, during the past few years, the waste quantity remained but revenues from their sale decreased considerably. In particular, decreasing demand for leather from the car industry caused hide prices to plummet. Therefore, these additional revenue streams have become less proportionate to the input. Both effects are more strongly present in the cattle subsector than in the pig subsector, as shown through the imprecision of the results.

Finally, in terms of precision, the Schroeter model estimates the labour and capital cost function; however, these costs are often a fraction of the total costs of the firm. Basing the model on a proportionally small part of the cost structure also induces numerical imprecision, as reflected in the results.

Annex D Data origins of the slaughterhouse market analysis

Some limitations were encountered in the data gathering process, including, first, a limitation related to artisanal or municipal slaughterhouses, and, second, a limitation related to accountancy changes. The third limitation was the result of the combination of different firms at the same site.

The total number of slaughterhouses could not be included in the study. Several smaller artisanal butchers provided data on slaughtered animals but not detailed financial data. Fortunately, these slaughterhouses represent only a small share of the sector's total activity. However, the situation differed for municipal slaughterhouses, which are still owned by the municipality and do not provide individual balance sheets. Their financial activity is an integral part of the city's finances. This type of firm could not be integrated into this study, including the two largest slaughterhouses in Belgium: Ath and Aubel.

The construction of the panel data could not cover a large time span. The number of slaughtered animals per individual slaughterhouse is provided by the Federal Agency for Safety of the Food Chain (FAVV). The financial data are derived from the financial balances and the results are deposed at the Belgian National Bank. The FAVV changed its accountancy system in 2006; therefore, company registration data before 2006 does not automatically match the data for after 2006. Many company registrations in the 2005 database have no connection with the registration information at the National Bank balance office. Given the discrepancies between FAVV data before 2006 and after 2006, the percentages show markedly different results for the representativity of the database before and after 2006.

Several companies work at the same site, which may induce the slaughtered animal to be registered under one company at the FAVV. However, in the balance sheet, the purchase of the animal, the work, and the production of output are registered under another company at the same site. The different companies may have ties through holdings or other owner structures, but not always; therefore, the data were matched on a case-by-case basis. For some complex sites, including four or more different companies and holding structures, the entire group of firms was removed from the database. In those situations, the entity that accounted for the financial transactions related to the slaughter activity could not be correctly determined.

Data source description for each variable in the slaughterhouse market analysis

Name and registration, and number of slaughtered animals per facility:

The list of official registered sites that have a valid permit for slaughtering live animals was transmitted by the FAVV, combined with the number of live animals slaughtered per year at the site. The FAVV changed the database architecture and information procedure between 2005 and 2006. As a result, many sites active before 2006 could not be combined with a valid VAT-registration.

Capital and labour input, and annual added value:

Financial data for each site were derived from yearly balance sheets declared at the National Bank of Belgium (NBB). This process includes data on total fixed assets (k), total labour expenses (l), and total added value (AV).

Capital prices:

The capital price is used to weight capital inputs between two consecutive years when constructing the Törnqvist price index. The price is determined at the individual firm level. The common loan interest for corporate middle-term investments is the individual depreciation rate of the fixed assets at the company, and is corrected for inflation using the inflation index (Eurostat).

Labour price:

The labour price index was provided by the National Price Observatorium. The index aggregates hourly average labour rates for the slaughterhouse sector for each year.

Live cow price:

These prices per unit weight are determined using the prices for live animals transmitted at cattle fairs. These prices are registered by BIRB (Belgian Intervention and Restitution Bureau for the Common Agricultural Policy) and form the price for one live cow based on the weighted average. The weights stem from the distribution of cows, bulls, and heifers of different categories that are annually presented in Belgian slaughterhouses. The prices are corrected for inflation.

Live pig price:

The price per unit weight was been provided by VEVA, an independent community of pig farmers that collects weekly data. These data include premiums and additions given to pig farmers on top of the net advertised price. The prices are corrected for inflation.

Animal live weights:

The average weight of animals in different categories is determined from slaughtered weight statistics (Eurostat). Table 3 reports the resulting nominal prices per animal.

Four input markets exist for the firms under investigation: capital (K), labour (L), live cattle (c), and live pigs (p). The live cattle input contains all types of cows and calves. The value of one unit relative to one standard cow was weighed using livestock unit (LSU) coefficients from the European Farm Accountancy Data Network (FADN).

Annex E Sustainability assessments of biobased technology

This chapter is based on the article published in Environmental Impact Assessment Review: Maes, D. and Van Passel, S. (2014). Advantages and limitations of exergy indicators to assess sustainability of bioenergy and biobased materials. Environmental Impact Assessment Review 45: 19-29.Contrary to the article, the described method is applied here to the manure treatment technologies.

The biobased technologies, such as new manure treatment technologies, can lead to an environmental impact in very different aspects. Whereas the initial concepts claim improvements in climate change impact and water use, the impacts on eutrophication and land use are less clear. Therefore, for biobased technologies, these impacts should not only be assessed, but also weighed against each other. And this makes a holistic assessment challenging.

Indicators based on exergy can remediate some of these shortcomings. Exergy is being applied as a useful metric in environmental impact assessments (Banerjee et al., 2011; Chen et al., 2009; Hau et al., 2003; Hepbasli, 2008; Kirova-Yordanova, 2010; Yi et al., 2004). It can account for materials and energy flows alike and can be used for the analysis of complex production pathways (Apaiah et al., 2006; Bakshi, 2000; Huang et al., 2007; Zhang et al., 2010a). However, the integration of exergy-based environmental impact measures is not straightforward, due to both technical limitations and theoretical limitations. Various different applications of exergy exist, but not all are appropriate within the framework of a sustainability assessment. Also, this evolution to use exergy-based indicators is relatively new. The application is not yet wide-spread, despite its potential to deliver more coherent and holistic sustainability assessments.

Exergy-based indicators within a life cycle context

Exergy or 'available energy' has been defined as "*the maximum amount of useful work that can be obtained from [a] system or resource when it is brought to equilibrium with the surroundings through reversible processes in which the system is allowed to interact only with the environment*"(Dewulf et al., 2008). Three points should be highlighted. First, whereas the term "energy" counts all energy flows regardless of their working potential, exergy only considers the highly qualitative, useful part of energy (Dincer, 2002). Second, exergy, contrary to energy, is not preserved. The exergy content of a flow changes when energy forms are transformed from one into another. Because these transformations always cause exergy destruction, the amount of exergy destruction in a process is also a measure of efficiency. Third, energy forms are interpreted thermodynamically and include all possible forms such as chemical, mechanical, thermal, electrical or potential energy. This means that exergy equally accounts for materials, movements, currents or heat and the transformations between them. Especially the inclusion of all chemical substances is interesting.

Objective valuation of energy and materials

The standard method to utilise exergy within a life cycle context is the calculation of the Cumulative Exergy Content (CEC) (Szargut et al., 1988). The CEC accounts for the cumulative quantity of exergy used during the life cycle of a product. Its applicability is very broad because it includes exergy streams not only from energy flows, but also for material inputs for the process, such as fuels, minerals or gases. This approach forms the basis of all further exergy calculations in a life cycle context (Bösch et al., 2007; Szargut, 2005) and has been widely applied in numerous domains (Sciubba et al., 2007). The Cumulative Exergy Extraction from the Natural Environment (CEENE) further extends the CEC to include organic resources extracted from ecosystems as well (Dewulf et al., 2007).

The generalised thermodynamical basis for the determination of the exergy values, ensures that different exergy results can be directly added and compared. For instance, comparing the intrinsic exergy content of wood particles and exergy in heat generated by wood burning, shows that combustion destroys a large part of the initial value of the wood.

As Gasparatos et al. (2008) note, one apparent disadvantage is that a reference framework is needed for every exergy calculation. In practise, the first development of CEC provided a detailed and generally applicable reference system that remains the practical baseline for all exergy calculations based on CEC (Szargut, 2005). The framework determines the exergy value of a particular chemical compound compared to the standard chemical composition of the earth's bio- and lithosphere. Over time, this system has been updated (Szargut et al., 2005). It is a fixed environment independent of technical or operational assumptions. Contrary to comparisons of energy-based results, this exergy reference does not presuppose technical processes for energy transformation nor pathways of fuels production to which the process under investigation is compared, making calculations and comparison of results much more objective and robust.

Solar irradiation to approximate ecosystem contributions

For biobased processes, sunshine is essential in the biomass provision pathway. Hybrid biobased processes combine inputs of solar and fossil origin. A precise view on the balance between these two sources is crucial during the analysis of the sustainability of the process. For the purpose of sustainability assessments, some practitioners chose to partly omit the direct contribution of solar exergy for the biological organisms (Bastianoni et al., 2005), while others opt to totally omit the solar contributions (Hoang et al., 2011; Hoang et al., 2010; Illge et al., 2008; Van Passel et al., 2009). There are two approaches possible to include solar irradiation. A first approach is to include sunshine only indirectly, as represented by the biomass provided by the ecosystem to the industrial process (Sewalt et al., 2001). A more inclusive approach includes all solar irradiation directly, such as embedded in the CEENE methodology (Dewulf et al., 2007). This choice counts the total amount of solar exergy that was needed to produce the biomass, and extends thereby the horizon of the production chain to include the activity of the ecosystem that produces the biomass.

This extension opens the possibility to further broaden the horizon of the environmental impact analysis to the absorption of emitted pollutants by ecosystems. Three options are present in literature. Firstly, some projects account for the impact of pollution of ecosystems by counting the exergy content of the released pollutant itself (Gasparatos et al., 2009; Huang et al., 2007; Zhang et al., 2010a). The exergy content of a pollutant is a measure of the thermodynamic work the pollutant can perform, and thus an approximate measure of the damage the pollutant can create when released in the biosphere. This approach is used for macro-economic assessments, but it is not very precise. A second approach is to include the activity of the ecosystem to absorb pollution, and is proposed by Dewulf and Van Langenhove (2002a). This method links exergy valuation of ecosystems with the 'Ecological Damage Effects' (EDE), a standardised environmental impact measure from LCA (Goedkoop et al., 1999). As such it provides a practical weight to aggregate pollution impacts from an LCA proportionally to the sunshine needed for the ecosystem to restore itself. Thirdly, when impact data from LCA are not available, it remains possible to calculate directly the solar irradiation necessary for the ecosystem to function. In case of sequestration, the pollutant is one of the input resources of the ecosystem, with a corresponding exergy cost. This approach is used in this article to estimate the exergy demand of carbon sequestration.

Annex F (p. 215) gathers an overview of articles that evaluate the production of bioenergy or biobased materials within a life cycle context. An overview of the applied methods is equally provided. It is remarkable that a majority of articles restrict the analysis of environmental impacts to the inclusion of renewable resources.

Valuation of living organisms

An advanced extension of the exergy theory concerns valuations of living organisms. This extension is proposed by Jørgensen (2002) as Eco-Exergy (EE). Standard exergy theory describes the exergy content of biological organisms as the chemical exergy of the dead matter that organisms contain. EE values the chemical content of living organisms together with their information content. The living organisms contain exergy through their chemical composition, but also through the information contained in its structure and form, more specifically expressed by the structure of its DNA. Based on the physical law of Boltzmann linking information theory and thermodynamics, EE combines both aspects (Jørgensen, 2007). The exergetic value of the information contained in living organisms often surpasses the chemical exergy content with several orders of magnitude (Fonseca et al., 2000). This approach has been elaborated as an indicator for ecosystems evolution and health (Jørgensen et al., 2004a; Jørgensen et al., 2004b). The detailed EE approach is promising and might uncover missing links in current exergy LCA, such as ecosystem costs and contributions due to decreasing biodiversity. The current results are effectively applied as indicators for impacts on living organisms and their organisation (Jørgensen, 2006). This shows that this measure can be a useful indicator alongside other indicators of biodiversity and related environmental impact (Gontier et al., 2006). Currently it is not recommendable to combine EE with other exergy-based measures in calculations. The principle link between information theory and entropy has been criticised and remains debated (Corning et al., 1998a; b; Kline, 1999). The direct inclusion of EE in cumulative exergy analysis is not warranted because it departs from the pure thermodynamical measure, and the information measure of EE, based on essential DNA strands, is debated among biologists (Silow et al., 2010). It remains challenging to interpret these valuations of living ecosystems and organisms in relation with standard thermodynamical measurements, even if both are expressed in the same units.

Limitations of exergy-based indicators

As opposed to carbon or energy related measures, measures in exergy can extend the scope of the analysis to include energy, inorganic materials and fuels, organic matter, and even ecosystem activity related to the absorption of pollutants. This is an advantage over LCA because the environmental impacts can be aggregated over different dimensions. These advantages are unfortunately not sufficient to use exergy as a measure for all ecosystem services. Inclusion is limited to ecosystem services that concern material or energy flows. Other ecosystem services, such as noise reduction or cultural values, are immaterial, and can be objectively assessed neither with energy-, carbon- nor with exergy-based values.

Application to immaterial resources

The application of exergy terms to immaterial resources, such as temperature regulation, information exchange or cultural services, is similar to the inclusion of eco-exergy. Exergy is a fundamental thermodynamic measure for physical entities and exchanges, and is thus applicable to all material and energy flows. Immaterial resources have found parallel expressions in exergy, but as these measures depart from the thermodynamic basis, their inclusion is problematic. For instance, there are various attempts to express the two primordial economic resources, labour and capital, in terms of exergy (Sciubba, 2001; 2011; Ukidwe, 2005), but these approaches do not provide correct valuations in the context of a sustainability assessment as labour and capital values are immaterial and constituted of information.

Loss of information after aggregation

During the sustainability assessment, all inputs can be added up to one quantity measured in exergy. This total input is often the basis for efficiency measurements and scenario comparison. Whether the solar exergy is accounted for directly or indirectly, there is one consequence that requires a second indication. The inclusion of solar irradiation generates exergy flows that can be both renewable and non-renewable. The exergy value for both is the same, while the sustainability performance is different (Stougie et al., 2011). Methods that define sustainability on an exergy-basis only, differ in calculation principles, but they all include a clear distinction of exergy inputs between renewable and non-renewable sources (Dewulf et al., 2000; Lems et al., 2003; Sewalt et al., 2001). The renewable fraction of input (RF) is an important indicator for the sustainability of the process, because this information gets lost when the total exergy input is determined by adding all resources and impacts together.

A correct interpretation needs to review both the total input and the renewable fraction in conjunction.

Exergy as an ecocentric valuation

Exergy measurements might be possible, but not appropriate for every type of productive resource. The use of exergy analysis is limited by the implicit value-assignation, as the choice for a biophysical metric is at the same time a value decision. A biophysical metric - and cumulative exergy content in particular – determines an ecocentric value for each flow (Gasparatos et al., 2008). Contrary to anthropocentric tools such as monetary or composite metrics, the biophysical metric is in principle more objective. It attributes a value to a product according to the exergy used up or 'invested' in the product during its production. This type of value is a 'cost of production' value, and is not applicable to all types of flows from an economic point of view. The alternative economic value assignment is based on utility. Utility incorporates the desirability of the product for a consumer and is as such independent of the cost and investments necessary to build the product. This alternative disregards the cost of production and determines the value on human behaviour based on choice and preferences.

Moreover, the energy cost of production theory has been shown to be inconsistent with market prices (Ayres, 2004). The theory is not applicable as a general economic theory because values determined by the energy cost of production rarely match values of the produced output. This is exactly because value determinations are not only governed by production costs alone but also by human preferences for goods or services, whenever interactions between humans are involved. An exergy cost of production, looks at flows and services from an ecocentric view, and is not influenced by human preferences for value determination (Raugei, 2011). Hence, this approach is not directly suitable for exchanges within the economy or with society, such as capital or labour. The situation is different for exchanges with ecosystems. There are no choices, decision or markets in an economic sense in the natural environment (Ayres, 2004), and thus no expression of preferences in order to determine different exchange values. For exchanges with ecosystems, the exergy cost is an appropriate and more objective measure (Valero, 2006). For other exchanges, involving human preferences and choices, other solutions have to be found.

Output valuation

The economic interpretation of exergy values has effects on the valuation of process inputs, but also on the valuation of the outputs. In most research projects using exergy analysis, the output is valued in net exergy content (Apaiah et al., 2006; Chen et al., 2009; Hepbasli, 2008; Kaushik et al., 2011; Talens Peiró et al., 2010; Zhu et al., 2005). According to the economic interpretation of exergy content, this approach views both inputs and outputs from an ecocentric point of view. It looks at the process under investigation as a matter- and energy-transforming unit within the biosphere.

The alternative is to value the output in monetary terms, which corresponds to the anthropocentric valuation of the output. This second approach acknowledges the fact that some outputs are more valuable for humans than others, and that the output ultimately achieves its value through interaction with customers. Both approaches are valid and appropriate if all outputs are materials or energy flows. The underlying premises should be taken into account during the interpretation of the results.

Framework to assess sustainability of biobased outputs

Exergy accounting can value material and energy inputs in an objective way by determining their exergy cost of production. Ecosystem activity to absorb pollutants or to provide organic matter can also be quantified similarly. And exergy is not suitable for the valuation of immaterial exchanges, information, or exchanges that are determined by human interactions and preferences. Inclusive sustainability assessments should incorporate many different aspects, and should provide solutions to aggregate impacts measured in exergy with other impacts. The first section of this chapter builds a framework, allowing all relevant aspects and impacts to be categorised and measured. The second section looks at existing composite indicators with exergy, and determines options for aggregation in this case.

Impact structure for an inclusive sustainability assessment

In a first step, impacts are structured according to (i) the nature of the exchange, and (ii) the origin or destination of the exchange. Berkes and Folke (1994) distinguish three kinds of exchanges between an economic process and ecosystems: non-renewable resources extracted from ecosystems, renewable resources produced and maintained by ecosystems, and environmental services. Distinctions in our framework are then detailed as follows:

- Non-renewable resources: these are resources that are not regenerated during the period of the project under investigation. In this case, the assessment looks at the influence of an economic process during its lifetime (e.g. 25 to 30 years). Non-renewable resources include all fossil fuels and minerals, geological mineral deposits and fossil water reserves. It also includes organic matter from biological systems that take longer than the project lifetime to grow or impacts on ecosystems that require the ecosystems longer than the project lifetime to recover.

- Renewable resources: these are resources that are actively regenerated by ecosystems or other systems (e.g. lithosphere). These include grown organic matter, but also geothermal heat.
- Services: Services are exchanges with the process that are not based on matter or energy exchange. For interactions with ecosystems, the term ecosystem services covers a large variety of meanings and interactions (Fisher et al., 2009). This is a much more limited definition, as for instance the provision of rainwater to the economic process is not an ecosystem service. Rainwater is considered a material resource. Ecosystem services that remain under this restricted category are for instance pollination by bees or cultural and touristic qualities of the landscape that are used by the economic process.

Impacts are also structured according to the origin or destination of the exchange: society, the biosphere and the economy as shown in Figure 1. Other projects similarly distinguish flow origins in principle areas (Dewulf et al., 2007; Dewulf et al., 2002b; Simpson et al., 2011). This resembles the representation of the economic process according to ecological economics (Gowdy et al., 2005). In Figure E. 1, the different flows are visualised combining the distinction according to the nature of exchange and the origin. CEC and CEENE can account for all exchanges of materials and energy flows to and from the economic process, including organic materials.

		From & to			
		Biosphere	**Lithosphere**	**Sun**	**Society**
Can be accounted for in exergy terms	**Non-renewed resources**	Diverse ecosystem contributions: materials, ecosystem damage due to waste absorption or emission capture and storage...	Minerals Fossil fuels Historic water reserves Waste storage		
	Renewed resources	Diverse ecosystem contributions: materials, ecosystem damage due to waste absorption or emission capture and storage...	Geothermal heat Water	Solar irradiation	
Cannot be accounted for in exergy terms	**Services**	Soil fertility, Pollination, Noise reduction, Genetic information, Biodiversity, Touristic qualities	Land use		Labour Capital

Figure E. 1: An overview of inputs for the economic process shows the potential broad application of exergy as a metric for environmental impacts.

Damages caused by pollutants and emissions can both be material and immaterial. The material effects of pollution absorption by the biosphere can be assessed by counting the biomass loss caused by the pollution, and can be measured in exergy terms. The immaterial aspects, such as structural degradation or biodiversity reduction cannot be analysed in classical exergy metrics. It should be treated as an environmental impact assessment in an alternative metric. Also all exchanges with society, as well as all immaterial services should be accounted for in different metrics or dimensions.

Measure determination and aggregation across different dimensions

With an extended view over the production chain and the diversity of impacts accounted for, the exergy measurements do not suffice. It is remarkable that most methods for the assessment of agricultural sustainability (Acosta-Alba et al., 2011; van der Werf et al., 2007; Van Passel et al., 2011), fall within the category of composite indicators. The sustainability analysis touches upon very diverse range of aspects that cannot be aggregated without having to turn to composite metrics in the end. Exergy-based measures aggregate different forms of energy, materials, or pollution abatement on a standard physical basis, which is an important advantage. However, exergy-based measures cannot avoid the use of aggregating and weighing altogether.

Exergy-based measures are only rarely applied in combination with other indicators. The early development of the exergy cost method led to the combination of exergetic and economic costs. The resulting field of exergoeconomics or thermoeconomics has been fruitful for the design of complex energy systems and is still in evolution (Kim, 2010; Kim et al., 1998; Rosen, 2008; Tsatsaronis, 2006; Tsatsaronis et al., 1994; Valero et al., 1994). It remains for a large part focused on cost allocation, and design optimisation of energy producing plants (Abusoglu et al., 2009). This approach compares exergy investments with economic costs and benefits of the process. This approach does not see economic costs as a valuation method for impacts that cannot be assessed by exergy, and as such the approach does not combine the measured impacts in two different metrics. It rather provides a ratio between efficiency in exergy terms and economic benefit. Focussing more on environmental impacts, Verdesca et al. (2006) combine exergy-based values and economic added values for the appraisal of the ecosystem contribution to the economy. Yi et al. (2004) equally derive economic-environmental ratios to evaluate the exergy-use during the life cycle of an industrial process. But strictly speaking, these applications do not combine two impacts in two different dimensions to complete an inclusive sustainability assessment.

In order to combine impacts measured in different dimensions into a single composite indicator, various methods for aggregation are available (Nardo et al., 2005; Wang et al., 2009). Most often, the different dimensions are combined in indicators by means of weights and ratios. These weights can be determined through an overall ideal vision of sustainability, aligned to policy decisions, or through discussion with experts and the community involved. The advantages of weighing are surely the large flexibility and capacity for adaptation to local circumstances. It creates instruments that are able to combine aspects of a very different nature into one indicator. It increases clarity for discussions, but it should be noted that these weightings often lack theoretical underpinning and can be regarded as subjective. There are other approaches possible, based on multi-criteria analysis or efficiency measurements. The choice of aggregation method depends inherently of the practical case at hand. The next section illustrates the set-up of a combined sustainability assessment that makes use of exergy-based indicators for many of the environmental impacts, and that uses a standard economic frontier methodology to aggregate these impacts with measures in different dimensions.

An inclusive sustainability assessment methodology for this situation can partly be based on exergy-indicators. The sum of impacts accounted for in exergy covers all renewable and non-renewable inputs. The remaining aspects, services exchanged with society and land use, are divided in three components: land use, labour and capital. The total of four categories is aggregated with frontier analysis. Standard frontier methods, such as data envelopment analysis (DEA) or stochastic frontier analysis (SF) are readily being applied to combine measurements into one single indicator (Nardo et al., 2005). Standard production frontier analysis determines the processes within a group that use all resources most efficiently. These maximally efficient processes constitute together the efficiency frontier. The processes on the frontier utilise all resources combined as efficiently as possible. Other processes are enclosed by the frontier and perform less efficiently. The further the process is located from the frontier, the less efficient it is. This defines an overall economic efficiency θ for each process. A process that is on the efficiency frontier has θ equal to 100%.

Hoang and Rao (2010) combine this approach with a minimisation of the Cumulative Exergy Content of the productive inputs. After determination of the overall economic efficiency θ for each process k, Hoang and Rao (2010) determine the particular process on the frontier that has the minimal cumulative exergy input per unit output. The most sustainable production process thus achieves a maximally efficient resource use on the frontier and at the same time a minimal CEC per unit output. This leads to the additional definition of the allocative efficiency (AE) of each process. This AE describes the reduction in CEC input use that the process can obtain by moving along the efficiency frontier. This movement represents not an overall efficiency gain, but a modification in the allocation between the different input resources while keeping the overall production efficiency the same. The combination of θ resulting from standard economic efficiency analysis and AE resulting from CEC minimisation determines the most sustainable process.

In the economic approach, the output is not valued in a biophysical metric, but in monetary terms. The output ultimately achieves its value through interaction with customers, and monetary terms are much more suitable to indicate the value of the final products. We apply this efficiency approach to integrate both environmental and economic aspects. The production efficiency analysis chosen in this case is the Data Envelopment Analysis (DEA). The sustainable efficiency (SE) for firm k is :

$$SE = AE \cdot \theta^k \tag{50}$$

Here, θ^k is the production efficiency derived from the DEA analysis for firm k. AE is the Allocative Efficiency, it describes the distance of the efficient firm on the DEA frontier to the optimal sustainable firm j. θ^k describes the relative efficiency of the firm without input substitution. But the combination of maximal production efficiency with minimal exergy inputs requires substitutions between input resources to achieve the optimal sustainable situation. AE describes this potential efficiency increase by modifying the allocation of inputs. The combination of both θ^k and AE determines the final Sustainable Efficiency (SE) for each firm. The detailed calculation procedure is derived from Hoang and Rao (2010), and presented in

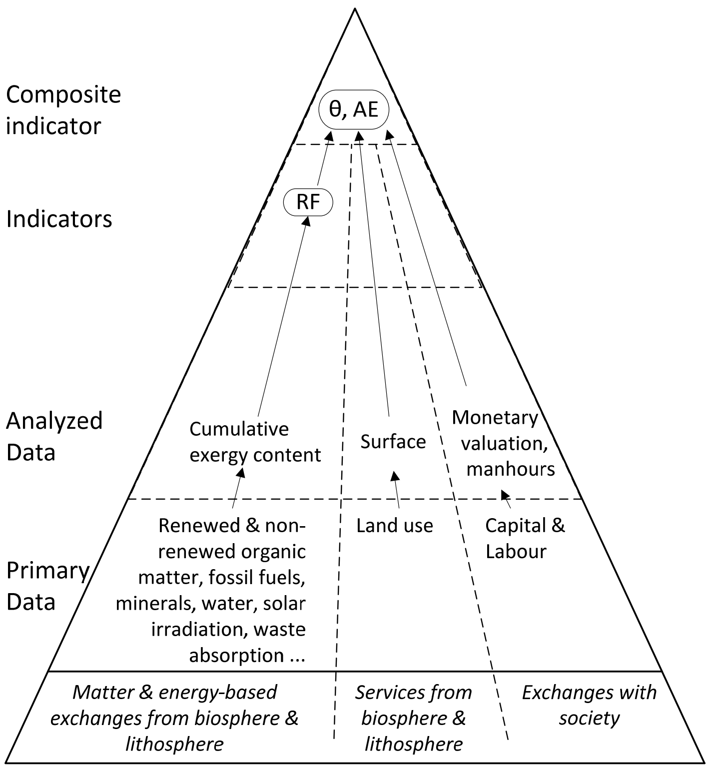

Figure E. 2: The 'Information pyramid' for the final structure of environmental sustainability indicators (adapted from Hammond et al. (1995))

Figure E. 2 summarizes the resulting indicator framework in an 'information pyramid' adapted from Hammond et al. (1995). Quantification starts from the primary data. These are transformed and aggregated into analysed data. The renewable fraction of the exergy input, denoted by indicator RF, remains essential for the description of sustainability of the process, as it contains information that is not available in the final index. This set-up summarizes the use of exergy-based measures of environmental impacts in a sustainability assessment. This approach is able to include multiple environmental impacts in the same objective units, and combines it with aspects that cannot be assessed in any biophysical measure. In principle, it gives a much more holistic result than energy-related sustainability measures for biobased projects.

Sustainability assessment of the manure treatment technologies

In line with the structure described in Figure E. 2, in- and outputs of different dimensions are included in the sustainability assessment of the manure treatment technologies:

- Physical inputs : The first physical input is the quantity of manure being treated, according to the technology specifically the dry or liquid fraction. Other inputs are additional chemicals such as lime (for quicklime treatment), water, energy for operation or energy for transport.
- Services are provided by society in the form of labour and investment capital. In order to maintain comparability between the different technologies, the investment capital is transformed in annual payments for interests and capital reimbursement.
- The processes produce various outputs. Valuable outputs are directly sold. To incorporate different environmental performances or different produced fertilisers, the comparison also regards the application of the produced fertiliser on land, and the potential leakage of nitrate and phosphate compounds in the natural environment after application. For instance, a large advantage of the biology treatment is the fact that the mineral compounds in the digestate are rendered 100% available for the plants. Mineral dry fertilisers or mineral concentrates can also present the same behaviour. Liquid fractions of manure however, are not entirely or directly taken up by plants. Potential leakage of compounds out of the agricultural land, are accounted for.
- Physical ecosystem contributions : At various points in the value chain the process counts on ecosystem contributions. The environment ensures the absorption of polluting emissions, created during transport of due to energy consumption. Also the aborption of waste flows, such as the clear liquid from reverse osmosis for instance, are effectuated by ecosystems and accounted for.

Many ecosystem resources and related ecosystem adaptations can be quantified through the CEENE approach. Two aspects still need clarification, the sequestration of emitted CO_2 and the sequestration of nitrate compounds. An estimation of the respective exergy costs is provided in Annex B

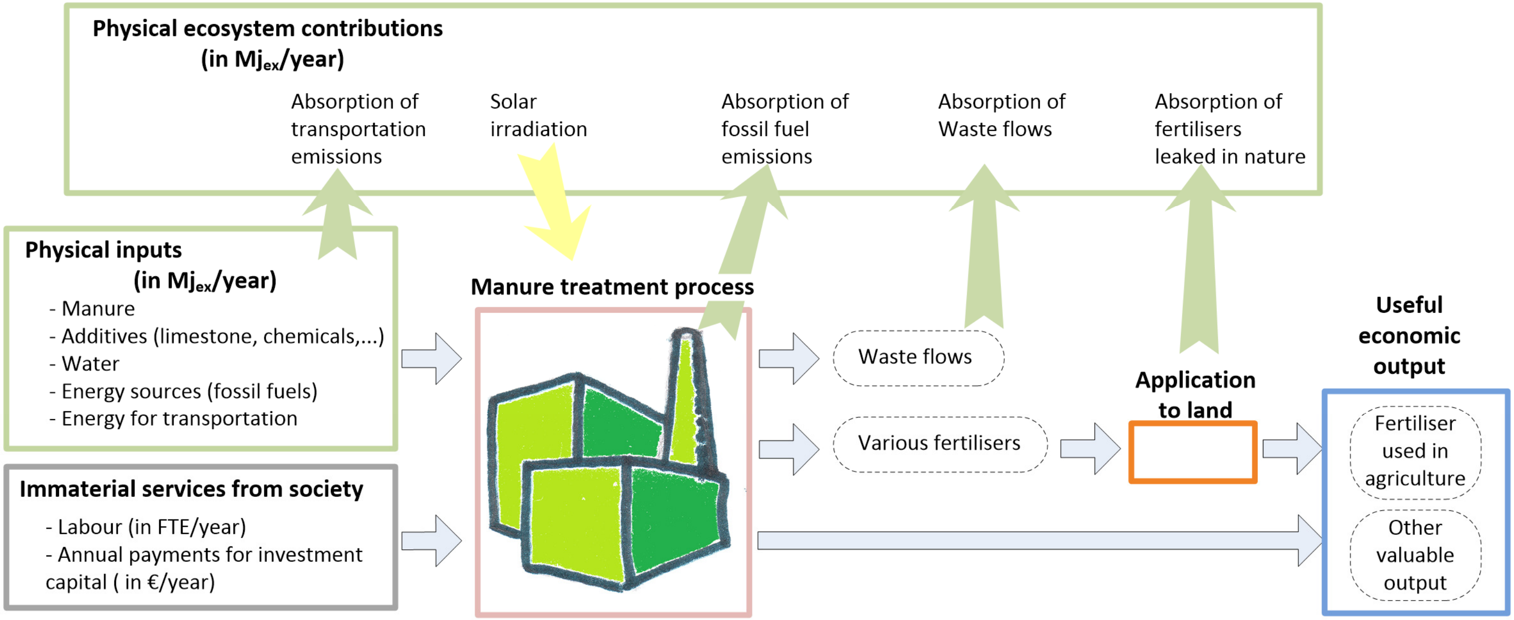

Figure E. 3: The schematic representation of in- and outputs considered for the sustainability assessment

The sustainability assessment has been performed for each technology for different treatment capacities : 2.500, 5.000, 7.500, 10.000, 15.000, 20.000, 30.000, 50.000, 75.000, 100.000, 200.000, 300.000 and 500.000 m^3/year. This results in 9 x 13 different scenarios. Figure E. 3 illustrates the different in- and outputs that are accounted for. The inputs can be gathered in three groups. The first group gathers all exergy-based inputs, both the productive inputs and the ecosystem contributions. The second group gathers inputs of labour, and the third of capital.

The manure treatment leads to a number of useful economic outputs. Several treatment methods have very few or even no productive outputs. For instance, constructed wetlands result in no productive outputs at all. To keep an input-output comparison, these methods have each been compared to a reference situation. In the reference situation, the same manure quantity as the quantity treated by the facility is spread directly on the field. The spreading of manure results in agricultural added value, and sometimes also in leaked compounds and thus ecosystem expenses for pollution absorption. It is assumed that the treatment of an equivalent amount of manure reduces a similar amount of added value for agriculture, and avoids a similar amount of pollution. By taking this replacement effect into account as well, every treatment facility has a defined productive output.

Ecocentric valuation of the output

The first results are given by the Renewable fraction of the physical inputs (RF). This indicator only deals with the inputs measured in exergy units, and shows the proportion of the physical inputs that is renewable. These results are indicated in Table E. 1.

It is remarkable that most renewable fractions are very high. The decreasing level of renewable fraction with increasing capacity can in most cases be attributed to the transportation costs. The energy requirement for the transportation of manure increases with the square root of treatment capacity. However it should also be noted that a high renewable fraction as such does not necessarily indicate a clean process. Ecosystem activities are also included and these are renewable contributions to the economic process.

Table E. 1: The renewable fractions for the different manure treatment technologies

	Annual capacity [m³/y]	2 500	5 000	7 500	10 000	15 000	20 000	30 000	50 000	75 000	100 000	200 000	300 000	500 000
1	Reverse Osmosis	93.5%	93.0%	92.6%	92.3%	91.7%	91.3%	90.4%	89.1%	87.7%	86.5%	83.0%	80.3%	76.3%
2	Biology treatment	90.0%	89.2%	88.6%	88.0%	87.1%	86.3%	85.0%	82.9%	80.8%	79.1%	74.0%	70.3%	65.1%
3	Constructed wetland	90.4%	89.6%	89.0%	88.5%	87.6%	86.9%	85.6%	83.5%	81.5%	79.8%	74.9%	71.3%	66.1%
4	Drying	97.9%	97.7%	97.6%	97.5%	97.3%	97.2%	96.9%	96.5%	96.0%	95.6%	94.3%	93.3%	91.7%
5	Composting	96.7%	96.6%	96.4%	96.3%	96.2%	96.0%	95.8%	95.3%	94.9%	94.5%	93.2%	92.3%	90.7%
6	Quicklime	99.7%	99.5%	99.4%	99.3%	99.1%	98.9%	98.6%	98.1%	97.7%	97.2%	95.9%	94.8%	93.1%
7	Algae production	83.9%	83.4%	83.1%	82.8%	82.2%	81.8%	81.0%	79.7%	78.5%	77.4%	74.1%	71.6%	68.0%
8	Duckweed production	83.9%	83.4%	83.1%	82.8%	82.2%	81.8%	81.0%	79.7%	78.5%	77.4%	74.1%	71.6%	68.0%
9	Pyrolysis + drying + RO	75.7%	75.3%	74.9%	74.6%	74.1%	73.7%	72.9%	71.7%	70.5%	69.4%	66.3%	64.0%	60.5%

Table E. 2: The efficiency indicator θ^k for each treatment technology, determined with Data Envelopment Analysis

	Annual capacity [m³/y]	2 500	5 000	7 500	10 000	15 000	20 000	30 000	50 000	75 000	100 000	200 000	300 000	500 000
1	Reverse Osmosis	31.2%	31.0%	30.9%	30.8%	30.6%	30.5%	30.4%	30.3%	30.2%	30.3%	33.0%	35.6%	39.1%
2	Biology treatment	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
3	Constructed wetland	3.0%	3.0%	3.0%	3.0%	2.9%	2.9%	2.9%	2.8%	2.7%	2.7%	2.5%	2.4%	2.2%
4	Drying	67.5%	67.6%	67.7%	67.8%	67.9%	68.1%	68.4%	68.7%	69.1%	69.5%	74.4%	82.8%	**100%**
5	Composting	60.2%	60.1%	60.0%	59.9%	59.8%	59.7%	59.5%	59.2%	58.9%	58.7%	57.9%	57.3%	56.3%
6	Quicklime	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
7	Algae production	6.1%	6.1%	6.1%	6.0%	6.0%	5.9%	5.9%	5.8%	5.7%	5.6%	5.4%	5.2%	5.0%
8	Duckweed production	6.1%	6.1%	6.1%	6.0%	6.0%	5.9%	5.9%	5.8%	5.7%	5.6%	5.4%	5.2%	4.9%
9	Pyrolysis + drying + RO	93.3%	92.7%	92.3%	91.9%	91.2%	90.6%	89.5%	87.9%	86.3%	84.9%	80.6%	77.5%	72.8%

This means that highly polluting processes engender a lot of ecosystem contributions, which increases the RF-factor. The negative effect of high levels of pollutions is thus not visible in the RF. Pollution is more clearly visible in the efficiency factor θ^k, as the same quantity of outputs requires more inputs in the case of polluting processes.

The efficiency indicator θ^k is reported in Table E. 2. In this case the outputs are valued ecocentrically, in exergy terms. This θ^k is based on all three categories of inputs (physical, labour and capital), unlike the RF that is based on the physical inputs only. All treatment facilities that present a θ^k of 100% are part of the efficiency frontier. This means that within the group of examined facilities, there is no possibility to utilise the same inputs more efficiently. The efficiency of the other facilities is calculated relatively to this frontier. The results of this analysis indicate clear patterns. The most efficient technologies in this case are the quicklime treatment and the biology treatment, followed by the drying of manure. These three processes transform the manure in rather low value, but highly accessible fertilisers, and do not provide additional products of higher added value. The pyrolysis treatment also shows high efficiencies, and is in this case the only innovative treatment to do so. The innovative biobased technologies, algae and duckweed production and constructed wetlands, show extremely low efficiencies. The fact is that these technologies do not make use of many ecosystem contributions, as they cause very little pollution, and require relatively little energy. However, the production of the output is even less, and per unit output, the quantity of inputs is multiple times higher compared to more traditional technologies. Even if these more traditional technologies can cause higher pollutions along their value chain, their overall contribution in useful output is quite high.

This is also represented graphically in Figure E. 4. This figure presents the substitution between the physical and capital inputs for each technology, per unit output. Other substitutions, such as between labour and capital, or between labour and physical inputs, present a very similar picture.

Every technology shows a single crescent-like shape. At the left-upper corner, the lowest treatment capacities are located. These require relatively high capital inputs per unit output. Due to economies of scale, the capital inputs decrease for increasing treatment capacities. At the same time, increasing capacities require relatively more physical inputs, in terms of transportation energy and pollution abatement. The highest treatment capacities, of 500 000 m^3/y, are located at the bottom-right corner of each crescent.

The figure shows most clearly the relative positions of the technologies compared to each other. The most efficient technologies are located at the left-bottom corner of the graph. These are the quicklime treatment, drying and pyrolysis. In the opposite corner, the least efficient technologies are presented, the duckweed and algae productions and the constructed wetlands. The axes are given in logarithmic scale in order to keep the different technologies graphically on the same figure. In absolute numbers, the differences between the technologies are extremely large.

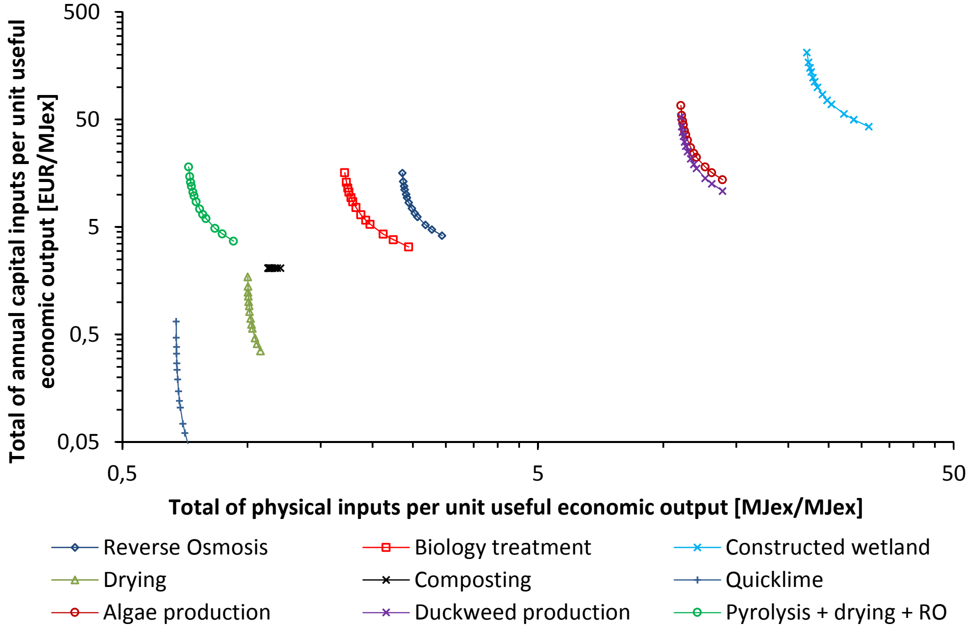

Figure E. 4: Graphic representation of the physical and capital inputs per unit output for each technology, when the output is valued in exergy terms.

When calculating the final Sustainable Efficiency (SE) for each case, these results are confirmed. The SE is reported in Table E. 3.

These results are to be interpreted with caution, considered the following elements. First of all, the calculations are based on the approximations in Table 3-2 and Table 3-3. These are tentative estimations of the economic performance of each process. Practical improvements and innovation can still change these performances considerably, causing shifts amongst technologies. But the overall distribution between traditional and innovative methods is unlikely to change through innovation, given a difference of a factor 100 between for instance the algae production and the quicklime treatment. Secondly, the costs of ecosystem contributions have been estimated very roughly. More precise investigations are required to detail these costs with a better precision.

The most important remark is that in this case the outputs have been valued ecocentrically, in exergy terms. As mentioned, both ecocentrical and anthropocentrical valuations are valid valuation approaches. But the choice has an important effect on the results.

Table E. 3: The final Sustainable efficiency (SE), considering output valuation in exergy.

	Annual capacity [m³/y]	2 500	5 000	7 500	10 000	15 000	20 000	30 000	50 000	75 000	100 000	200 000	300 000	500 000
1	Reverse Osmosis	8.9%	8.8%	8.7%	8.7%	8.6%	8.5%	8.4%	8.2%	8.1%	8.0%	8.3%	8.6%	9.0%
2	Biology treatment	39.3%	39.0%	38.7%	38.4%	38.0%	37.6%	37.0%	36.0%	35.0%	34.2%	31.8%	30.1%	27.6%
3	Constructed wetland	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.0%
4	Drying	45.5%	45.4%	45.4%	45.5%	45.5%	45.5%	45.5%	45.6%	45.6%	45.6%	48.2%	52.9%	62.8%
5	Composting	36.2%	36.1%	36.0%	35.9%	35.8%	35.6%	35.4%	35.1%	34.7%	34.4%	33.5%	32.8%	31.6%
6	Quicklime	100%	100%	99.9%	99.8%	99.7%	99.5%	99.3%	98.8%	98.3%	97.8%	96.4%	95.3%	93.5%
7	Algae production	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.2%
8	Duckweed production	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.2%
9	Pyrolysis + drying + RO	87.1%	86.0%	85.1%	84.4%	83.1%	82.0%	80.2%	77.3%	74.4%	72.0%	65.0%	60.1%	53.0%

Table E. 4: The efficiency indicator θ^k for each treatment technology, determined with anthropocentric – monetary – valuation of the outputs.

	Annual capacity [m³/y]	2 500	5 000	7 500	10 000	15 000	20 000	30 000	50 000	75 000	100 000	200 000	300 000	500 000
1	Reverse Osmosis	62.9%	66.2%	69.4%	72.0%	76.6%	80.9%	87.1%	93.6%	97.2%	98.9%	**100%**	**100%**	**100%**
2	Biology treatment	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
3	Constructed wetland	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
4	Drying	14.9%	16.0%	17.1%	18.2%	19.8%	20.9%	23.7%	28.0%	32.1%	35.3%	44.5%	50.9%	60.5%
5	Composting	11.9%	11.9%	11.9%	11.9%	11.9%	11.9%	11.8%	11.8%	11.8%	11.7%	11.6%	11.5%	12.0%
6	Quicklime	21.5%	26.3%	31.0%	34.7%	40.5%	45.0%	51.7%	60.7%	68.2%	73.5%	86.0%	92.7%	**100%**
7	Algae production	69.2%	70.1%	70.8%	71.4%	72.2%	73.0%	74.2%	76.9%	79.3%	81.4%	87.2%	93.3%	**100%**
8	Duckweed production	70.7%	72.3%	73.3%	74.2%	75.7%	77.1%	78.8%	81.4%	83.0%	85.5%	92.4%	96.4%	**100%**
9	Pyrolysis + drying + RO	**100%**	**100%**	**100%**	**100%**	**100%**	99.8%	99.2%	98.3%	97.5%	96.8%	94.8%	93.3%	91.2%

Anthropocentric valuation of the outputs

When the former analyses are performed with a different type of output valuation, the results are radically different. Amongst the various types of output, there is a large difference between valuation in exergy terms (the ecocentric approach), and valuation in monetary terms (the anthropocentric approach). Table E. 5 shows different prices per GJ actual exergy content for different substances. A monetary valuation of the outputs establishes a much higher value for algae than for dried manure for instance. Also the production of mineral fertiliser concentrates is much more valuable to society than the exergy content would attribute to it. The distinction between these two approaches becomes increasingly important as innovative biobased projects often produce products of added value, in addition to traditional outputs such as fertilizer replacements. Especially these new biobased products present significant valuation differences. It is therefore all the more important to denote clearly the choice made when evaluating innovative biobased projects.

Table E. 5: The ratio between the value in EUR and in GJ exergy for different types of output.

Substance	**Price per unit net exergy content** [EUR / GJex]
Dried fertiliser	1.5
Waste wood	3.5
Natural gas	8,2 - 9,2
Algae	15.1
Electricity	17
Ureum	21
Mineral fertiliser concentrate	602
Bell peppers	440
Young sprouts	10.402

The valuation choice for the output does not give any difference for the Renewable Fraction, so RF reported in Table E. 1 remains valid. However, the efficiency indicator, θ^k, is changed. The results for θ^k with anthropocentric valuation are reported in Table E. 4. The results show again clear patterns with regard to the different technologies, but these patterns are the opposite of the results with ecocentric valuation. In this case, the biobased technologies, and all innovative technologies obtain very good scores. The traditional technologies, with the exception of the biology treatment, have reduced results. Figure E. 1 illustrates these trends graphically.

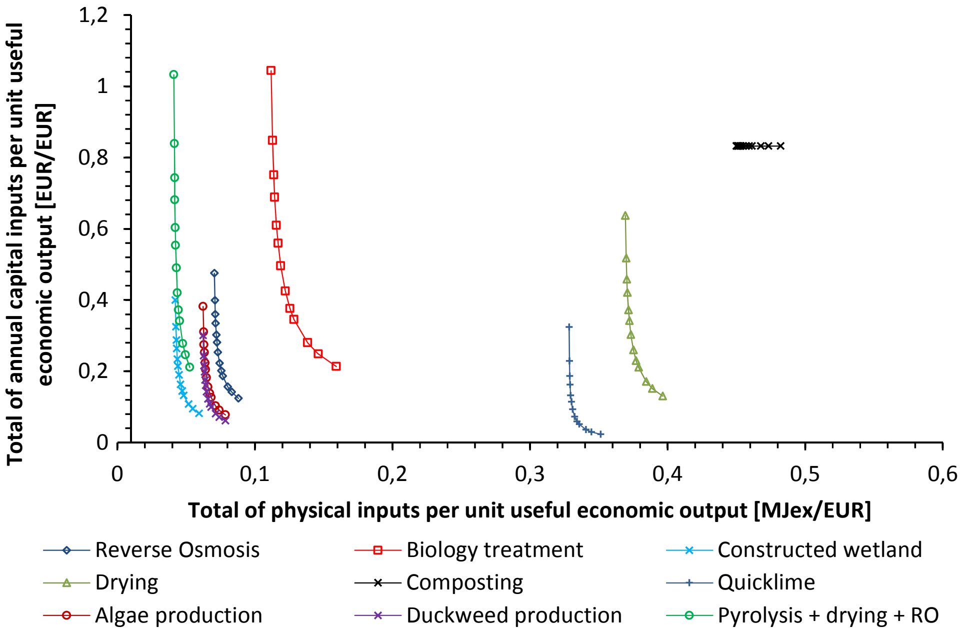

Figure E. 5: Graphic representation of the physical and capital inputs per unit output for each technology, when the output is valued in monetary terms.

When the produced outputs of the processes are estimated in Euro, the production efficiencies of the different projects are much more favourable for the biobased processes. The top performance is given by the constructed wetlands, closely followed by the algae and duckweed productions. It is remarkable that the pyrolysis technology is the only technology to obtain a good score in both cases. This is because the pyrolysis facilities produce different types of output. On the one hand, they produce large volumes of low-value products. These are higher valued in the case of the ecocentric valuation. But the pyrolysis facilities equally produce small quantities of high value products, such as heavy oil or biochar. These outputs are responsible for the good score in the case of anthropocentric valuation of the technology. The final Sustainable efficiency (SE) is reported in Table E. 6. These results repeat the same trends. Constructed wetlands and Pyrolysis obtain very good scores, followed by the innovative biobased technologies. The traditional technologies obtain efficiency scores that are very unfavourable.

Table E. 6: The final Sustainable efficiency (SE), considering output valuation in monetary terms (EUR).

	Annual capacity [m³/y]	2 500	5 000	7 500	10 000	15 000	20 000	30 000	50 000	75 000	100 000	200 000	300 000	500 000
1	Reverse Osmosis	36.7%	38.5%	40.1%	41.4%	43.8%	46.0%	49.0%	51.8%	52.9%	53.1%	51.3%	49.5%	46.8%
2	Biology treatment	36.8%	36.5%	36.2%	36.0%	35.6%	35.2%	34.6%	33.7%	32.8%	32.0%	29.8%	28.2%	25.8%
3	Constructed wetland	97.5%	96.6%	95.9%	95.3%	94.3%	93.4%	91.9%	89.5%	87.1%	85.2%	79.4%	75.2%	69.2%
4	Drying	1.7%	1.8%	1.9%	2.0%	2.2%	2.3%	2.6%	3.1%	3.5%	3.8%	4.8%	5.4%	6.3%
5	Composting	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.0%	1.0%	1.0%	1.0%
6	Quicklime	2.7%	3.3%	3.9%	4.3%	5.1%	5.6%	6.4%	7.5%	8.4%	9.0%	10.4%	11.1%	11.7%
7	Algae production	45.6%	45.9%	46.2%	46.4%	46.6%	46.8%	47.1%	48.0%	48.6%	49.1%	50.2%	51.8%	52.3%
8	Duckweed production	46.6%	47.4%	47.9%	48.2%	48.8%	49.4%	50.0%	50.8%	50.9%	51.6%	53.2%	53.5%	52.3%
9	Pyrolysis + drying + RO	100.0%	99.4%	98.9%	98.4%	97.7%	96.9%	95.2%	92.6%	90.1%	88.0%	81.9%	77.5%	71.2%

Multiple conclusions can be drawn from these results. With respect to the method as such, the applications show that the method is capable of combining very diverse aspects in different dimensions into a single indicator. Specifically for the measurements in exergy, a large number of different aspects can be included. Materials, sunshine, pollution absorption or water are all included. The combination with other dimensions, such as labour or capital can be done through the efficiency analysis. The overall results balance the different dimensions and give a holistic measurement. This type of approach only establishes relative efficiencies, comparing the different technologies of the entire group to each other. Results from other studies, applying the same methodology on other technologies, cannot be compared to these results. The results are only valid within the group contained in the study.

In this case, the performances of the technologies have been estimated very roughly. Only few data are available on the real applications of traditional technologies. Moreover, precise figures for the innovative technologies are still lacking, because there are hardly any full-scale applications of these technologies in practice. Also, the current evolution in technical and economic performance through constant innovation is likely to change these estimations. However, the results show that even with only a moderate precision, the calculated efficiencies depend much more on the methodological assumptions than on the estimated variables. Both in the case of ecocentric and anthropocentric valuation of the output, the differences between traditional and innovative technologies are so large, that even significant advances in performance of the innovative technologies are unlikely to change the overall trend.

With ecocentric valuation, the overall trend is that the traditional technologies are at an advantage due to their capacity to create large volumes of low-value biobased products. With anthropocentric valuation, the overall trend is exactly the opposite. Here, products are preferred that present a high value to society. The overall trend is that the innovative technologies are much more efficient than traditional technologies in the creation of socially desired products. They can do so with a much lower cost to society and to the environment. Pyrolysis is the exception is this case, performing very well in both approaches.

Annex F Method review for environmental assessment of biobased products

The following table gives an overview of papers investigating the production of bioenergy and biobased materials from a life cycle perspective with exergy-based indicators. The following different methodologies are used in the papers:

CEC : The standard method to utilise exergy within a life cycle context is the calculation of the Cumulative Exergy Content (CEC) (Szargut et al., 1988). The CEC accounts for the cumulative quantity of exergy being destroyed or used during the life cycle of a product. The CEC can account for mineral resources and fossil inputs in production processes.

CEENE : The Cumulative Exergy Extraction from the Natural Environment (CEENE) further extends the CEC to include also resources extracted from renewable sources and ecosystems (Dewulf et al., 2007). CEENE includes renewable matter by first counting the total solar exergy on the land that was needed to produce the resource. Then two percent of this total irradiation is included in the total exergy accumulation of the product. This percentage represents the maximum metabolic efficiency of the natural organisms. Algae have shown to transform solar exergy into biomass with an efficiency of about 2%. Higher efficiencies are only reported for species in ideal lab-conditions or engineered organisms (Melis, 2009; Zhu et al., 2008). As such CEENE values the biomass production as if the natural environment produced biomass with maximum efficiency. If the actual ecosystem produces the renewable resources less efficiently, the ecosystem will require more land and more solar irradiation, and this will have a corresponding impact on the overall result.

EEA : Extended exergy accounting (EEA) is based on CEC and includes two factors representing the needs for capital and labour (Sciubba, 2001). Both are defined on a macroeconomic basis and form a ratio between labour or capital and the exergy needed to provide this service (Sciubba, 2011). These extensions express all productive factors that are usually regarded in economic analysis in exergetic terms. EEA shows then an exergetic parallel view of the economic analysis.

ECEC: Even with all the different extensions and evolutions of exergy theory, one point of concern remains the correct inclusion of the work of ecosystems in the overall lifecycle of a product. CEENE has made a step to integrate renewable resources, but other ecosystem services are still hard to account for. Ecological Cumulative Exergy Consumption (ECEC) proposes to make a link between exergy analysis and the knowledge of ecological processes gained through Emergy analysis (Hau et al., 2003). Emergy is a different physical metric, and is defined as *"the availability of energy of one kind that is used up in transformations directly and indirectly to make a product or service."*(Odum et al., 2000). Emergy analysis traces back solar energy expenditure during the entire life cycle of the object under investigation, and includes essential contributions from ecosystems and the earth's crust (Odum, 1996). It has been applied to estimate the energy density of renewable fuels, wind, rain, volcanic heat, waves and tidal energy to name but a few (Brown et al., 2001; Odum, 1996). However, the theory has also been extended to evaluate the value of money or human labour. This and other aspects of Emergy analysis have been controversial and did limit the integration of Emergy analysis in other domains (Hau et al., 2004).

The ECEC approach makes use of the transformaties in Emergy analysis in a CEC calculation and avoids thus more controversial parts of Emergy literature such as the link with money or the Maximal Empower principle. But Emergy analysis has been evaluated not to be consistent with the second law of thermodynamics, especially when accounting for heat transfer (Sciubba, 2010). Whereas direct integration of emergy results in exergy calculations is often proposed (Bastianoni et al., 2007; Hau et al., 2003), this difference in approach makes this integration untenable. But even when the integration in an exergy-based analysis should be done cautiously, this does not reduce the merit of Emergy analysis as such (Jørgensen et al., 2004a; Sciubba, 2010).

Table F. 1 : Papers investigating the production of bioenergy and biobased production from a life cycle perspective with exergy-based indicators

Paper	Type of bioenergy or biobased product	Method	Particularities
Dewulf et al. (2000)	Bio-ethanol from wheat grain	CEC	Sustainability assessed with renewability and efficiency indicators. Extended CEC with inclusion of solar irradiation.
Dewulf et al. (2005)	Biodiesel production	CEC	Comparison of three production pathways
Brehmer et al. (2008)	Comparison of different legumes as biorefinery feedstock	CEC	The paper describes the efficiency of the legume production
Yang et al. (2009)	Corn-based ethanol	CEC	Cradle-to-gate analysis without environmental effects
Urban et al. (2009)	1,3-Propanediol from fossil and from renewable sources	CEC and ECEC	Comparison of different methods to see the effect of included ecosystem services
Baral et al. (2010)	Comparison of different transport fuels	ECEC	
Buchgeister (2010)	Electricity production using a solid oxide fuel cell with biomass gasification	Exergy and LCA	Exergy-based analysis, but not over the entire life cycle. Life cycle impacts are distributed pro rata of exergy contents
Talens Peiró et al. (2010)	Biodiesel production	EEA	Comparison of two production pathways
Banerjee et al. (2011)	Biomass boiler for heat	CEC and EEA	Comparison with other technologies
De Meester et al. (2011)	Comparison of biorefinery scenarios for the production of food, biobased products and bioenergy	CEENE	Cradle-to-gate analysis including environmental impacts.
Liao et al. (2011)	Bioethanol from corn	Combined CEENE, CEC and EEA	Combined methodology
Özilgen et al. (2011)	Vegetable olive, sunflower and soybean oil production	CEC	Thorough cradle-to-gate life cycle view. No integration of emissions or sunlight
Rubio Rodríguez et al. (2011)	Different transport fuels	Combined CEC, EEA and CEENE	Combined methodology
Christopher et al. (2012)	Comparison of renewable pathways of hydrogen production	CEC	Life Cycle view from Cradle to gate, does not include environmental impacts
De Meester et al. (2012)	Anaerobic digestion for heat and electricity production	CEENE	Cradle-to-gate analysis including environmental effects and sunlight
Neupane et al. (2013)	Wood-derived ethanol	ECEC	
Taelman et al. (2013)	Algae for Aquaculture feedstock	CEENE	Includes scenarios for increased efficiency

Annex G Estimation of exergy costs for pollution abatement

Some industrial processes sequester carbon, and the related exergy costs have been calculated. Valero and Botero (2002) report exergy abatement costs for emissions from electricity plants ranging between 1.27 and 2.04 MJ/kg CO_2. These exclude the disposal of the liquefied gas. Dewulf et al. (2002a) report an abatement cost of 5.86 MJ/kg, for a similar process, including underground storage of the emissions. These are abatement technologies in industrial applications based on non-renewable exergy inputs. In this case, the pollutants are absorbed by the natural environment. For an abatement cost based on renewable exergy inputs, estimation is made for the abatement cost of CO_2 and N through forest growth. This estimation gives a first idea on the order of magnitude of renewable exergy required for pollution abatement, but this is very rudimentary and primarily shows that further research is required to detail this aspect in exergy-based life cycles.

Natural processes sequester CO_2 by building up natural carbon reserves. The energy needed for the sequestration of CO_2 could be estimated. A crude estimation of this exergy cost per unit CO_2 can be done based on the chemical equation for organic matter (Jørgensen et al., 2004a).

$$3.500\ CO_2 + 2.700\ H_2O + 600\ HNO_3 \leftrightarrow C_{3.500}H_{6.000}O_{3000}N_{600} + 4.250\ O_2 \qquad (51)$$

Detailed long term measurements of inputs and outputs of forests yielded indications for all flows in this equation. The sequestration is fuelled by solar exergy. But most of this exergy is used up for the evaporation of water. An overview of the inputs and outputs of forest area are given in Table 4. These flows are based on measurements reported by Berbigier et al. (2001).

The total amount of exergy in the inputs is attributed to the outputs pro rata of their intrinsic exergy content. This defines the total exergy cost for every output separately (Valero et al., 1986). The exergy cost for sequestering CO_2 with the biological process in a natural forest is estimated at about 100 MJ/kg CO_2. When comparing this solar exergy to fossil exergy costs, only 2% is accounted for, which gives an equivalent of roughly 2 MJ/kg CO_2 in fossil terms. This is comparable to the sequestration costs reported with industrial processes. Another input of the economic process is oxygen. The production cost of oxygen turns out to be about 1.1 MJ/kg. This is a "cumulative exergy cost" of oxygen that is approximately nine times the net exergy content of oxygen as defined by the CEC method.

Table G. 1 : Inputs and outputs of 1 ha European forest, with indication of the exergy cost of the outputs

Input	Quantity		Exergy content		Quantity			
CO2	6.4	t/ha	19.9	kJ/mol	2 871	MJ/ha		
Solar energy	35 418 909	MJ/ha	0.93	kJ/kJ	33 035 217	MJ/ha		
H2O (liquid)	9 300	t/ha	0.9	kJ/mol	465 000	MJ/ha		
HNO3	21 429	mol/ha	43.5	kJ/mol	932	MJ/ha		
Output	Quantity		Exergy content		Quantity		Exergy cost	
$C_{3500}H_{6000}O_{3000}N_{600}$	35.71	mol/ha	1 952 280	kJ/mol	69 724	MJ/ha	17.61	MJ/mol
H2O (vapour)	6 653.76	t/ha	9.50	kJ/mol	3 511 706	MJ/ha	4.76	MJ/kg
H2O (Liquid)	2 644.51	t/ha	0.90	kJ/mol	132 225	MJ/ha	0.45	MJ/kg
O2	4.86	t/ha	3.97	kJ/mol	603	MJ/ha	1.12	MJ/kg

	Gross exergy cost		Nett exergy cost	
C (sequestered)	98.9	MJ/kg CO2	1.98	MJ/kg CO2
N (sequestered)	2 096.5	MJ/kg N	41.93	MJ/kg N

Annex H DEA for indicator aggregation

The chosen efficiency comparison is based on Data Envelopment Analysis (DEA) (Coelli et al., 2005). The DEA is defined for K firms, each producing a vector $\mathbf{y}$ of M outputs, $\boldsymbol{y} \in \boldsymbol{R}_{+}^{M}$, requiring an input vector $\mathbf{x}$ of N inputs, $\boldsymbol{x} \in \boldsymbol{R}_{+}^{N}$. For the k^{th} firm, $1 \leq k \leq K$, the output and input vectors are defined as :

$$\mathbf{y}^{k} = \left[y_{1}^{k}, \ldots, y_{m}^{k}, \ldots, y_{M}^{k}\right]^{T}; 1 \leq m \leq M \tag{52}$$

$$\mathbf{x}^{k} = \left[x_{1}^{k}, \ldots, x_{n}^{k}, \ldots, x_{N}^{k}\right]^{T}; 1 \leq n \leq N \tag{53}$$

The total output and input matrices are defined as:

$$Y = \left[y^{1}\middle|\ldots y^{k}\middle|\ldots y^{K}\right]; Y \in R_{+}^{MxK} \tag{54}$$

$$X = \left[x^{1}\middle|\ldots x^{k}\middle|\ldots x^{K}\right]; X \in R_{+}^{NxK} \tag{55}$$

For each firm a minimal scalar θ^{k} is derived that satisfies:

$$min_{\theta,\lambda}\theta^{k}, \tag{56}$$

$$y^{k} \leq \lambda * Y;$$

$$\theta^{k} \cdot x^{k} \geq \lambda * X;$$

$$\lambda \geq 0;$$

$$\lambda \in R_{+}^{Kx1};$$

This definition is the envelopment form of DEA, as outlined by Coelli et al. (2005). This algorithm seeks the minimal linearly reduced input for firm k that can produce the same output as firm k. If a linear combination of all firms in the set K can produce y^{k}, for only the fraction of inputs $\theta^{k}x^{k}$, then θ^{k} indicates the Production Efficiency (PE) of the k^{th} firm.

Following the definitions of Hoang and Rao (2010) this leads to the following formulas for the sustainable efficiency (SE) and its components.

If p_m is the market price for output y_m then:

$\mathbf{p} = \left[p_{1}, \ldots, p_{m}, \ldots, p_{M}\right]$; $1 \leq m \leq M$ is the price matrix for output

$P^{k} = \boldsymbol{p} \cdot \boldsymbol{y}^{k}; 1 \leq k \leq K$ is the total turnover of firm k

If c_n is the CEC of input x_n then:

$\mathbf{c} = \left[c_1 , \ldots , c_n , \ldots , c_N\right]$; $1 \leq n \leq N$ is the cumulative exergy content matrix for input

$C^k = \boldsymbol{c} \cdot \boldsymbol{x}^k$; $1 \leq k \leq K$ is the total cumulative exergy input of firm k

The optimal sustainable firm j is defined as:

- Firm j is on the efficiency frontier, $\theta^j = 1$;
- $\forall k$; $1 \leq k \leq$ K and k ≠ j; $C^j/_{P^j} < C^k/_{P^k}$;

The sustainable efficiency (SE) for firm k is thus:

$$SE = C^j/_{P^j} \cdot P^k/_{C^k} = C^j/_{P^j} \cdot P^k/_{\theta^k C^k} \cdot \theta^k = AE \cdot \theta^k \tag{57}$$

Here, θ^k is the production efficiency derived from the DEA analysis for firm k. AE is the Allocative Efficiency, it describes the distance of the efficient firm on the DEA frontier to the optimal sustainable firm j. Contrary to θ^k, the transition along the frontier to firm j requires substitutions between input resources to achieve the optimal sustainable situation. AE describes thus the potential efficiency increase by modifying the allocation of inputs.

Annex I Data descriptions

This annex collects all data that enter the calculation, and distinguishes between original data (secondary use), and results from calibrations.

Data for the construction of the farm agents

The individual data for the farm agents all stem from the FADN database. This is secondary use of empirical data collected by the farm monitoring network.

Table I. 1 : Data requirements at the level of the individual farm agents

Factor	Unit	Description
Age	Year	Age of the farm owner
Risk factor	%	Maximum level of financial risk
# of working persons in the household	/	Nr of household members of working age
Total used acreage	ha	Total used land (rented + owned)
Rented land	ha	Total rented land
Owned area leased to others	ha	Total land, leased to others
Milk production deviation	%	Production efficiency
Cow production deviation	%	Production efficiency
Pig production deviation	%	Production efficiency
Crops	ha	Nr of ha used for crops
Horticulture	ha	Nr of ha used for horticulture
Forage	ha	Nr of ha used for forage
Grassland	ha	Nr of ha in pastures and grassland
Dairy cows	LSU	Total stock of dairy cows
Cattle	LSU	Total stock of cattle (except dairy cows)
Pigs	LSU	Total pig stock
Fixed total Assets (without land)	EUR	Total fixed assets at the end of 2007 (no land)
Fixed total Assets (Land)	EUR	Total fixed assets at the end of 2007
Total liabilities (EUR)	EUR	Total loans and liabilities
Loan percentage (%)	%	Loans as percentage of total assets
Total land rent (EUR)	EUR	Annual rent for land
Average land rent price (EUR/ha)	EUR/ha	Average rent price per ha
Total Cash	EUR	Total available liquid assets

The data in Table I. 1 are available for each reference farm agent. In total, 29 different reference agents are selected. There are also factors that determine how the different types and reference farms are distributed among the total farm population. These data are required by different calibration exercises, and are listed in Table I. 2.

Table I. 2 : Data requirements at the level of the farm agent population

Factor	Unit	Description
Weight	/	Nr of times that the reference agent is copied in the initial farm database.
Percentage of Stable farms	%	Proportion of the total farm agent population that are Stable family farms
Population adaptiveness	%	Frequency of the growing farms, industrial farms and innovator farms to review their strategy.
Transaction costs	/	Additional cost in case of farm structure change
Land market availability	%	Annual chance that a plot of agricultural land will be available during a year.

Data for the external actors on the land market

Multiple actors intervene on the land market. Several actors are not modelled in detail, but their impacts on the land market are approximated with generic actions.

Table I. 3 : Data requirements at the level of the farm agent population

For the hobby farmers	**Unit**	**Description**
The initial acreage;	/	Initial surface occupied for hobby farming
The annual growth rate of the surface;	%	Annual growth rate of the hobby farming surface
Offered land price mark-up;	%	Additional price that the hobby farmers are willing to pay for new land purchases
For the crop farmers	**Unit**	**Description**
Percentage offered for sale;	%	Share of the land owned by crop farmers that is offered for sale in one year.
Percentage demanded for purchase;	%	Share of the land owned by crop farmers that is demanded for purchase in one year.
Percentage offered for lease;	%	Share of the land owned by crop farmers that is offered for lease in one year.
Percentage demanded for leasing;	%	Share of the land owned by crop farmers that is offered for rent in one year.

Data for the manure treatment companies

The data required for the manure treatment companies are reported in Table 3-2 and Table 3-3. These technological data are derived from individual case studies and literature.

The innovation dynamics are governed by the assumption on the random walk for the innovation in each company, reported in Table 3-4. The robustness of these assumptions has been tested.

Marco-economic variables

All agents depend on external prices, and these prices start from empirical price levels, and follow trajectories outlined by the scenarios.

Table I. 4 : Price data

Variable	Unit	Description
Capital price	%	Market average for interests on loan
Subsidies for farmers	EUR	Subsidies for different types of production
Price levels for meat and dairy products	%	Price evolution for meat (beef and pork) and dairy products on the consumer market
Demand levels for meat and dairy products	Qty	Evolution of the demand for meat and dairy products in volumes
Price levels for crops, horticulture products and forage	%	Price evolution for three land-based outputs
Feedstock costs	EUR	Price evolution for feedstock for cattle and pigs
Wages	EUR	Wage evolution
N-fertiliser and P-fertiliser	EUR/kg	Price evolution of fertiliser in EUR per nitrate or phosphate content
Energy price	%	Evolution of the energy price
Land rents	EUR/ha	Rent prices are fixed, and the evolution is prescribed.

The market prices for all outputs of the manure treatment companies are mostly related to existing price trends, described above. This means that the initial price in the model is based on empirical data, and the subsequent prices during the simulations follow the same in- or decrease as general prices that are closely related to this output.

Table I. 5 : Links with price evolutions of general products

Output	Processes	Price evolution linked with
Thick fraction	Reverse osmosis	Mineral N-fertiliser prices
Permeate	Reverse osmosis, Pyrolysis	Evolution of dry manure on the internal market
Distillate	Reverse osmosis, Pyrolysis	Evolution of liquid manure on the internal market
Digestate	Biology treatment	Evolution of dry manure on the internal market
Dried manure	Drying	Evolution of energy price
Fertiliser	Quicklime	Evolution of N-fertiliser
Compost	Quicklime, Composting	Evolution of N-fertiliser
Algae	Algae production	General inflation
Duckweed	Duckweed production	Evolution of animal feedstock prices
Black char	Pyrolysis	General inflation
Heavy fuel	Pyrolysis	Evolution of energy prices