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The bioeconomy is a shared vision for a future European industry entirely based on organic matter. Authorities support this technological development with subsidies and policies stimulating R&D. One major limitation for the bioeconomy is that R&D and industrial growth require the continuous availability of biomass as a primary resource. This resource dependence is already present during the formative years of new biobased innovations and influences the pilot and demonstration phase of the development. Traditionally, it is assumed that public support for pilot and demonstration initiatives may overcome this hurdle.

In this paper, we investigate how this resource constraint limits the effectiveness of bioeconomy policies. The future development of the biobased sector is simulated including the inherent dependence of industrial activity on biomass. We simulate the future growth and technological diversity of an emerging biotechnological sector: the sector of manure transformation in Belgium. The paper reports the evolutions for three policy scenarios. The model explicitly accounts for endogenous innovation and knowledge transfer mechanisms. The results show that policies may have an important impact on the sector structure in the long run, but the sector growth remains ultimately constrained by the availability of inputs. So bioeconomy policies to promote innovation will be less effective, unless mechanisms are included to alleviate the resource constraint.

Keywords: Bioeconomy, green certificates, innovation policy, biotechnology, resource constraint

1. Introduction

The biobased economy started as a promising segment of new biotech applications. Early appearances of the biobased economy can be traced back to developments in the health sector [1]. 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 with biobased processes. Contrary to the production of high-value low-volume health products, renewable fuels and energy require large volumes of organic matter of various qualities [2]. The potential number of products rises significantly as this set-up can produce biobased bulk chemicals, animal feedstock, various energy carriers, fertilisers and additives for larger markets [3-5]. Currently it has grown to a vision for a new industrial structure in Europe where all products, from energy sources, plastics and food to high value additives and pharmaceuticals, are entirely based on organic matter, thereby annihilating any need for fossil fuels [6]. The turnover of bioeconomy in the EU was estimated in 2012 to be about 2.4 billion EUR, and showed a large potential for growth in renewable energy an biobased industries [7].

The design of effective policies for the Bioeconomy is a challenging task. There are numerous proposals to build policy strategies and outlines. The European Commission recently renewed its Bioeconomy strategy [8], providing synergies in European R&D budgets, accompanied by national action plans. The OECD has been actively involved in policy guidance for the bioeconomy [9] and for the use of biotech in the environment [10]. National reviews of current developments have also been collected in order to present general directions for policy guidance [11]. On a national and regional level, the participatory vision exercises and policy studies for the bioeconomy have been conducted in several countries, amongst others in Finland [12, 13] the Netherlands [14, 15], Belgium [16], Australia [17] or Brazil [18]. Complementary analyses have been performed on very detailed subjects, such as the development of a dynamic market for the trade of manure and organic waste [19]. These national implementation reports lead to a large list of policy instruments, that can be categorised in four groups: (i) Legal adaptation to allow the sale of new biobased production products and to create quality standards, (ii) Coordination of initiatives from voluntary coordination through stakeholder meetings, to stricter coordination, and obligatory contributions to public institutions for biowaste collection. (iii) Stimulation of private investments in new biobased plants through investment support or public-private partnerships, (iv) Public financial support for targeted research, as subsidies for in-house development in companies, and for industrialisation. The first two groups of policies address structural barriers for biobased technologies present in markets and legal prescriptions [20], and make it structurally possible to set up new economic initiatives. The last two groups increase the profitability of new initiatives, either by intervening in the launch or operation of the investment itself, or by supporting the innovation process that comes before the investment.

Policies that intervene in the launch or operation of biobased investments are often regarded as primary requirements to enable the emergence of the bioeconomy. This type of policies has been largely employed to stimulate the transition in the energy sector. These proposals often reiterate the importance of market-based subsidies for biobased products and support for industrial activity [21]. This support is mostly in the form of grants and supplementary operational income, based on green certificates or feed-inn tariffs [22]. Hansen and Berlina [23] credit the growing market share of biobased grid energy in Sweden to a combination of structural support and financial policy instruments that alleviate operational costs, such as the biomass supply, or increase the operational income, such as green certificates. Proskurina et al. [24] show that the European member states employ a vast range of operational subsidies per MWh from woody biomass in order to reach their renewable electricity objectives.

However, the creation of effective policy instruments for the bioeconomy is more complex. Many technological solutions are under development and a long innovation trajectory is still needed to bring these solutions to the market. This innovation trajectory is not solely market driven, and other policies are necessary besides the support for industrial activity. Verbong, Geels [25] investigate the policy frameworks for past technological transitions. They conclude that a close adherence to industrial policies is problematic, and that the learning effects of innovative activities were not sufficiently guarded by the past policy instruments. Support for the emergence of innovative technologies needs to be included as well, and this implies support for R&D and innovation. The emergence of innovative technologies still requires the design of specific policies to this effect [26]. Innovation follows complex dynamics, where interaction, participatory activity and common vision creation is necessary [27]. Moreover, in the case of biobased industries, the development of biobased solutions needs a lot of synthetic knowledge on plant engineering, the organisation of biomass provision, machinery for pre-treatment etc. This synthetic knowledge is different from the analytic knowledge base in the form of publications and patents of biobased solutions [28]. Synthetic knowledge is built up by practical experience and is embodied by experts who can accumulate knowledge through years of practical experience. Therefore, support of R&D activity in industry has to target pioneer installations and demonstration plants in order to provide opportunities for experts to acquire this practical knowledge. Such R&D support has to include a structural solution for knowledge exchange, and the control of learning effects and knowledge absorption are essential.

In the case of the bioeconomy, an additional challenge for policy design is the inherent dependence on biomass as the primary resource for industrial production. This dependence on organic matter creates additional challenges for companies that are engineering sustainable solutions [29]. Every new application has to be integrated in a new biomass value chain reaching from the land to the customers [30]. The relation between the innovation dynamics and physical resources has been raised before [31]. Sporleder and Bolland [32] detail the economic characteristics that flow from this restriction; the dependence on organic matter leads for instance to seasonal risks for the supply of inputs, and induces the needs of buffer stocks in the value chain. These constraints, connected with the requirement to guarantee the sustainability of the biomass use, is also a domain that requires specific policy initiatives [33]. Detailed simulations in cases where no innovation dynamics are present, have shown that policies that tackle this resource constraint can lead to significant increases in the industrial use of renewable resources [34, 35]. Also public-private partnerships are helpful to create new supply chains of biomass [36].

In these cases a mix of policy instruments are necessary. Philp [37] advocates a practical combination of operational support and subsidies, together with R&D support. This would also imply that both options may be beneficial to support the emergence of a new innovative sector. It is not certain that both types of policies are complementary for the emergence of innovative biobased technologies. For instance, Jacobsson et al. [38] find that in a related sector, a green certificate system does not incite the development of innovative investments in offshore wind energy. The conclusion that a mix of policy instruments is to be advised, can thus be too simplistic.

In this paper, we look specifically at the effect of these two types of policies for the case of innovative biobased technologies. The analysis evaluates the impact of an policy that stimulates industrial operation and an R&D policy on a diverse technological landscape. The policy that stimulates industrial operation provides direct or indirect subsidies for every unit of industrial activity. This can be per unit of produced biomaterial or bioenergy. The R&D policy does not interfere in the operation itself, but cofinances the steps preceding the industrial investment: applied research, pilot phases and development. Technologies differ in terms of their distance to the market, their biomass dependence and transformation efficiency, as well as their optimal investment scales. Policies that intend to stimulate the emergence of new biobased technologies affect the innovation trajectories of all technologies at the same time but to a different degree. The same group of technologies compete on the same market for primary resources, and may benefit from operational subsidies as well. The interest of the analysis is on the long-term impact of policies, i.e. the impact on technology deployment decades after the policy has ended.

This analysis is based on empirical data of an emerging biobased industrial sector. In this case, the analysis is made for a specific biobased sector with high biomass-intensity: the sector of manure treatment in Belgium. This empirical foundation makes it possible to include details on the technological diversity that are characteristic for the biobased economy. Every technology has individual biomass requirements, and creates different added value per ton of organic input. Moreover, the emergence of new technologies is confronted with the existence of incumbent solutions that compete for the same resources. The technological diversity, and importance of incumbent industries can this way be included in the analysis of policy impacts.

To replicate the complex dynamics of innovation and technological shifts in reality, an agent-based model (ABM) is built based on empirical data to forecast the sector evolution. Several policy scenarios are created and simulated. The emergence of a biobased economy, and the implied replacement of incumbent industries, creates numerous complex dynamic effects. Evolutionary economics is a scientific discipline that is capable of integrating essential features of these transitions, such as complexity, multiple levels, adaptation, co-dynamics, emergence and heterogeneity [39]. Evolutionary economics has since long focused on economic change and its underlying dynamics [40]. Agent-based models (ABM) are particularly suited for the simulation of economic evolutions [41, 42]. ABM models are founded on groups of autonomous agents that have individual behaviours, technical characteristics and communication possibilities. Other modelling techniques, such as partial equilibrium (PE) models or linear programming, can integrate several of these features, but not all. For instance, PE is capable of representing economic complexity, learning and microeconomic consistency. But it is harder to apply with heterogeneity and special behavioural characteristics. A survey of Holtz [43] shows that sector transitions can be modelled with other approaches, but all projects that integrate empirical data are obliged to apply an agent-based approach. However, as explained by Haegeman et al. [44], this quantitative basis does not imply that the simulated evolutions have predictive value. The combination of policy scenarios, technological change and diversity is often investigated with the help of ABM models. This approach has been helpful to investigate the impact of policies for the mitigation of nutrient emissions in pig farms [45], to simulate the emergence of a biobased industrial ecosystem [46], or to uncover the role of the value chain structure in the success of new biobased initiatives [47].

The rest of this paper is structured as follows. Chapter 2 introduces the policy scenarios, the considered technologies, and model of endogenous innovation. Chapter 3 reports and discusses the results. Chapter 4 concludes.

2. Sector description and model construction

In order to show the impact of policy instruments on the emergence of the bioeconomy, this paper simulates the impact of different policy scenarios on a specific biobased sector. The simulation is based on empirical technological data, and uses an ABM approach, to include a variety of technological actors with different characteristics, dynamics of industrial R&D, and group effects. This section describes the chosen policy scenarios, the technologies, the model for endogenous innovation inside the companies, and the simulation choices.

The scenarios each combine regular policy instruments that are proposed by national and regional strategy reports for the Bioeconomy. Because of the complexities in the dynamics of technological innovation, intuitive predictions of policy impact are confronted with large uncertainties. This is an area where simulation brings more insight to build intuitive understanding of the actual dynamics [48]. In this case, the simulations are based on scenarios that describe widely different public strategies, while the total set of scenarios covers then a full range of probable and improbable outcomes [49]. This way, the scenarios provide the extremes for the entire range of options that is open for policy design.

Three scenarios are considered. The reference scenario is a minimalist scenario, focusing solely on the regulatory barriers that need to be removed before innovative biotech solutions may appear. In the reference scenario, only the structural policies are applied. These policy instruments do not interfere directly with market conditions and technology niche management. The second scenario takes the approach that has been applied to stimulate the emergence of renewable energy technologies. In this case, regulatory barriers are removed, and the industrial application of new biotech solution is given large incentives in the form of operational subsidies for biobased end products, to change the profitability of industrial activity. The rationale behind this approach is that the industrial revenues will help to fund R&D for biobased technologies, so these will be profitable without government incentives in the long run. The third scenario takes the opposite side of the spectrum and supports only R&D, and does not interfere with market conditions for biobased products. The rationale in the third scenario is that increased R&D will speed up the appearance of profitable biobased solutions under the current market conditions. The scenarios are stylized versions of policy strategies that are being applied for instance to stimulate nanotechnologies, health innovations (scenario 3), or renewable energy, and environmental technologies (scenario 2). The focus is here to see if the biomass constraint of biobased technologies change the effectiveness of these strategies. The overview of the scenarios is given in Table 1. Each form of public financial support is limited in time. Subsidies are granted from 2010 to 2023 only.

Table 1 : Scenario construction

		Scenarios		
Policy categories	**Description**	**I. Reference scenario**	**II. Industrial activity**	**III. R&D**
(i) Legal adaptation to allow the sale of new biobased products	Legal barriers are removed, and biobased products can be brought to the market.	X	X	X
(ii) Coordination of initiatives	Coordination platforms are set up to motivate partnerships	X	X	X
(iii) Stimulation of private investments	Private funds are willing to invest in the creation of new parent companies	X	X	X
(iv) Public financial support	Scenario “II. Stimulation policy for industrial activity”: Support of 2.65 EUR per ton of liquid manure treated, and 3.65 EUR per ton of dry manure.		X	
	Scenario “III. Stimulation policy for R&D”: Reimbursement of 80% of the amount spent on internal innovation.			X

2.1. *Industrialisation of manure treatment technologies*

In this case, the emerging biobased sector transforms manure, an organic waste stream. Every industrial application will need this resource, and this will be reflected in its price. The model adopts a standard linear relation between price and demand of the manure. There is also a cut-off maximum price. In reality, when the local price for biomass increases too much, the industrial plants can import it from other countries. The cut-off price equals the cost for purchase and transport of the biomass internationally. The biomass constraint for manure has been implemented this way so the conclusions remain transferable to other biobased sectors. This constraint is a flexible limitation of the regional biomass availability. A linear price function does not set a fixed finite amount of biomass that can be delivered, it represents a potential for adaptation in agriculture and forestry to changing market conditions, as regional supply increases with increasing demand from an emerging biobased industry. The formulas for this market constraint are included in Annex A.

Manure is an important by-product of animal farming. In regions with high animal density, manure is treated and transformed in exportable fertilisers, safe effluents or valuable new products. There are four traditional technologies to treat manure. The most common technology at the site of the farm is biology treatment [50, 51]. In 2012, about 60% of the installations in Belgium were based on the biology treatment of the thin fraction of manure [52]. 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.

Many new technologies for manure treatment are being investigated but these are currently not mature enough to compete with the existing manure treatment solutions. There is a large diversity in solutions that are being investigated. Five sets of innovative technologies are considered here and these solutions cover a large range of potential technologies for manure treatment. For each selected technology, research for industrialisation is on-going at the moment. Technical details on each technology are included in Annex A. The combination of four technologies of traditional manure treatment, complemented with the five innovative solutions, leads to nine types of technologies that are included in this analysis, as listed in Table 2. Distinction is being made between mature, experimental and innovative technologies. Mature technologies are applied on the market at this moment. Experimental technologies are installed in test pilots and experimental full-scale applications. Innovative technologies are under development, and pre-industrial sized proof-of-concepts still have to be delivered. The starting population of treatment plants in the simulation is composed of mature technologies only, complemented with the limited number of experimental treatment plants currently in operation.

Table 2. Considered technological options for manure treatment.

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

[1] : The constructed wetland is here an addition to a biology treatment

[2] : The algae production is an addition to a reverse osmosis filtration.

For each technology costs and benefits are estimated. The empirical cost and performance data is based on preliminary reporting and private expertise during technology evaluation projects. Some of the inputs are based on technical reports [53-56]. 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 data illustrate an initial performance of the technology. Under current market circumstances without any financial support, the innovative or experimental technologies are not profitable.

2.2.Simulated emergence of a technological breakthroughs

The successful emergence of biobased niche technologies can be represented schematically as in Figure 1. In order to incorporate the incremental nature of the innovation process and the importance of synthetic knowledge accumulation, the process is simulated as a repeating cycle of industrialisation efforts. The crucial point for the emergence of innovative technologies is the provision of resources to be invested in internal R&D for each company. As categorized by Pavitt [57], technology provision to agriculture is sector of specialised suppliers where most innovation activities are internal. Increased R&D funds and efforts lead to higher chances of breakthroughs to improve the production efficiencies of the technology. New plants generate additional income, and a percentage of this income can again be devoted to internal R&D. In the case of biobased innovation, 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. New production efficiencies emerge endogenously inside the parent company. Each parent company derives improved production efficiencies from its own R&D activities. Next to these internal activities, improved efficiencies can also be procured from competitors through technology licensing as well. The figure also indicates the entry points where the different policies modify these dynamics.

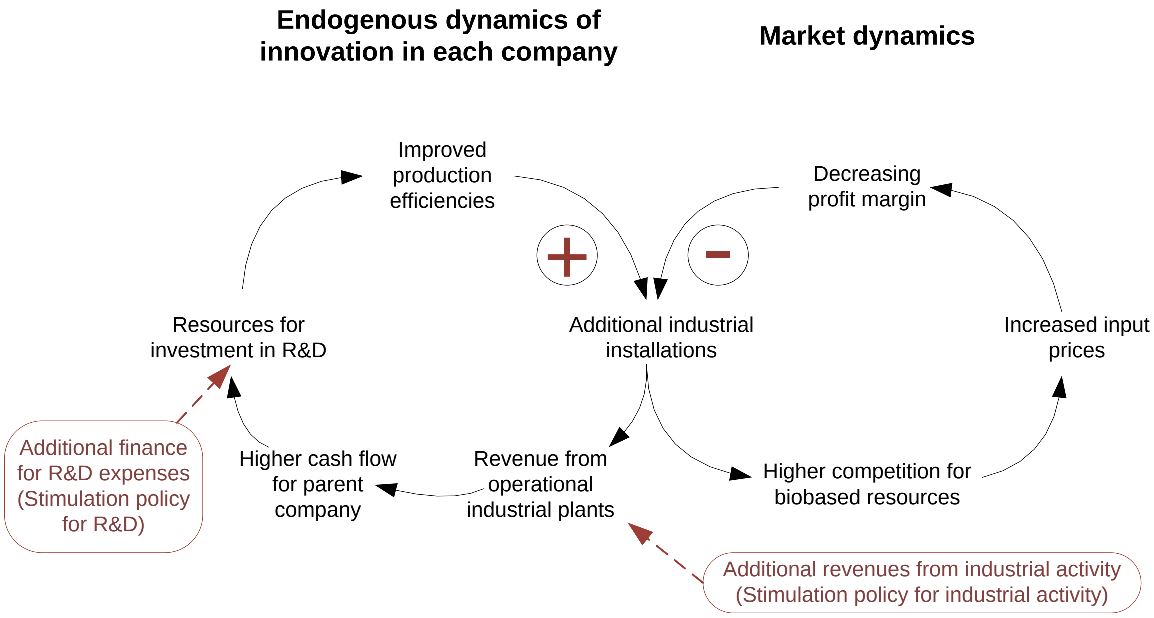

Figure 1 : Representation of the dynamics of endogenous innovation emergence and the interaction with different policies

2.3.Agent structure and decisions

The simulation approach has been built during discussions with experts from the Flemish Coordination Centre or Manure treatment (VCM). The VCM is a not-for-profit organisation that represents all regional private actors, involved in manure treatment. The centre informs their members on legal changes, collects information on R&D and innovation efforts from its members, and is therefore very well placed to detail the innovation dynamics of the sector. The structure has been set up according to their understanding of the sector configuration. 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 by internal R&D. A treatment company creates industrial treatment projects, using personal funds and loans. 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 2. The treatment projects are the active agents in the ABM that are responsible for the manure treatment. The company continuously invests in research for technology improvement, and always keeps one project in a latent state. This latent project is not launched yet, but 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. Over time, a parent company can be leading several manure treatment projects simultaneously.

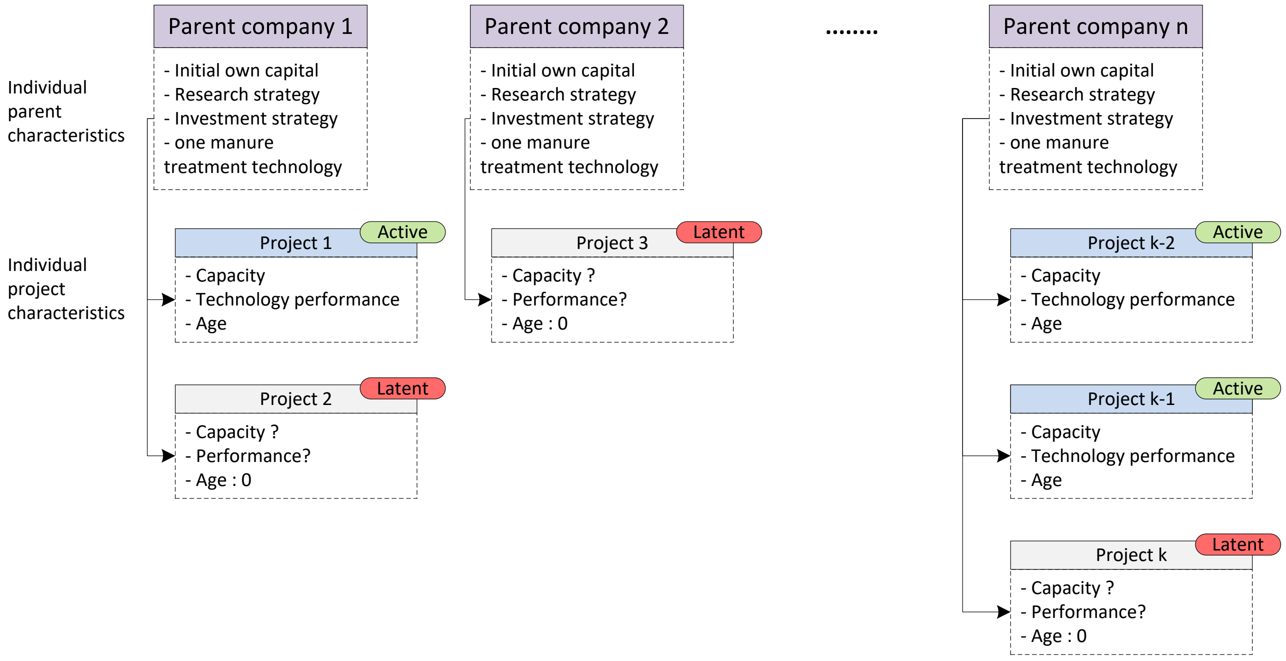

Figure 2 : Each parent company is specialised in one technology, and invests in individual projects.

Figure 3 shows the different steps taken by the technology agents every year. At the start of the model, Parent company agents are created. These agents invest in internal R&D, check for new investments, and initiate technology projects. R&D delivers results at the end of the year, and the technology characteristics of the parent company are adapted. Parent companies invest in projects when the technology performance is sufficient. Projects start buying manure, treat it, and create outputs that are sold. At the end of the year, the profitability is checked and it is decided whether the project continues.

Each manure treatment project uses economic inputs, capital labour and land, but also material inputs, manure and energy. This leads to matter-based outputs, (fertilisers, feedstock, additives, fuels …) that simultaneously have a physical and economic value. 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*), and these rules are included in Annex A. 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 [58].

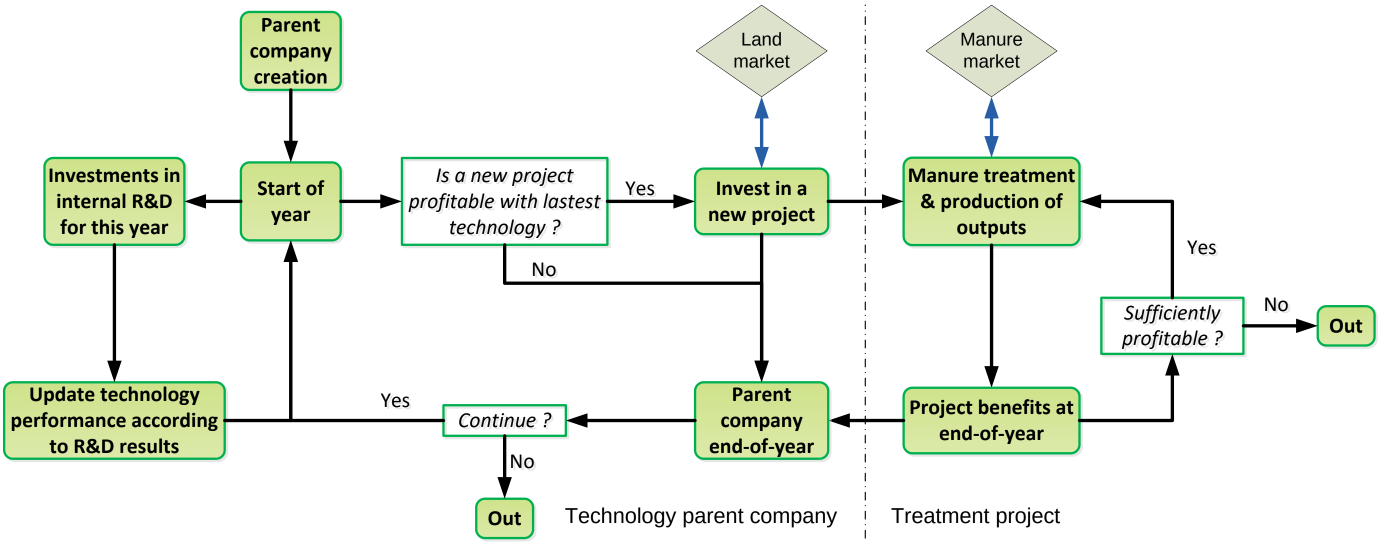

Figure 3: Annual cycle of steps for technology parent companies and their treatment projects

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. The agent in the ABM is based on an accounting structure. This structure gathers costs and benefits, and determines the annual cash flow to determine the chance for survival.

Stochasticity is present at several levels in the simulation. The initial population of manure treatment companies replicates technically the sector in Flanders in 2010. This population respects the initial distribution of technologies, as well as the different sizes of companies and manure treatment plants. Other variables are distributed randomly over all agents, such as the innovation variables, and prediction of future manure price levels. Secondly, the success of R&D efforts of manure treatment companies are decided by a Markov step model. This leads to different emerging technologies for each simulation run. For each scenario, 100 separate individual runs are simulated, and averages are discussed in the results. Deviations from the average are reported in the annex.

3. Results and discussion

The general trends are illustrated in Figure 4. This figure indicates the total installed capacity of each technology. All scenarios present the same phase-out for some traditional technologies; such as biology or composting. 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 technological renewal does not eradicate all existing solutions. The case of drying shows a traditional technology that continues to maintain a sizable market share up to 2050. Other traditional technologies, such as quicklime, remain in operation, but for a very small fraction. These installations are maintained once the investment is done. However, there is no incentive for growth as these are not competitive against the newer technologies that emerge over the years. This result is similar to the view in other studies, where the introduction of new technologies does not lead to a total makeover of the sector, but a diversity of technologies remains over time [59].

The growth in the sector can be attributed mainly to installations for duckweed and algae production. Pyrolysis is the new technology that requires the longest period to emerge in a sizable fraction. This technology seems to require larger R&D investments before the solution is competitive.

Table 3 : Average sector capacities and structure for the different scenarios

Sector situation in the period 2041-2050	Scen I Reference	Scen II Industrial simulation	Scen III R&D stimulation
Sector capacity [1 000 m³/year] (*)	3 791	3 746	4 410
Active parent companies (*)	14.8	13.3	18.3
Industrial plants per company (*)	2.6	2.8	2.4
Liquid manure price [€/m³] during support period (2010-2025)	-12.3	-9.6	-12.3
Liquid manure price [€/m³] in the long term (2041-2050)	-7.4	-6.6	-4.2
Total policy cost [M€]	0.0	144.9	25.1
(*) : 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 two stimulation policies have a significant impact on the sector evolution. The support 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 higher, around -10 €/m³ compared to -12.5 €/m³ on average in the other situations. This indicates a higher demand for manure as input for the biobased companies, and a larger benefit for the farmers. 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 second policy, 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. At the end of the support period there is no significant effect on the sector size, nor on prices. However, the benefit from increased R&D between 2010 and 2025, continues to have effect in the years after the support period and leads to slightly 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: -2 €/m³ compared to -6.5 €/m³ for the other situations.

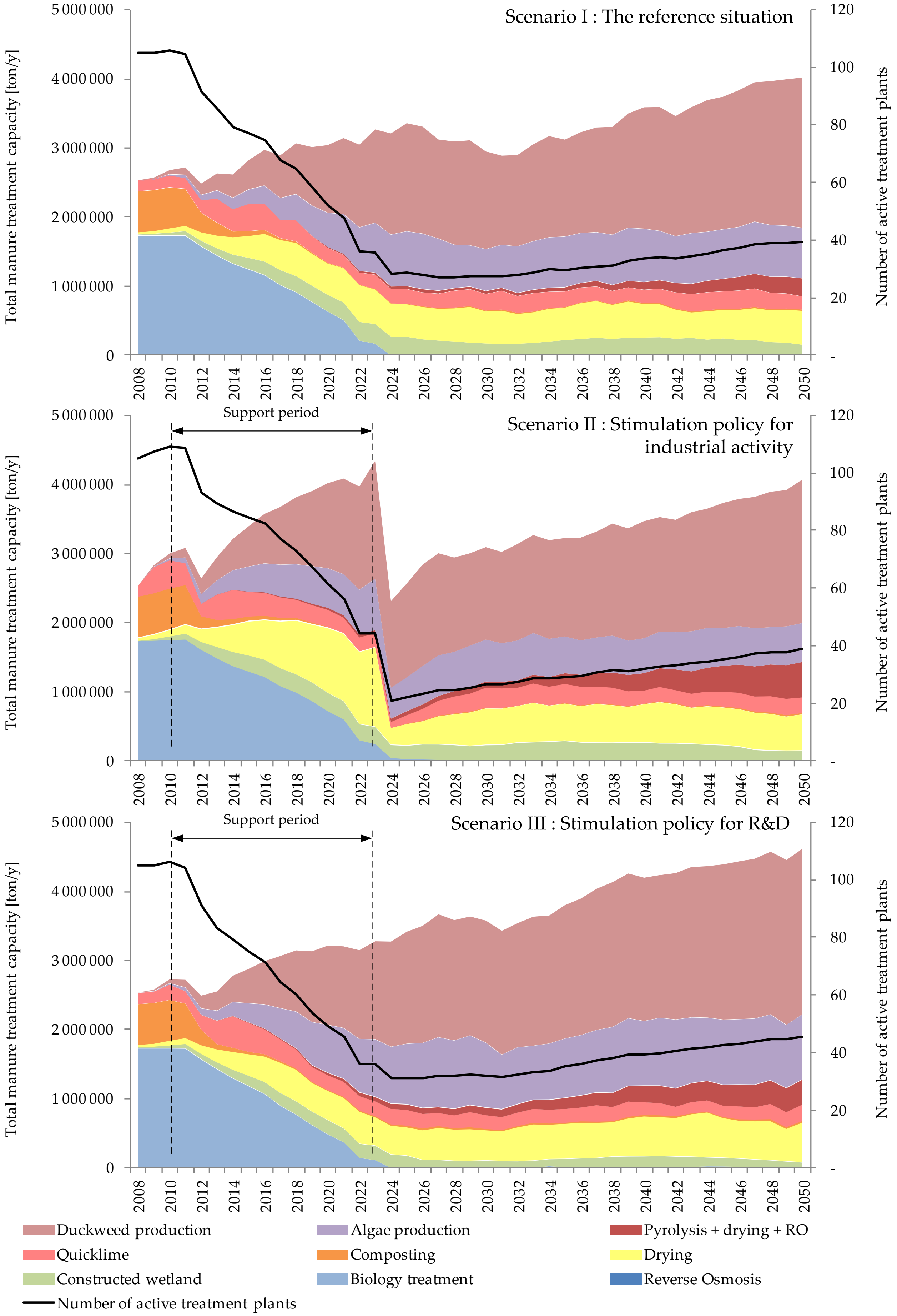

Figure 4 : Sector evolution subjected to different policies

From a public perspective, it is necessary to analyse the cost effectiveness of the different options. 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, there is no policy cost. The total cost for scenario II rises to 145 million EUR on average over the total period of 14 years. As discussed, the sector does not show a large increase in capacity in the long term, despite this large support. The total cost for scenario III reaches 25 million EUR over the same period, and this support is capable of increasing the sector capacity in the long term.

This first description could lead to a conclusion that investment in R&D for technology improvement is better than operational support for sustainable technologies. But a more detailed look shows that not every policy is fully effective. This requires a look at the financial decision at the company level. In the reference scenario I, 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 II, 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 manure. 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 long-term effect of the stimulation policy for industrial activity is close to zero.

In scenario III 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. However, technological progress has to be translated in practical applications and treatment plants if the sector efficiency needs to increase. So, the technological advances are faster in this scenario, but the translation into practice is actually slower. In the end, the efficiencies in scenario III are only slightly higher than in scenario I. The main difference is that in scenario III the internal R&D is financed by governmental support, whereas in scenario I it is financed by revenue from active manure treatment plants, and both sources can be complementary. This shows the importance of the early investments in treatment plants, even if the technology still is being improved.

When looking at the effectiveness of the public expenses for each policy, an important remark is necessary. Scenarios I, II, and III 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 II and III. 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 I. 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 I 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 I, this situation as such is not very likely. However, the situation becomes more likely if the investment funds are provided by public institutions. 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 I. But this means that the comparison of the public costs for different policies should be interpreted with this limitation in mind.

Figure 5 shows the emergence of the sector structure. The starting situation for all scenarios is the same, at 1.7 treatment plants per parent company on average. During the first decades, there is no large difference. Between 2020 and 2027, important changes in the sector structure are noticed, when the parent companies of the traditional companies are forced out by bankruptcy, a new sector structure emerges, concentrated around a relatively small number of parent companies, each operating 5 treatment plants. In the following years, new entrants join the sector, and apply the technologies developed from the existing companies for a licensing cost. The sector is composed of 14 to 18 individual parent companies, operating only 2.5 treatment plants on average.

There is however very little sign of total sector growth. In the third scenario, the sector size is 16% larger than in the reference scenario. This difference is relatively small, and can be attributed to higher technological effectiveness, and thus higher added value. In this case, innovation has an effect on the diffusion of technology breakthroughs, and on the innovation speed, but this does not translate in sector growth. The sector growth is mostly restrained by the availability of manure in this case, and this limitation is not affected by the innovation structure.

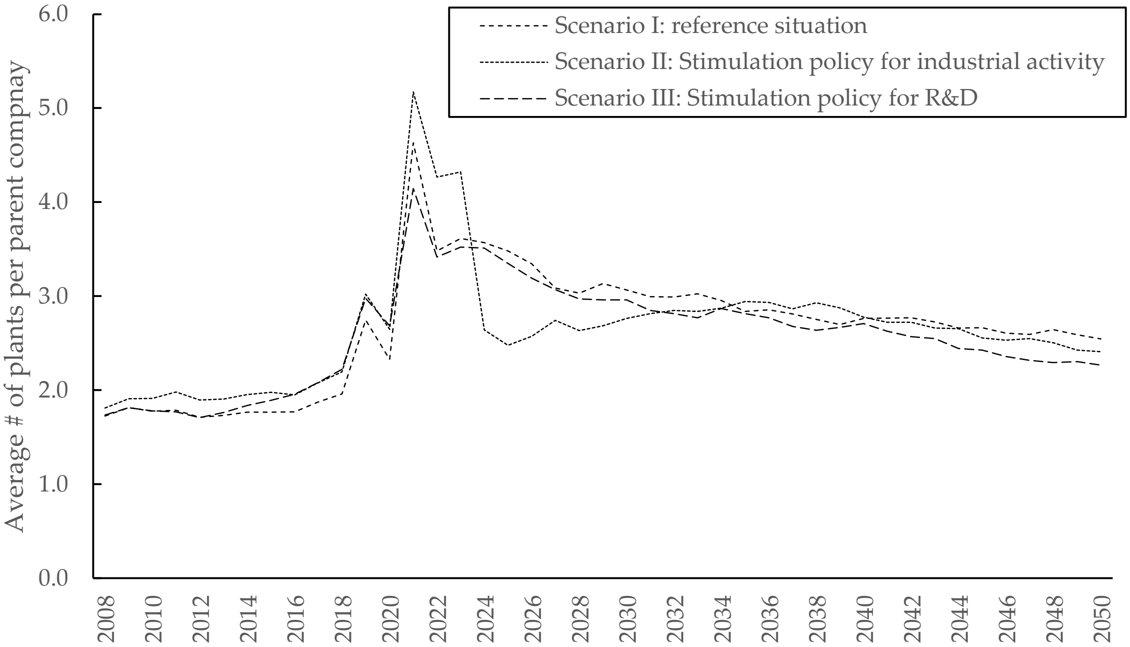

Figure 5 : Evolution of the average number of operational treatment plants per parent company.

The total sector growth does not seem to be stimulated by the promotion of innovation. In this case, innovation has an effect on the diffusion of technology breakthroughs, and on the innovation speed, but this does not translate in sector growth. The limited availability of manure turns out to be an important constraint to 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 reality, companies benefit from other options that are not included in this simulation. A logical option to escape regional shortage of resources is internationalisation. In this simulation, parent companies are capable of importing manure from abroad to supplement local manure, but the price of imported manure is high. It 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. This is equally beneficial for the innovation dynamics of the company, as revenues from foreign treatment plants will also supplement the R&D budgets and contribute to a faster technological development.

From a policy perspective however, international expansion is to be included in the policy mix from the start. The simulations show the importance of early investments in order to drive cash flows that can finance further improvements of the technology. Investments in foreign industrial plants also serve this purpose. This means for policy makers that active support for internationalisation of experimental biobased technologies makes sense, even if regional development is a policy objective.

4. Conclusions

The bioeconomy is a strategic objective of the European Commission, and its emergence is supported on European, national and regional levels. This development depends on organic matter as the primary input for the industrial process, and requires the accumulation of practical knowledge for successful applications. Authorities support biobased developments with standard policies, such as subsidies for industrial activity and for private R&D. The characteristics of the emerging bioeconomy cause standard policies not to yield the same effect as in other sectors. We analyse the innovation dynamics specifically in the emerging sector of manure treatment by simulating industrial investments and endogenous innovation within an open market environment. The simulations allow to compare the long term effects of policies. In the case of the biobased manure treatment, the total sector size is limited by the availability of manure. It is therefore very difficult for policies to increase the sector size in the long term.

As R&D helps innovative technologies to become more profitable, the market shares of technologies show a transition during the evolution. At first, traditional technologies make up the bulk of the sector. During a transition phase, innovative technologies are increasingly industrialised, and finally take over most of the market. This technological shift goes together with a structural shift in the sector towards a diversified sector of smaller companies.

A policy that provides operational support to new technologies leads to a fast sector growth during the implementation. It also leads to a strong sector decline when the policy is ended and the long-term effects on the sector structure or size are very small. A policy that focuses on R&D does not increase the sector size during its implementation, but the impact of the policy is significant decades after the policies have ended. The technology development speed up during the implementation, and this leads to higher added value provided by the technologies in the subsequent years. These higher added values also translate into higher prices for the biomaterials that are the primary resources of the sector.

In each situation, the availability of manure remains the main constraint. The policy to partly reimburse R&D costs for private companies can increase the sector capacity by approximately 16%, compared to the reference situation. R&D policies are successful to the extent that they lead to higher speeds of technological development, and allow more immature technologies to reach the market. However, this cannot influence the sector size, as it is not sufficient to counter the biomass restriction to sector growth.

The results in this analysis are obtained by simulating the innovation dynamics within a region. Simulated actors could import biomass from other regions, but transport costs make this solution unattractive. However, the simulations do not include options for actors to invest in other regions where the availability of biomass is ensured. Companies can continue research, but industrialisation can be done in different regions in order to avoid local biomass shortages or price peaks. Such strategies can include a focus on international cooperation and exchange from the early start of the company. In this context, support for international investment is very appropriate even for technologies that are still in a formative phase. This international expansion offers alternatives to circumvent the regional biomass constraints. But this also changes markedly the innovation dynamics, and this needs to be analysed in future research.

These results highlight a general impediment to the swift emergence of new biobased technologies. Each development needs large amounts of biomass to be able to grow, and this effects indirectly the impact of policies dedicated to support the bioeconomy. In this case, the sector is based on manure. Other biobased technologies are based on existing crops or waste streams from agriculture and the food industry. The sector depends ultimately on a large surfaces of land upstream in the value chain dedicated to grow the necessary biomass. This has to be considered by policy makers willing to support the emerging bioeconomy. Solutions to reduce the biomass constraint have to be included in every innovation policy for the biobased economy, because other industrial and R&D policies are less effective while the biomass constraint is present.

Annex A : Technical data, model details and control

Description of the five innovative technologies considered

The first innovation, constructed wetlands, is the only new 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 new installations [60]. The solution has shown significant benefits for local biodiversity [61]. The four other innovative technologies focus on the production of added value, rather than on the reduction of the pollution from manure. The first innovative treatment method to transform manure into valuable outputs at the farm scale, is reverse osmosis. This filtration technique extracts a concentrate with high mineral content from the manure, creating a valuable fertilising concentrate, and facilitating the disposal of the remaining elements in manure. There is a growing experience with this technology [62, 63], and the number of practical applications is growing [64]. A second solution is the cultivation of duckweed in an open air pond. The pond is fed with moderate quantities of the thin fraction of manure, and duckweed can be sifted out of the water and 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 third technology 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. The algae can be sterilised and used for fodder production, for bioenergy or biofuel. 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 with higher added value. In this case the algae can be used for the production of chemical bulk products or as input for the agro-industry. The fourth technology is pyrolysis. This is a process to dissociate the manure into three energy products. It heats the manure 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. 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 [65]. 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 [66]. The valuable outputs are the remaining biofuel and the solid biochar. Biochar has multiple uses, for soil improvement [67], carbon sequestration [68], but also for cleantech and remediation technologies [69]. This makes the biochar a commodity with increasing value.

Table 4. 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 $LU = a\,Cap^{\alpha}$ [m^2]	
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 5. 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 tables do not indicate the transportation cost of the manure to the treatment plant. The transportation cost is the main cost to counter the economies of scale. Levelled manure price on the market are maintained, and this assumes that the receiver has to pay for the manure transportation. Based on analysis of manure transport to regional biorefineries [20] 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 (d) to be travelled by the manure is a direct function of the total quantity required.

$$d = 0.023\ Cap^{0.6} [\text{km}]$$

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.

Details on the Markov step model to simulate endogenous innovation

For the definition of the innovative dynamics, 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 $[\gamma, \delta_q, \delta_p, \delta_I]$ 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 6: 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%

General simulation details

The initial situation of the model is based on the actual sector structure in reality, as reported in Table 7. The agent-based model is built on a Matlab R2012b routine. At the initiation, not every technology is available, exactly like in the real situation in Belgium. At the initiation, the sector consists of 62 agents for the mature technologies with 105 treatment projects in total. In addition, 28 agents, specialised in the experimental and innovative technologies are present, without any functional treatment project. The innovative and experimental technologies are not yet being applied on the market.

The simulation starts from 2010 and continues to 2050. Every year, new parent companies can emerge on the market, specialised in traditional technologies or in innovative technologies. The initial characteristics for all technologies are described in Table 9 and Table 10. All agents invest in R&D which enables them to improve the technology efficiencies over time. A growing number of treatment plants leads also to a growing manure demand. This leads to higher manure prices. The price is determined on the demand of the sector itself, Q_D, as illustrated in Table 8.The remaining quantity Q_F is directly spread on fields and is assumed to be fixed during the simulation. If necessary, manure can also be imported from abroad, at the price of 2 €/m³. This assumes that manure is shipped for other regions with manure surplus, and transport costs are almost covered by the negative price of manure. This is high compared to the regional market prices of -16.7 €/m³ for liquid and -8 €/m³ for dry manure at the initialisation of the simulation.

Table 7: Initial population of manure treatment agents, compared with the real situation in 2011

	Simulated capacity	**Real capacity 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 + RO	-	-	-	-	-	-	-
* These numbers are the same in reality and in the initial population of the simulation.							

Table 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

Table 9: The different variables determining the characteristics of each individual parent company, according to the technology

		Research investment (as % of liquid assets) $\log(\gamma) = N(m, \nu)$				**Investment for imitation (as % of liquid assets)** $\log(\theta) = N(m, \nu)$				**Initial capital** $\log(Cap) = N(m, \nu)$			
		Av	Stdev	m	ν	Av	Stdev	m	ν	Av	Stdev	m	ν
1	Reverse Osmosis	0.8%	0.004	-4.96	0.47	0.4%	0.002	-5.66	0.47	3 200 000	640 000	14.96	0.20
2	Biology treatment	0.8%	0.004	-4.96	0.47	0.4%	0.002	-5.66	0.47	3 200 000	640 000	14.96	0.20
3	Constructed wetland	1.6%	0.008	-4.27	0.47	0.8%	0.004	-4.96	0.47	3 200 000	640 000	14.96	0.20
4	Drying	0.8%	0.004	-4.96	0.47	0.4%	0.002	-5.66	0.47	3 200 000	640 000	14.96	0.20
5	Composting	0.5%	0.002	-5.47	0.47	0.2%	0.001	-6.17	0.47	3 200 000	640 000	14.96	0.20
6	Quicklime	0.5%	0.002	-5.47	0.47	0.2%	0.001	-6.17	0.47	3 200 000	640 000	14.96	0.20
7	Algae production	1.6%	0.008	-4.27	0.47	0.8%	0.004	-4.96	0.47	3 200 000	640 000	14.96	0.20
8	Duckweed production	1.6%	0.008	-4.27	0.47	0.8%	0.004	-4.96	0.47	3 200 000	640 000	14.96	0.20
9	Pyrolysis + drying + RO	1.6%	0.008	-4.27	0.47	0.8%	0.004	-4.96	0.47	3 200 000	640 000	14.96	0.20

Table 10: Characteristics of innovation random walk, according to the technology.

		Initial average	Standard deviation	**Innovation characteristics, (**$Mean = (B + \delta C_n)$**)**								
				Physical production efficiency			Quality increase			Investment cost		
		Av	Stdev	B	δ	Var.	B	δ	Var.	B	δ	Var.
1	Reverse Osmosis	1	0.2	1.000	0.030	0.200	1.000	0.050	0.200	1.000	-0.010	0.200
2	Biology treatment	1	0.2	1.000	0.005	0.200	1.000	0.010	0.200	1.000	-0.003	0.200
3	Constructed wetland	1	0.2	1.000	0.030	0.200	1.000	0.000	0.200	1.000	-0.010	0.200
4	Drying	1	0.2	1.000	0.005	0.200	1.000	0.010	0.200	1.000	-0.003	0.200
5	Composting	1	0.2	1.000	0.005	0.200	1.000	0.010	0.200	1.000	-0.003	0.200
6	Quicklime	1	0.2	1.000	0.005	0.200	1.000	0.010	0.200	1.000	-0.003	0.200
7	Algae production	1	0.2	1.000	0.030	0.200	1.000	0.050	0.200	1.000	-0.010	0.200
8	Duckweed production	1	0.2	1.000	0.030	0.200	1.000	0.050	0.200	1.000	-0.010	0.200
9	Pyrolysis + drying + RO	1	0.2	1.000	0.030	0.200	1.000	0.050	0.200	1.000	-0.010	0.200

Deviations of individual simulation runs from the average results

Table 11: Deviations from average for single individual simulation runs (# = 100)

Total sector capacity in 1000 tonnes									
	Scen I **Reference**			**Scen II** **Industrial simulation**			**Scen III** **R&D stimulation**		
	Average	**St.Dev.**	***%***	**Average**	**St.Dev.**	***%***	**Average**	**St.Dev.**	***%***
2010	2 678	204	*8%*	2 998	250	*8%*	2 721	207	*8%*
2011	2 718	282	*10%*	3 080	379	*12%*	2 715	313	*12%*
2012	2 482	399	*16%*	2 640	513	*19%*	2 485	420	*17%*
2013	2 631	431	*16%*	2 947	627	*21%*	2 546	479	*19%*
2014	2 616	521	*20%*	3 209	647	*20%*	2 773	493	*18%*
2015	2 825	565	*20%*	3 392	719	*21%*	2 873	582	*20%*
2016	2 967	581	*20%*	3 571	714	*20%*	2 983	603	*20%*
2017	2 883	616	*21%*	3 671	699	*19%*	3 058	633	*21%*
2018	3 038	655	*22%*	3 811	703	*18%*	3 139	765	*24%*
2019	3 013	661	*22%*	3 900	663	*17%*	3 126	701	*22%*
2020	3 034	702	*23%*	4 015	695	*17%*	3 209	700	*22%*
2021	3 131	679	*22%*	4 082	749	*18%*	3 198	795	*25%*
2022	3 031	679	*22%*	3 967	779	*20%*	3 143	783	*25%*
2023	3 277	785	*24%*	4 338	754	*17%*	3 271	756	*23%*
2024	3 281	702	*21%*	2 310	1 198	*52%*	3 267	916	*28%*
2025	3 379	656	*19%*	2 565	1 129	*44%*	3 410	910	*27%*
2026	3 275	837	*26%*	2 836	1 057	*37%*	3 495	878	*25%*
2027	3 125	1 097	*35%*	3 002	1 107	*37%*	3 662	796	*22%*
2028	3 118	1 173	*38%*	2 941	1 232	*42%*	3 579	1 132	*32%*
2029	3 135	1 262	*40%*	3 002	1 221	*41%*	3 630	1 375	*38%*
2030	2 862	1 347	*47%*	3 090	1 151	*37%*	3 570	1 399	*39%*
2031	2 921	1 317	*45%*	3 022	1 219	*40%*	3 423	1 625	*47%*
2032	3 020	1 254	*42%*	3 135	1 150	*37%*	3 533	1 584	*45%*
2033	3 222	1 126	*35%*	3 266	1 227	*38%*	3 627	1 565	*43%*
2034	3 171	1 114	*35%*	3 192	1 230	*39%*	3 644	1 702	*47%*
2035	3 172	1 225	*39%*	3 222	1 252	*39%*	3 796	1 574	*41%*
2036	3 217	1 162	*36%*	3 228	1 208	*37%*	3 890	1 487	*38%*
2037	3 345	1 085	*32%*	3 315	1 202	*36%*	4 032	1 358	*34%*
2038	3 424	1 138	*33%*	3 431	1 088	*32%*	4 127	1 311	*32%*
2039	3 448	1 150	*33%*	3 362	1 156	*34%*	4 252	1 329	*31%*
2040	3 468	1 252	*36%*	3 466	1 099	*32%*	4 191	1 446	*34%*
2041	3 614	1 152	*32%*	3 525	1 178	*33%*	4 229	1 435	*34%*
2042	3 493	1 211	*35%*	3 486	1 314	*38%*	4 258	1 419	*33%*
2043	3 576	1 205	*34%*	3 596	1 164	*32%*	4 346	1 413	*33%*
2044	3 696	1 154	*31%*	3 647	1 210	*33%*	4 358	1 443	*33%*
2045	3 732	1 167	*31%*	3 729	1 231	*33%*	4 385	1 370	*31%*
2046	3 751	1 193	*32%*	3 787	1 315	*35%*	4 427	1 380	*31%*
2047	3 841	1 166	*30%*	3 816	1 290	*34%*	4 467	1 314	*29%*
2048	3 900	1 148	*29%*	3 891	1 388	*36%*	4 568	1 400	*31%*
2049	3 908	1 111	*28%*	3 916	1 334	*34%*	4 448	1 441	*32%*
2050	4 029	990	*25%*	4 065	1 350	*33%*	4 609	1 403	*30%*

Robustness control of the innovation variables

The emergence of innovations in the manure treatment sector depends on the innovation variables in Table 13. 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. 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.

Table 12 : Assumption of the innovation random walks for different types of technology maturity

Technology type	Technologies	Proportion of R&D investment	Increase in production efficiency	Increase in quality	Decrease in investment cost
		γ	δ_q	δ_p	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%

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 13.

Table 13 : 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 14 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 15. The simulations have been executed according to scenario I, the reference scenario. 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 14 : 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 6. 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 7, it is visible that the distribution is quite similar.

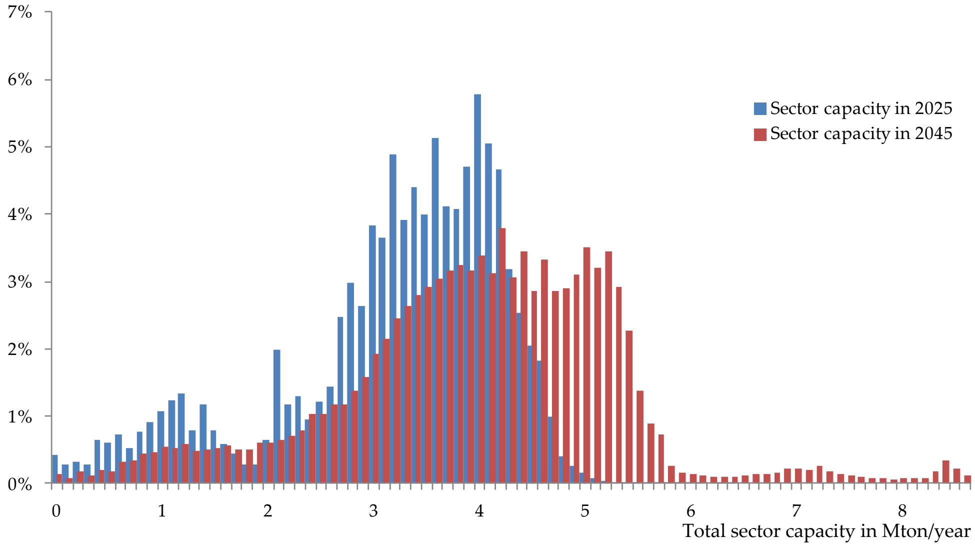

Figure 6 : Distribution of total capacities in 2025 and 2045 in the sensitivity analysis

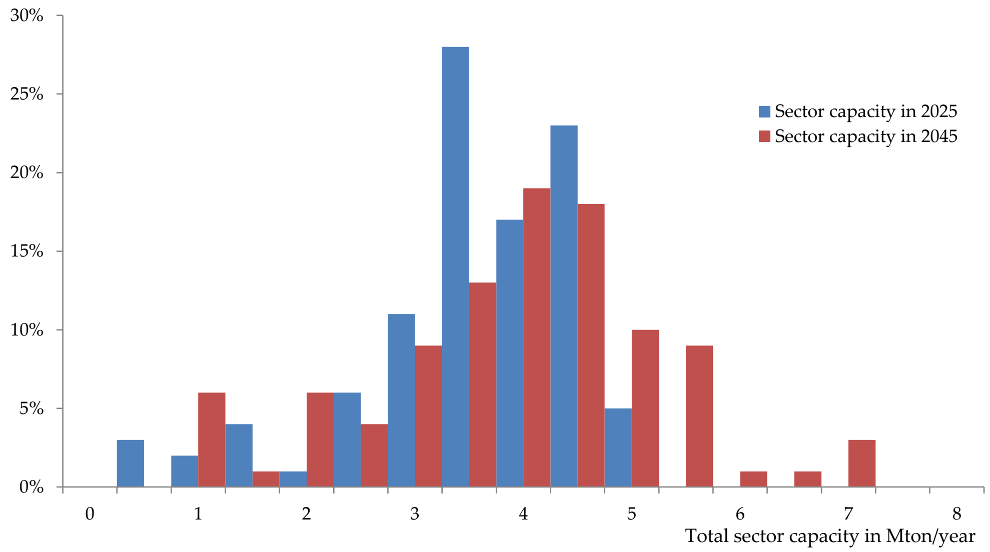

Figure 7 : Distribution of total capacities in 2025 and 2045 in the reference case

Annex B: ODD-Protocol

Table B. 1: Description of the ABM model based on the ODD protocol [70]

Overview

1. **Purpose**: The purpose of this agent-based model is to simulate the evolution in manure treatment technologies. The model looks at sector transition and growth, and can account for policy measures and different innovation structures. The aim is to advise policy makers on optimal measures to stimulate the introduction of new sustainable manure treatment technologies.
2. **Entities, state variables and scales**: The main agents are the technology parent companies. These are specialised in distinct technologies for manure treatment, invest internally in innovation to improve their technology, 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. Technology parent companies invest in new treatment projects when they esteem the investment to be viable. Scarcity of biomass is simulated with two open markets for manure (one for liquid and one for solid manure). All actors are connected to these markets, their biomass demands depend on their specific technology and the capacity of their active treatment plants.
5. **Emergence**: New actors are introduced annually. 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. In an open innovation structure, new technological development can also be transmitted amongst actors.
6. **Adaptation and objectives**: The technology companies are profit-maximising entities, with a time-horizon of 15 years.
7. **Learning**: Learning capacity is implemented through efficiency investments, and investments in R&D.
8. **Prediction**: 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 publish average transaction prices, that are used for prediction s of the agents for the next period.
10. **Stochasticity**: Stochasticity is present in the emergence of new technological breakthroughs. The success of R&D investments is a random process, depending on the invested capital in R&D, and the firm's experience in R&D, accumulated over the years.

11. **Initialisation**: The model is initialised by a group of reference agents, calibrated to represent the Flemish manure treatment sector both in production as in technical characteristics.
12. **Input Data**: The input data is collected in Annex A.

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