Defining relevance and finding rules: an agent-based model of biomass use in the Humber area

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Abstract. The field of industrial ecology applies ecosystem theory to industrial production, human consumption and societies. This article presents a case study of the development of the bio-based economy in the area surrounding the Humber estuary in the North-East of England. The study developed an agent-based model to simulate the evolution of the industrial system. We explain how the qualitative research process led to the development of a toy model that has successively been specified.

1 Introduction

The field of industrial ecology applies ecosystem theory to industrial production, human consumption and societies. As such, the models developed in this field are often conceptual, remote from actors' self-perception and sometimes on the brink of committing a natural fallacy. Yet the dynamics that can be observed in socio-metabolic systems are hugely interesting from an epistemic point of view and indeed for the future of industrialised societies with respect to their ontological dimensions.

Against this background, the Evolution and Resilience of Industrial Ecosystems project (ERIE) at the University of Surrey[3] is carrying out a case study of the area surrounding the Humber estuary in the North-East of England. The area is of interest for a variety of reasons: It hosts two deep water ports, existing chemical industry of national significance, and an agricultural hinterland. All of these factors are relevant in explaining the growth of a bio-based economy in the area. The industries utilising biomass include chemistry, the energy sector and agriculture. All are intricately linked although the policies that drive the development of the system are partly carried out independently. Our research was interested in the analysis of the development of a bio-based economy in the area. In particular, we wanted to explore the evolution of the bio-based economy in the Humber area with the help of an agent-based model.

Our methodology consisted of two methods that we applied in three phases. In the first phase we used qualitative semi-structured interviews to elicit relations and interactions between actors that we intended to translate into behavioural agent rules. From

[3] http//erie.surrey.ac.uk

this data we created a toy model, which, helped us to specify relevant problems and come up with a refined conceptual model. In the second phase of our research we collected more specific data by means of a participatory workshop. In this workshop we brought together the key stakeholders that we had identified in the first phase. The exercise also gave us an opportunity to receive feedback on our conceptual model. Finally, it established a basis for future collaborative modelling with the stakeholders in phase 3 as we plan to put successive versions of the model online during its development.

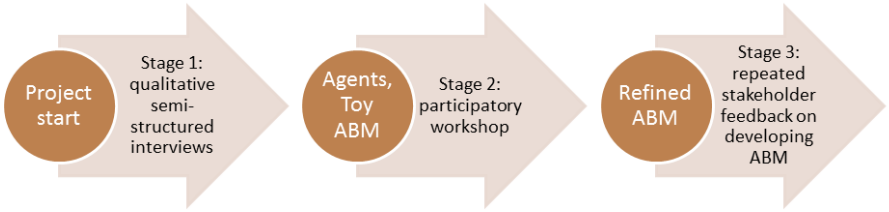

Fig. 1. The research stages

2 Information and data gathering

Since we had to approach the field with no particular (socio-economic) theory in mind the ERIE team opted for an altered grounded-theory approach [13]. As would be expected it took time and resources to establish working social relationships with relevant people working within the area's industries, and to obtain data about the system.

Our data was mainly collected through semi-structured interviews with 21 stakeholders. We employed two independent coding strategies to analyse the interviews leading to two different outputs: one for an agent-based model and the other for a network model. In what follows we will only be concerned with the former. The first coding strategy utilised established notions of cognition, social networks and institutions as foci [5] to distill relevant information from the interviews. We employed these frames to cover all relevant social aspects that might contribute to the economic-metabolic network but also to establish common ground between the different disciplinary orientations within the team.

Beckert's theory overcomes some of the difficulties associated with social network analysis or institutionalism as stand-alone social theories. It owes to Fligstein's work on fields, which states that a population of actors constitute a social arena by orienting their actions towards each other. Beckert argues that all three structural features, cognition, social networks and institutions, are important to explain the dynamics of markets.

1. Network structures position organisations and individual actors in a structural space. Fields can comprise specific structures of social networks which create power differences between firms and status hierarchies.
2. The relative performance of actors is anchored in regulative institutional rules which allow and support certain types of behaviour while discouraging others.
3. Cognitive frames provide the mental organisation of social environments and thereby contribute to order market fields.

Coding and analyzing the interviews provided us with an understanding of the networks in the area. We learned for instance that two local organisations became particularly important for facilitating the transfer of ecological capability in the area after the abolition of the Regional Development Agency Yorkshire Forward. These were the Humber Chemical Forum (HCF) and the Humber Industry Nature Conservation Association (HINCA). While HCF is highly relevant in developing the skill base for the industries in the area, HINCA has become highly important in overcoming obstacles resulting from the deficits of the planning process. Both organisations facilitate cooperation amongst the companies and the local authorities in the area. HINCA assumed its central role not least due to national and international regulation for protecting bird habitats. Nearly all changes to companies' operations need to go through the planning system which creates uncertainties companies are keen to avoid. Furthermore, dyadic relationships between companies exist that represent industrial symbiosis or the exchange of by-products, e.g. the supply of organic waste. These were promoted by another stakeholder, the National Industrial Symbiosis Programme represented by Linked2Energy in this area. In coding the interviews we defined actors cognition as including environmental management knowledge and skills, eco-innovations and others. Process innovations that we learnt of were all related to technical and social innovations. However, we discovered interdependencies between technical and social aspects of process innovations, e.g. when companies choose a particular form of financing to develop their eco-innovation. Our interviews were less conclusive with respect to institutions impacting on the area, which we ascribed to the change in government that took place immediately after the project started. However, we identified key policies that exerted downward pressures on the industry in the area including financial incentives. Several policy instruments provide various financial incentives to promote the uptake of eco-innovations.

This direct empirical information was supplemented by a literature review of the relevant policy documents. There are a variety of policies from national government and the EU that impact on firms in the area, e.g. both, national and European bodies provide relevant funding for the area that has some effect on a bio-based economy. For the purpose of the model we have only focused on policies supporting the development of a bio-based economy, which are: Landfill Tax, Renewable Obligation (RO), Feed-in Tariffs (FIT), Renewable Transport Fuel Obligation (RTFO), and Renewable Heat Incentive (RHI). These policies influence the incentive landscape to which economic actors adapt[4]. They can be rather easily translated into incentives on which agents in the ABM act.

[4] We distinguish between actors in the real-world and agents in the model throughout this paper.

The resulting information might have lent itself to setting up a SKIN-type of agent-based model [8]. However, two reasons spoke against the implementation of a SKIN model. Firstly, it had become clear from the interviews that the development of a regional bio-based industry was compromised by strong network externalities. Although these were partly internalised for some biomass flows (e.g. used cooking oil contributed significantly to biofuel production in the UK) they were not internalised for others (e.g. large quantities of wood are imported from Scandinavia). Yet SKIN is not designed to cover negative network externalities. Secondly, the team had a strong interest in policy implementation and the effect of different policy instruments on the different process innovations. This resulted in the conceptual idea of a network (of nodes and ties) that is differentially influenced by the implementation of government policies. Two policy instruments were selected: facilitation of recyclate use (that is source-segregated organic waste that has been recycled and ceased to be considered waste by the regulator) and renewable energy policy.

3 The toy model

In specifying the agent-based model we followed ideas presented in [7]. In the toy model we considered only a limited number of actors relevant for the growth of the bio-based economy. We implemented food processors, composters, aerobic digesters, and biofuel refineries. In each time step, the following happens: (i) the waste suppliers, (ii) food processors supply any existing waste contracts that they have, (iii) new waste contracts are made. The exchange of biomass by necessity conforms to a constant material and energy balance. Material flow analyses are the stronghold of industrial ecology and they were integrated in the model by specifying in-flows and out-flows for each type of bio-processor, which allowed tracking the material energetic footprint of the biomass traded.

The maintenance of constant material and energy balance allows tracking of certain ecological effects of network evolution, including carbon emissions. Furthermore, a decision was made that proved to be crucial for the further development of the ABM: agents would exchange materials according to prices. While information on current prices for waste and primary resources was easy to obtain, prices are influenced by factors external to the system. The prices, which translate into costs or revenues for companies are matched by two cost components constituting the firm agent; on-going operational costs and start-up costs, modelled as a loan repayable with interest over time. Using this setup, the financial position of each company is updated each period by the income generated from energy production and any gate fees receivable, less the cost of materials, operating costs and realisation of start-up costs. This position must remain positive, if not the company goes bankrupt and is eliminated from the model. The rules of the agent-based model thus read:

1. The food processors produce waste.
2. Food processors supply any existing waste contracts that they have. Finances are updated accordingly.
3. New waste contracts are made and finances updated accordingly.

4. Food processors update the price that they pay to get rid of waste: if they have managed to get rid of all their waste, then they decrease the price they pay, if they have waste left, then they increase the price they pay.
5. Finances of food processors are updated - they receive money for the products that they develop and pay money to get rid of all remaining waste to landfill.
6. Companies that process waste, process any waste that they have received.
7. Finances of waste producing companies are updated.
8. Any company that has no money goes bust.
9. New contacts are made - how often depends on the contacts-rate slider.
10. New waste processors are created - how often depends on the slider called company-creation-rate. Biodiesel plants are created providing there is enough waste oil available to operate. Either composters or AD plants are started (50/50) depending on whether there is solid waste and, for AD plants, only if a "profitability" measure is satisfied.
11. Update any contract details - end any contracts that have reached the end of their contract period.

The above resulted in a toy ABM, which already reproduces some of the properties that we observed in the real world at the macro-level. For example, we can see from the model the impact that the RO incentives have in reducing organic waste going to landfill, or the volatility in waste prices, and the effect of this in the spread of company profitability. The macro data used for this hands-on validation exists in the form of reports and other qualitative data as well as quantitative data of particular material flows. Additionally, we can probe the relationship between the level of RO incentive and the proportion of anaerobic digesters to composters, and more generally the extent to which policy driven financial incentives affect the financial viability of different agents within the model.

In developing an ABM one problem is the difficulty in distinguishing between endogenous and exogenous drivers because they are commonly entangled in practice. Waste policy had clearly initiated the drive towards a bio-based economy but the introduction of a variety of climate change policy measures overlaid the initial patterns. HCF and HINCA were clearly facilitating endogenous growth of the knowledge network that might be considered one layer of the multiplex regional network, but both stand outside the production network. Furthermore, despite the empirical evidence we found for the coordinating role of HCF and HINCA we are unaware of a defendable method to determine the importance of these actions (in particular not in comparison to the exogenous influence on the network through, for instance, climate change policies). Since the ERIE model was intended to have the primary objective of representing the dynamic flows of biomass in the industrial production system, regulation not directly aimed at these flows has not been considered in the initial toy model. Even if such regulation may have indirectly induced additional and sometimes qualitatively important incentives.

The toy model does not allow discrimination between policy instruments. This does not allow for the intended comparison between a weak (facilitation) and strong policy instrument (economic incentives). Yet, interdependences also existed in practice, for example where facilitation was added to the existing UK waste policy, whereas the

economic incentives were introduced as part of climate change policy. This shows the difficulty to empirically distinguish between and analytically model the co-evolution of policies and also the area network and national and international policies. This is partly because political actors (Local Authorities) are only represented in the model as suppliers of organic waste. They do not appear in their regulatory function, where they are left with the obligation to implement waste policy. By contrast the framework for waste and climate change policy is set at the national, European level, and indeed globally (Kyoto protocol).

Another reason for revising the model is that while policy-makers do consider interdependencies between the various instruments to some degree in the process of policy design, policies are u sually analysed using general equilibrium models. There are multiple financial incentives (including landfill tax escalator, ROCs, FITs, RTOCs and RHI) that overlap although the instruments are designed to act differentially on different actors. Yet for all practical purposes the micro-economic policy instruments are simply simulated with a macro-economic equilibrium model (MARKAL model). These considerations led to a more basic revision of the concept behind the toy model. We tried to separate more clearly endogenous and exogenous drivers and indeed, we came to conceptualise the network as an emerging market.

4 Refining the concept

In order to distinguish more clearly between endogenous and exogenous drivers we saw the need to revisit the emergence of a network from the behaviour of individual firms. Parts of the emerging market for organic waste have a specific trait: agreed sales prices for bio waste are unknown to competitors. This situation very much resembles a fish market, where individual bids are made secretly (no auction). Such a market has been modelled empirically and it is considered valid economic theory [16]. This context however, is only true with regard to a fraction of processed biomass, namely the food waste arising from food processing. The situation is different for all other forms of biomass since these are traded nationally and globally (even if some supply is provided locally). In our revised concept of the agent-based model there are four providers of biomass: importers, forestry/agriculture, food processors, and municipalities (see Figure 2). The biomass they produce can be specified further. Food processors produce biodegradable waste and oil. The former requires a quick turnover while the latter can be stored for some time. Forestry and agriculture provide input such as corn, straw, and wood, which can all be stored but which have some seasonality attached to them in the case of the first two. By contrast, wood can be supplied according to demand and left standing as a living forest or stored to wait for a better price. Similarly, soy, rape and palm oil that importers provide can be sold according to world market prices. Thus, there are distinct differences between bilateral price negotiations and contracts that are informed by a global or regional price (a price known by all in an area).

In the interviews we learnt of three types of facilitators: consultants who can be divided into consultants who simply arrange contracts and oil brokers who also own the biomass. Both types of facilitators observe market price development of the different biomass primary resources for producers (mostly from the energy sector). Then we also

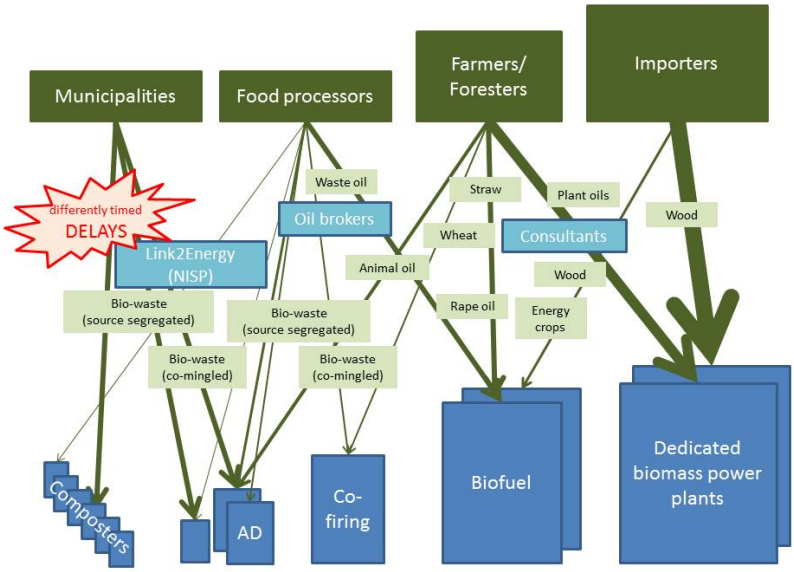

Fig. 2. Different interactions between companies and biomass flows

have Link2Energy/NISP that used to offer a free service (mostly between composters and anaerobic digestion plants and their suppliers). Additionally, processors may decide to set up contracts by themselves. Drawing on external facilitators or setting up supply on their own corresponds to different transaction costs for all processors. These costs will differ for each company depending largely on the amount of biomass they require and the scale of the supply.

The different processors have sector specific ways of buying in supply. Dedicated biomass power plants secure their supply chain with long-term contracts of several years (as long as possible without freezing the market price). The same is true for biofuel producers. The situation is slightly more relaxed for anaerobic digesters since their capital costs are lower. However, they process considerable quantities of organic waste that are usually governed by long-term contracts (of up to 20 years). Composters and co-firing plants can take in biodegradable waste quite spontaneously (and potentially sporadically in the case of co-firing). They don't require upfront investment but simply have to calculate their fees against operational costs. As this already indicates, the duration of contracts with suppliers very much depends on the size of the processor and the specifics of the biomass resource.

Furthermore, the revised agent-based model will distinguish between material/energy and information flows. The use of biomass is path-dependent (cascading) or may entail trails for recycling organic waste whereas the diffusion of information is not. Following [6] we can discriminate between walks, trails, and paths. Walks are

sequences of flows where nodes as well as ties are passed time and again e.g. money handed on in payments. Trails are sequences where nodes, but not ties, are passed repeatedly. Paths are sequences in which neither nodes nor ties are passed more than once. The flows are transferred in their entirety. Material/energy flows generally belong to this last category representing the irreversible dissipative economic structures of the real world. Although recycling reintroduces trail characteristics these may be neglected since we don't simulate regional energy supply or nutrient cycles.

With regard to information, [6] distinguishes between serial and parallel processing. The diffusion of information (price, quality and quantity) of agents operating in the waste context can be represented as a serial diffusion process (perhaps involving some kind of learning). By contrast the diffusion of information of consultants might be represented as a parallel process in which agents basically have access to the same information (prices in a global market). This leaves us with the oil brokers. Unlike facilitators and consultants, oil brokers could behave strategically and hold the flow (subject to long-term supply contracts) since they own the resource. (From the interviews we learnt that biofuel refineries are making some efforts for vertical integration but the high price for waste oil appears to hamper these attempts.)

To summarise, information is seen to spread through serial processes in the case of biodegradable waste and through parallel processes in the case of consultants and oil brokers with the latter having the power to delay flows. We also want to distinguish between: suppliers, facilitators, and processors, different material inputs and time delays. Yet we needed more empirical specifications for an agent-based model, which we obtained from the stakeholders in a workshop.

5 Stakeholder workshop

It is widely accepted that stakeholders can bring valuable first-hand knowledge to the research process, can meaningfully contribute to selecting a model and developing it, can help in collecting data and integrating it, to develop scenarios, interpret results, and formulate collective strategies or policy alternatives [3,12]. On the other hand engaging stakeholders is time-consuming, may bring plural perceptions to the research process rather than unambiguous data, can be difficult to manage if it is not increasing the chances of project failure altogether, and might be difficult to carry out in monodisciplinary research projects [9,17]. Despite these potential pitfalls "participatory modelling, with its various types and clones, has emerged as a powerful tool that can (a) enhance the stakeholders knowledge and understanding of a system and its dynamics under various conditions, as in collaborative learning, and (b) identify and clarify the impacts of solutions to a given problem, usually related to supporting decision making, policy, regulation or management." [14].

This constitutes the context for the participatory workshop that we carried out in January 2013. We sought direct feedback on the existing conceptualisation of the agent-based model by presenting the concept to the stakeholders and prompting responses. The presentation of the concept as well as the introduction to the existing toy model passed the plausibility test as both were approved by the stakeholders. We also used the workshop to gather more information and data needed to empirically specify the agent-

based model. Initially we had planned to divide the stakeholders into four different groups each group working through a particular set of questions to provide information and in some cases basic data. The topics of each group were:

1. Biomass Specification Organic Waste and Virgin Input
2. Firm Specification Bio-Processors
3. Specification of Service Providers Facilitators and Brokers
4. Policy Questions & Measures of Success

Each of these headlines involved several questions. Some of these were more qualitative in nature whereas others were more quantitative. We ask for the specification of biomass (1) in order to model delays that translate into dynamics in the system (e.g. supply chain fluctuations; price volatility). The specificities of the biomass may amplify or reduce these dynamics. The firm specification (2) related to the size and capital structure of companies and the agents properties in the model. We were also interested in obtaining information about the service providers (3). However due to an unexpectedly low turnout of stakeholders we decided to cancel this group and obtain this information in future via other means. Finally, we asked questions on policy in order to validate our concept according to these criteria later in the project (4).

The first two topics proved challenging because they involved a long list of sub questions. We collected data on the capital costs of the different technologies and on specific resource prices. Furthermore, we learnt that biomass processors can set up different production lines for biomass and oil to derive their intermediate inputs from different sources and to differentiate their products according to market price for either product category. This seemed to provide qualitative evidence for the hypothesis that price volatility is indeed a concern for producers. We also obtained some confirmation for properties demonstrated by the toy model. We heard that biofuel producers were indeed operating at a very tight margin as suggested by the model and that the path-dependencies we had observed appeared reasonable to stakeholders.

Overall we considered the workshop a success despite the fact that the turnout was lower than expected from advance confirmations. This was not least because stakeholders expressed interest in providing input into successive versions of the agent-based model, which will be made available to them online in the near future.

6 Revising the rules of the ABM

Some of the information gathered at the workshop can directly be used to revise agents and their decision rules, e.g. we learnt about different processors' cost structures, durations of supply contracts according to processor type, and processors' flexibility in using different inputs. By contrast, other aspects can only be implemented together with the above conceptual approach, e.g. the effects of seasonality of (primary) biomass or the possibility to store biomass (thus mitigating possible supply volatility). (The toy model only covered organic waste without delays.) The revised ABM will be able to model the different streams and markets. These are partly interdependent and the interdependency between markets for primary biomass and secondary (recycled) biomass is crucial to keep the development of renewable energy from biomass on a sustainable

trajectory. (It is also of considerable practical interest for instance for the stakeholders.) Interdependence is generally typical for markets emerging from the internalisation of environmental externalities. Another benefit of the above conceptual approach of differentiated flows is that it could also take the spread of pathogens into account. By contrast this is outside the realm of economic models.

- Food processors seek contracts (with introduction of waste tax) and individual offers are made secretly (no auction) Municipalities seek contracts and suitable (scale) processors.
- All processors seek suppliers. Depending on the scale of operation they preferably use the intermediaries – true for all processors equal or bigger than anaerobic digestors.
- In network terms the emerging process might be seen as a diffusion of information (price, quality and quantity). Agents operating in the waste context would be represented as a serial diffusion process (perhaps with some kind of learning). By contrast the diffusion of information of consultants might be represented as a parallel process in which agents basically have access to the same information (prices in a global market). This leaves us with the oil brokers. Unlike facilitators and brokers they could behave strategically and hold the flow (subject to long-term supply contracts) since they own the resource.

7 Discussion

The ERIE project progressed in two phases. Both relied on qualitative methods to define rules for the agents of an agent-based model. Despite this similarity we consider the two phases as distinct. The first phase consisting of semi-structured interviews effectively enabled us to understand relevant aspects of the developing bio-based economy in the Humber area. Whereas we had a clearly defined theoretical framework and collected sufficient data from the standpoint of qualitative social research we did not obtain enough data to create a defensible and relevant agent-based model. Instead we had to acknowledge that networks and institutions are empirically more complex than cognition resulting in an under-defined toy model. This led to a second phase in which we redesigned our conceptual model according to empirical problem observation and economic literature. We entered a third phase where we engage in a participatory modelling process, which is on-going. One of the reasons for choosing a participatory method over conventional qualitative methods such as interviews is the higher information density achievable with participatory exercises.

Once implemented in an agent-based model the empirically established rules should already result in complex dynamics such as market price fluctuations. The aim is to detect price volatility emerging from these interactions and mitigating effects resulting from e.g. long-term contracts or government policies. Price volatility is a widely recognised problem for companies and may become more pertinent in future as some studies suggest a strong relationship between bio energy and oil prices [10]. Furthermore, price volatility is a particular problem of secondary material (recyclate) markets more generally because these markets often lack market clearance of waste outputs according

to supply and demand [1,2,4]. For this reason the UK government has endorsed the creation of recyclate markets from early on [15] by creating for instance one of the facilitators (NISP) we saw in the area network. This might be of less concern in respect to organic waste as it can either be recycled to land (source-segregated organic waste) or brown field sites (co-mingled organic waste). There is thus a host of questions around the evolution of the bio-based economic system we can now explore with the revised agent-based model.

We want to pursue three research questions in particular: firstly, we want to understand path dependency in the evolution of the bio-based economy in the Humber area. We conceive of path dependency as emerging from the adaptation of companies to different incentives that are introduced sequentially. The concept of a bio-based economy involves biomass processing industries such as composters, anaerobic digesters, biofuel plants, bio plastics producers, and others [11]. While the processing options imply irreversible cascades of biomass use, any real-world implementation may fail to fully exploit the available technological potential if lock-ins occur early in the development. In addition to that, we would like to know whether the sequence in which the policies were introduced had a positive (dampening) effect on price volatility or what else might dampen price volatility (e.g. contract duration). Obviously, this is important for future policy implementation as it may allow or disallow the exploitation of the full technological and economic potential of biomass use.

Secondly, we are interested in explaining how resilient the system is to external shocks in the short term, e.g. seasonal loss of agricultural land due to flood, and how robust to long term stress e.g. of rising oil prices or permanent loss of agricultural land? We are thus interested in endogenous and exogenous shocks.

Finally, we want to know whether there are negative network externalities that might reintroduce price volatility (e.g. of biofuel)? While we believe that there is evidence for this in regard to the use of used cooking oil for biofuel production (e.g. sharp price increase in the last four years) we need to understand whether negative network externalities also applied to other biomass flows and indeed the bio-based economy at the Humber as a whole.

8 Conclusions

As this work has progressed we have become interested in the emerging interdependencies between the different biomass flows in the development of a bio-based economy, in particular in the sequence of the earlier waste policy and the later renewable energy policy. This problem, which resulted in a restated and better specified research question, was not obvious from the outset of the research project. In this respect the first phase of the research project represents a search for relevance. The second phase is now quickly leading to an agent-based model capable of answering very specific research questions. The re-conceptualisation of the agent-based model will allow a relevant simulation of the bio-based economic system. It will reflect endogenous development of the network more effectively, as much as complexity is now emerging from the interaction of economic actors. This should allow us to arrive at more reliable predictions of effects from different policies.

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