Agent-based modelling and material flow analysis in market economies:

Some results of the research project AMOSS¹

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¹ The research project AMOSS (“Akteursbasierte Modellierung und Steuerung von Stoffstrominnovationen”, translation: Agent-based modelling and management of material flows) has been funded by the German Ministry for Education and Research. It deals with the recycling potential of two major material flows associated with the car industry: plastics and tyres. This interdisciplinary research project pursued a new modelling methodology combining agent-based simulation and life cycle analysis. This methodology is used as a basis for a multidimensional analysis of material flow scenarios covering economic and environmental impacts. Scenarios include the replication of historic developments and an assessment of policy tools.
1. Introduction

Modern market economies depend upon a broad variety of materials. Furthermore, it seems that there is still no general trend for a decrease in the scale of material use. This is a source of concern, however, because significant environmental impacts are associated with current material use patterns. In the light of these problems, several questions arise: (i) What kind of problems can be associated with material use? (ii) What are the reasons for these problematic use patterns? and especially (iii) What is the scope for policy interventions to overcome these problems? The area of research that traditionally deals with these questions is industrial ecology. So far, research in this field has mainly been performed from a technological and natural science perspective focusing on material flow analyses and material flow strategies. From an economic perspective, such an approach has an important deficit: it does not provide a coherent account of the factors that influence the dynamics of material flows. This, however, is a necessary condition to assess the potential of policy strategies. The following contribution tries to make a step in this direction by referring to the example of car plastics. The topic has been chosen because the environmental impacts associated with car plastics are significant and have led to both an intensive debate and the subsequent introduction of new regulation on the European level (Huber (2004); Leone (2000)).

A particular focus will be put on the agents’ motivations, constraints and decisions that shape material flows. We assume that such an agent-based approach does not only allow us to study development paths and transition dynamics to more environmentally benign use patterns of material flows. It is also a relevant starting point to assess the opportunities for policy interventions and innovations. This is due to the fact that it focuses on the relevant agents at which policy interventions can be addressed or who are the protagonists of the innovations that are required to implement material flow strategies.

All in all, we try to achieve two goals: Firstly, we want to improve the understanding of the economic factors that influence material use patterns from a conceptual point of view. Secondly, we use a new modelling framework for depicting the central drivers of material flow dynamics. We proceed as follows:

- In section 2 we show how the contribution relates to the current literature in the field of Industrial Ecology. We are particularly interested in approaches that model and explain structures and changes of material flows.
- In section 3 we introduce the agents and their interaction that are relevant for our case study.
In section 4 the theoretical background for our modelling approach is provided. We assume that a thorough understanding of agent behaviour (4.1.), the market process (4.2.) and an evaluation of the institutional framework (4.3.) is necessary to identify the drivers of material flows and the scope for policy intervention.

In section 5 we introduce the modelling framework that serves to study material flows on the basis of agent behaviour.

In section 6 some simulation results are presented.

In Section 7 some conclusions are presented.

2. Relevant fields of research

2.1. Industrial ecology

Industrial ecology is an interdisciplinary attempt to figure out orientations and strategies for reducing the impact of industrial activity on the environment (cf. Erkman and Ramaswamy (2006) and Bergh and Janssen (2004) for an introduction). Research in industrial ecology has provided us with tools to study the relationship between the economy and the environment systematically (for example through material flow analysis). Furthermore, strategies have been suggested to reduce the burden of material impact on the environment. These strategies are derived from a comprehensive leitbild for shaping the relationship between ecology and economy. This research, can been criticized in at least two ways: Firstly, there have been few attempts to actually explain the dynamics of material flows. This means that from a social science perspective, the reason for certain material use patterns have not been dealt with comprehensively. Secondly, the potential for the success of policy strategies has not been studied thoroughly. This includes also factors that prevent these strategies from being adopted more broadly. In this regard, the approach can be supplement by an agent-based approach (as suggested by Andrews (2001)). Such an approach would look at the motivation, goals and the decisions of agents regarding the material flows. This also includes a consideration of (individual) incentives that make certain material use patterns attractive, the analysis of social dilemmas as well as innovations as a way to overcome adverse material use patterns. Hence, thirdly the appropriateness of the leitbild of industrial ecology is at stake.
2.2. Modelling of material flows

Currently, system dynamics models and input-output analyses are the most widely used modelling approaches in material flow analyses (cf. for example Amaral et al. (2006), Lander (2005), Seebach (1996) for system dynamics models and Meade (1995), Paulus (2004) for input-output-models). These approaches are useful to study the interaction between the economy and the environment as a whole. Nevertheless, they are less apt to deal with the intricacies of agent behaviour and processes of change: In input-output-models and system dynamics models individual processes are not considered or they are substituted for by methodological simplifications (for example by assumptions of optimizing behaviour and representative agents). The drawback of such a simplification is, for example, that incentives or constraints that work for/against agents participating in cooperations (which is often a requirement for effective material flow management) cannot be traced. Furthermore, material flows are subject to processes of change. Input-output approaches and system dynamics models can capture these issues not appropriately. Finally it can be argued that agent-based heterogeneity and processes of change are closely linked. Keeping track of these difference is crucial: our assumption is that (i) it is not sufficient to consider only single agents (or a stylized aggregation of them) and (ii) that simplifications hide important lower level processes that shape the aggregate outcome (for example selection processes).

In the light of these deficits a new methodological approach has been suggested: agent based-modelling (Axtell and Andrews (2002); Kraines and Wallace (2005)). Agent-based models are computer simulations whose dynamics depends on the decisions and interaction of software agents (Wooldridge (2002); Weiss (1999)). Multi-agent systems are created on the basis of object oriented programming. The software development process requires in the first step the specification of an appropriate agent architecture. In the second step, interaction rules are introduced that specify how agents influence other agents as well as objects.

Agent-based modelling has been applied in economics more broadly in recent years (cf. for an overview Safarzynska and Bergh (2010)). An important application has been the research on Schumpeterian (innovation) competition, the diffusion of innovation and network dynamics (cf. Dawid (2006)). The analysis of material systems with agent-based models has begun recently (cf. Davis et al. (2009)). The models available so far are important first steps in the direction of an agent-based analysis of material flows, but they still have several limitations: Often they only include a few stages of the whole material flow cycle. Furthermore, they often presuppose that agents pursue predefined strategies instead of allowing real choices on the part of the agents. Finally, it seems that they do not provide a coherent behavioural foundation and
abstract from coordination problems. The latter refers to the use of a singular representative agent per stage of the life cycle (Brouillat (2009)) or of ad hoc assumptions that guarantee market clearing (Davis et al. (2009)). In our view, these issues are important to account for the frictions and unrealised potentials in real material flow systems.

In spite of these criticisms, agent-based modelling still offers at least two important opportunities which we try to explore in the following sections: Firstly, such models provide coherent accounts of how certain dynamics come about. This is due to the fact that the dynamics results from a set of clearly defined rules according to which agents behave. Secondly, the modelling structure allows us to analyse important issues of an agent-based approach to material flows analysis such as heterogeneity and specific interaction contexts on different stages of the life cycle.

3. Material flow systems

3.1. A specific material flow system: car plastics

The material flows associated with car plastics in Germany are schematically illustrated in fig. 1 (cf. for detailed evidence (among others) Wallau (2001); Schenk (1998)). The material flow is closely linked to the life cycle of a car that spans over several stages. For each of these stages, agents can be identified that shape the quality, quantity and direction of the material flow:

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\[\text{In the diagram we abstract from certain institutions that belong to the material flow system. Referring to fig. 1 these include, for example, car dealerships, workshops and export brokers.}\]
- Primary production is concerned with the production of plastic parts which ultimately will become part of the final automobile. The car industry itself has a hierarchical structure, covering multiple tiers, i.e. firms that supply parts to Original Equipment Manufacturers (OEMs).

- The use phase covers the period between the purchase and the disposal of the car. During this period several circles of second hand use are possible - either nationally or internationally (through exports). At the end of the use phase the car enters either the local or a foreign disposal system.

- Disposal is typically organized in a system that comprises several stages. At the beginning, this involves a two stage treatment process. In the first stage cars are treated by a dismantler who removes residual liquids and dismantles certain parts, especially valuable spare parts. In the second stage, the cars are treated by shredder firms which results in a mechanical separation of the cars into several fractions. One of these fractions is automotive shredder residue (ASR) which contains most of the plastics that
has not been removed by the dismantlers in the preceding stage. Shredder residue can be (i) landfilled, (ii) used for energetic recovery or (iii) exported for treatment.

Apart from that, different options for recycling of plastic parts exist: it is possible to re-use plastic parts at an early stage (usually by dismantling plastic parts at the dismantler stage) or to process shredder residue fraction to create higher value materials. The recycled material can (at least partly) be re-used in the car industry or in other sectors of the economy.

Fig. 2: Material flows of car plastics (in tons) for Germany (2003).
In fig. 2 an attempt is made to quantify the material flow of car plastics for Germany in 2003. Two aspects regarding the structure of the material flow system are remarkable. Firstly, the system is characterized by a strong degree of openness: a great part of car plastics is exported. This is true for both primary production (many of the cars produced in Germany are exported) and the secondary production (due to export and disposal of old cars in foreign countries, a lot of cars leave the German material flow system). Secondly, the flows are unidirected. This refers to the relatively low amount of recycling activities.

3.2. In-depth analysis of material flow systems

In a more abstract way, a material flow system like the one for can plastics can be described on at least two levels: the agent level and the material level (cf. fig 3). The agent level comprises the agents (firms, consumers) and their interactions that span the various stages of the production cycle. The links considered in fig. 1 result from simple transfers or market exchanges. In order to get a comprehensive idea of the material flow, all those interaction contexts for which goods that consist of plastics have to be considered. In the case of car plastics, this includes the purchase of plastics components in primary production, trade with cars and the disposal of shredder residue. Material flows (the material level) are the tangible result of the agents’ interactions. The material under consideration (plastics) is a part of the goods transferred between agents. As has been mentioned in section 2 the material level has been at the centre of material flow analysis, the cornerstone of Industrial Ecology.

In the following sections, we argue, however, that an analysis of the agent level at different stages of the life cycle as well as the relations between these levels is of crucial importance for understanding the dynamics of material flows. The central assumption is that decisions on the agent level drive the quantity, quality and direction of material flows. This becomes obvious in processes of change: while these changes occur at both levels, a lot of changes should be attributed to the following processes on the agent level, especially

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3 Constructing such a material flow diagram is problematic for two reasons. Firstly, plastics are very heterogeneous so that a broad brush representation as in fig. 2 is not differentiated enough to capture important differences regarding the various types of materials. This is particularly important if environmental impacts are considered which can differ considerably with the different types of plastics used. Secondly, the data basis is very insecure (especially for disposal of plastic components) and in some cases it had to be extrapolated by using problematic assumption (for example by making estimations about an average car composition).
- allocation, i.e. the choice between different material use options based predominately on price and/or quality considerations\(^4\),
- accumulation, i.e. the increase of endowments of the agents, especially through investments and increases in production capacity,
- innovation, i.e. the introduction of new products, process and organisational processes.

On the level of material flows, these changes lead to one or more of the following phenomena:

- changing amounts of the material flow (volume), i.e. an increase/decrease of the volume (in terms of weight) of the material flow considered
- a changing quality of the material flow, i.e. changes in the composition of the material flow
- new links in the material flow system, i.e. between stages of the material flow constituted by the agents involved therein.

This classification will be referred to in section 4 to describe processes of change in material flows systems. Here the agent level will be analysed more thoroughly, in particular we try to explain with which decisions these processes are associated and under which conditions these decisions are triggered.

\[\text{Fig. 3: Levels of a material flow system.}\]

\(^4\) Such a choice occurs, for example, when an agent decides which disposal options she favours for a certain material.
4. Agents, markets, institutions and material flow systems

This section provides the conceptual foundation for our agent-based approach to the analysis of material flows. Central to this approach is a focus on agent behaviour which is used as a basis to explain material flow dynamics. We assume, that the use of bounded rationality in agents’ behaviour can help to analyse several empirical phenomena associated with material flows. This will be done in a twofold manner. In this section, we approach the topic from a theoretical point of view and particularly show the implications of the choice of such an agent concept for market processes and material flows. In section 5 this conceptual background will be used to figure out a simulation model.

4.1. Agents

An agent-based approach as proposed in section 2 requires a conceptual foundation of agent behaviour. Evolutionary economics generally considers agent behaviour as boundedly rational. Referring to Simon’s concept of bounded rationality (Simon (1955)) this includes at least three aspects: the limitation of information processing capacities of agents, the incompleteness of the choice set (not all potential options to act are known to the agents) and the inability to attach probabilities to the occurrence of future options. As a consequence of bounded rationality, knowledge then is necessarily incomplete. These constraints can be overcome to a certain degree by information gathering and learning, but success is not guaranteed and failure is possible. Hence, acquiring as well as exploiting new knowledge is an essential feature of the market process (Hayek 2002) (cf. section 4.2).

With regard to learning, the question arises under which conditions an agent engages in search behaviour. Referring again to Simon, two constructs have been particularly emphasized: the aspiration level and organisational slack (Cyert (1994); Cyert and March (1992); March and Simon (1993); Witt (1987)). Aspiration level refers to a specific state an agent aspires (like, for example, a certain profit goal). According to behavioural economic theory missing one’s aspiration level can trigger search behaviour. The aspiration level is contingent on past experience and is adjusted relative to past success. Slack on the over hand refers to excess capacities of agents’ endowments including knowledge, financial endowments and time. Taken together, these two constructs can be seen as reflecting two opposing motivations for search. Aspiration level is linked to failure while slack is related to success.
Search behavior in this view can be seen as a possible form of behavior (mode of action) that depends on specific situations and features in processes of change (Beckenbach (2004)). It can be assumed that, under normal conditions, routine behavior prevails. Apart from routine and innovation behavior, choice can be seen as a third mode of action. Like innovation, however, in a model of bounded rationality, the choice mode cannot be assumed to be activated most of the time. This is due to the fact that choice is cognitively demanding and requires intensive processes of information gathering and evaluation.

The implications of bounded rational behaviour are manifold and of great importance for the case study under considerations (cf. also Bergh et al. (2000)):

- Generally, we would assume that agents differ regarding their knowledge endowments and have differentiated action possibilities. They can improve on their action potential by learning, but heterogeneity is pervasive and not likely to diminish in the course of time (cf. section 4.2). Moreover, there may be specific phases in which innovation is more likely than at other times.
- Certain links between different agent groups in a material flow may not exist or may not be universally practiced (for example recycling loops). This may be due to the fact that certain options to act have not yet been explored even if the potential exists.
- Within a market both price and quality differentials can persist as the exchange relations are reproduced on a routine basis.
- Policy intervention can lead to different reactions by the agents depending on their state or their capacity to act. Policy can also be an incentive change an agent’s internal state, for example, towards the innovation mode which would lead to increased search activities.

4.2. Markets

The fundamental coordination of bounded rational agents is realized by markets. In this context markets are not conceptualized as clear-ct equilibrium states but rather as a flow of individual decisions both being generated and being influenced by a social outcome.

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5 Such routines can be discerned in behavioral regularities of agents, for example, of the dismantlers or shredder firms mentioned above. These routines refer (among others) to pricing procedures. An important pricing procedure in business is mark-up pricing.
According to this evolutionary view of the market process (Hayek (2002), Fehl (2005), Nelson and Winter (1982), Kirzner (1997)) it has been proposed that the market selects options. These options refer to the characteristics of products (attributes or prices), processes, organisational arrangements which the agents introduce to the market. Due to differences in the ability to meet the demand of buyers, some options will succeed allowing some firms to grow at the expense of others.

The process that results from the introduction of these hypotheses is necessarily characterised by disequilibria. A decisive role in this regard can be attributed to innovation. Innovation changes the boundary conditions for the agents within a market and requires continuous adaptation.

Another characteristic of the market process is its openness. This implies that the exact course or an endpoint of market development can neither be predicted (and hardly be imagined, cf. Hayek (2002)). The deeper reason for this is bounded rationality as introduced above. On the one hand, agents endowed with only limited information about the possibilities and consequences of their actions cannot be sure about the success of the results of their economic activity. On the other hand, the market process produces new information for the individual, which leads to a continual requirement for adjustment and the introduction of new options. All in all, the market can thus be characterized as a knowledge creating process and as the other side of the coin – as a knowledge destructing process.

The openness of the market process makes it hard to derive predictions for specific future developments. Nevertheless, due to both bounded rationality and the influence of an institutional framework (Dosi (1988), Saviotti (2005)) economic processes are often characterized by specific development patterns. An interpretation of these regularities has been provided by the concept of technological paradigms and path dependency. Technological paradigms (Dosi (1988), Kemp and Zundel (2007), Beckenbach and Nill (2005)) refer to the continual improvement of an underlying technology. Bounded rationally normally prevents individual agents from completely devising radically different technologies, as the knowledge base at a specific point in time is focused on the dominant technology. An institutional framework may support the application of a specific technology and further complicate the introduction of a new technology. Incremental innovations, on the other hand, are favoured as

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6 The exception from this rule is a radical invention being backed by innovators and opening up a niche in the market (cf. Beckenbach 2007).
agents may be perceive them as a less risky option, especially as major investments into a
technology might already have been made (sunk cost) (cf. Beckenbach and Nill (2005)).

4.3. Institutions

Institutions are coordination mechanisms of agent behaviour which (like the market process) are bound to change (Saviotti (2005)). This perspective is particularly stressed in the concept of co-evolutionary dynamics which postulates interdependence of innovations and institutions. In this view, institutions are facilitating and constraining innovations at the same time: they help to overcome barriers and define a direction for the innovation path. Hence, the future development of automotive material flows will depend on the influence of the end-of life vehicle regulation on (i) post-shredder-technology, (ii) markets for recycling goods and (iii) substitution of plastics for metals (cf. Mazzanti and Zoboli (2006)). In the light of the issues discussed above, these developments can be assumed to be the result of a co-evolutionary dynamics requiring on the one hand innovation on the part of the agents (for example by introducing new process or products) and on the other hand the appropriate institutions (for example new markets). It can be concluded that the actual material flow system is an ongoing process of market activities of agents and of adapting the institutional boundary conditions.

4.4. Conclusion

Based on these considerations, the features of the automotive material flow can be specified. In particular, we refer to certain trends that are characteristic of the current economic conditions (in Germany). These include

- Increases in the demands and prices for certain materials (especially metal prices).
- An increasing use of plastics in car manufacturing.
- A strong export demand for second hand cars in developing countries.
- A changing regulatory framework for the recycling industry (including recycling quotas, disposal requirements as specified for example in the EU end-of-life vehicle regulation).

Considering these trends and picking up the case study of car plastics we propose the following hypotheses:
- **Hypothesis 1**: The quantity and quality of recycling activities depend on the number of deregistered cars as well as export possibilities. Deregistration depends on demand of the customers; export possibilities depend on the stage of development of potentially importing countries.

This hypothesis refers to price differentials between developing countries and the local recycling system. In particular, the amount of cars exported is expected to increase if the prices consumers in developing countries are willing to pay is increasing.

- **Hypothesis 2**: The strictness of the regulation within the recycling system determines the degree to which recycling goals are achieved. Lack of stringency may lead to increased levels of export and put the viability of the recycling system at risk.

Given the different levels of development in different countries there is a trade off between an effective as well as efficient national recycling systems on one side and the time span of using a car on the other side. Hence, protecting a national system for car recycling by regulation has to deal with the export options for end-of-life vehicles.

- **Hypothesis 3**: The general trend towards increasing in the plastic component of cars leads to a recycling sector that is less viable and may potentially lead to higher exports. In contrast to that higher prices for secondary materials may offset these effects.

The trend towards as substitution of plastics for metals leads to high prices for end-of-life vehicles in the national recycling system. This is an incentive for exporting these vehicles (or hulks) given an appropriate foreign demand for them.

5. **Modelling a specific material flow system**

The purpose of the model is to explain material flows on the basis of the decisions and interactions of the agents as identified in section 3.1. In the model, each of the relevant agent groups is represented by a certain number of virtual agents. The material flow of car plastics can then be derived as the result of the exchange relations between the agents of different life cycle stages. In the following subsections the elements of the model will be introduced: the
agent architecture, the interactions contexts between the agents and, the representation of the materials and their transformations (cf. section 5.1.). In a second step, we will analyze the dynamics of activities by way of simulation (cf. section 5.2).

5.1. Elements of the model

Agents

As we have already seen in section 3 the agents influence the direction, quality and volume of material flows by specific decisions. In order to construct an agent architecture for such a material system, it is necessary to answer the following basic questions:

(i) what are the relevant decisions that influence the material flow?

(ii) under what conditions will the decisions be triggered?

Regarding the first question (i) we can identify the following decisions:

- Partner selection: This is tantamount to deciding on who interacts with whom. Indirectly, this decision implies a decision about the way material is used in the following life cycle stages

- Investment: This decision determines what capacity is available to transform material. For the model we assume that the actual degree of capacity use determines adaptations in the form of investment/disinvestment. This happens if average capacity use is higher (lower) than a certain average amount.

- Pricing: Pricing is crucial for determining which material/good will be acquired from which actor or which disposal option will be used for a certain material. In the model, we assume that pricing is dependent on the production cost and of competitive constellations (due to the simulated market processes). The general type of pricing is mark-up pricing, i.e. a profit margin is added on an agent’s average level of costs. The specific type of pricing is a reaction to prices set by competition which will be triggered under certain conditions (see below).

- Innovation: As innovation can take a lot of forms (particularly in the current material flows system under consideration) we assume that the reduction of the level of fixed cost as a first way to introduce innovation in the modelling context. We also assume
certain domain specific innovation options (including the use of recycled materials and the introduction of new disposal options)

The second question (ii) addresses the triggering conditions for actions performed by the agents. We assume that agents are characterised by certain goals, norms and endowments:

- The guiding principle of firm behaviour is fulfilling its profit aspirations.
- A firm’s endowment include accumulated financial endowments, machine equipment and knowledge.
- Norms are implemented as rules that change or constrain behavioural options (choice set) of the firms.

The activation of behavioural options crucially depends on the realisation of these variables. Referring to the considerations on slack and the aspiration level (cf. section 4.1), we postulate the following:

- The aspiration level is a desired level of profits. The desire level is simply an extrapolation (gliding average of past realisation of profits). Search behaviour will be triggered if the current realisation of profits falls below the aspiration level for a certain number of time steps. An aspiration discrepancy can then lead to search processes in the form of a reconfiguration of partner relations (i.e. a search for new exchange partners), pricing or – in case of persistent performance below aspiration - innovation.
- Slack will be operationalized as financial funds accumulated and unused production capacity (taking the current use of capacity as a reference). It is assumed that a high level of slack can trigger innovative search.

The introduction of these constructs allows us to differentiate between routine and innovation behaviour. Innovation behaviour is linked to the existence of slack and/or failure to fulfil aspirations. Regarding investments we assume that agents follow adaptation routines (for example regarding pricing or investment as mentioned above).

The activation of decision as described above can thus be traced to both firm specific factors (depending e.g. on endowments and internal states of the different firms) as well as environmental factors (depending e.g. on regulations and norms). An important feedback mechanism is the success of the firm in the market process which directly influences decision making. Fig. 4 sums up the most important characteristics of the agent architecture.
**Interactions**

Within the modelling framework the markets particularly relevant for the development of the material flows will be explicitly simulated. Agents belonging to these markets are determined on the basis of the technology they use: agents in need of a certain input will be matched with suppliers that produce the relevant input.

Through the interactions of agents that supply or demand goods with a market the prices and volume of goods exchanged are endogenously determined. Using a simplifying hypothesis, we assume that “bargaining power” will be reflected by assigning a specific market side the possibility to post the price for a good (or bad) at stake. This leads to a specific constellation of price makers within the population. The starting point for market interactions constitutes an initial matching where supplying and demanding agents form a network. The network is bound to change in the course of the simulation if the option 'partner change' (cf. above) is invoked. If this is not the case, the network of suppliers or buyers for a specific agent remains as it is.

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7 This includes the markets for cars (M(2)), end-of-life vehicles (M(3)), hulks (M(4)), used components (M(6)), recycled plastics (M(7)) (as introduced above, cf. section 3)
In the markets discussed so far the prices and quantities exchanged are determined endogenously. Choice among a range of partners will be made according to a set of criteria including price, amount received and the regulatory compatibility of the option. Based on these criteria the supplier chooses the option which results in the highest score based her individual preference function.

*Material flows and technologies*

As introduced above, material flows in the models are the result of an exchange and the transformation of complex goods in the course of a product life cycle. In the context of the model, accounting for these material characteristics is necessary for both the material characteristics and the transformations. Goods are characterized in two ways:

- by their components
- by composition of these components and the respective weights.

Such a conceptualisation allows us to keep track of the quantities and qualities of goods traded in the material flow system.

In the course of the life cycle, material flows are bound to transformation. These transformations are caused (and purposefully invoked) by agents using machinery. Two particular types of production technologies can be discerned which differ regarding the change of the material structure and functionality of the goods.

- **Joining/Dismantling.** These include all the actions that add or dismantle components to object. An example for a dismantling activity would be an agent demanding a spare part. In the model, this is depicted as a reduction of the number of sub components; construction is adding components another component.

- **Material transformation.** Material transformation is characterised by the creation of qualitatively new components for which reversibility is not possible. An example is the process of shredding, which leads to the production of outputs (scrap, shredder residue)

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8 Apart from that, there are markets for which the allocation is determined via a simple matching rule. This refers to the market for automotive shredder residue (M(5)) (as introduced above, cf. section 3). The introduction of such allocation procedures has been necessary as some aspects crucial for the dynamics in the field lie outside the scope of the model. Nevertheless, the inclusion of these processes as fully fledged markets in the model would not have increased the understanding of the overall market process.
whose functions differ considerably from their inputs (old vehicles)). In the model, we
use a transformation matrix to express this, i.e. we specify how products are created
through the production process and which new compositions they have.

5.2. Simulating material flow dynamics

The dynamics of the model is due to the sequence of the agents’ decisions that occur in every
time step of the simulation. A time step is composed of three distinctive substeps:

- In the first part of the time steps production and the transfer of goods and material
  occurs. Market exchanges are considered sequentially, market by market. This means
  that production and transfer starts with the market for plastics and leads via the market
  for plastics components to the market for cars. For secondary production it is assumed
  that the goods will be handed over to exchange partners who transform it depending on
  their respective capacities.

- In the second part of the time step, the performance of the agents depending on the
  actions performed in the first part of the time step is calculated. Thus, the costs, the
  revenue, and profits are derived.

- In the third part of the time step, the decision to adapt prices, quantities (by investing
  or changes in the production plans) or exchange partners happen (if the relevant
  triggering conditions are met). Apart from that, it is determined, whether innovation
  search will be triggered.

In fig. 5 it is shown how the market operations can be reconstructed from agents’ behaviour
taking hulks as an example.
Fig. 5: Market interactions in the market for hulks: sales per agent (upper left), purchases per agent (upper right), amount of hulks traded per time step (lower left) and value of hulks traded (lower right).

6. Simulation Results

6.1. Indicators and reference scenario

In the following section, scenarios that take up some of the hypotheses of section 4 will be presented. These scenarios are related to a reference scenario which captures some important characteristic of the material flow system under consideration. It reproduces the stylized facts
of firm behavior and market processes for the last 15 years in Germany and has been calibrated with data firm and market data. In our comparisons we concentrate on the following aspects:

- Local/foreign disposal of old cars (export dynamics). This refers to the share treated in the German recycling system versus cars exported to other countries. The export dynamics is important as it has implications for the economic viability of the German recycling system.

- The disposal of automotive shredder residue (ASR). This has been a major issue in recent years, especially the practice of land-filling ASR, which has a high environmental impact. We will use the amount and the types of disposal as an indicator in these scenarios.

- Prices of disposal. We use an indicator of the “system costs” of car recycling. This indicator is constructed by adding up the profits (respectively the payments) of the protagonists in the car recycling system (shredders, dismantlers, disposer of SLF as well as the consumers). In sum, this amount shows what value added the recycling system produces.  

Regarding these three indicators, the reference run is characterized by a high amount of exports in all time steps. The typical recycling option for ASR is land-filling. The costs of the recycling system as a whole are negative. This means that one or more of the agents have incurred losses.

6.2. Selected simulation scenarios

Apart from the standard scenario an export price scenario, a high metal price scenario, a plastic scenario and a regulation scenario are distinguished. Table 1 summarizes the corresponding parameter settings. For every scenario the relative weight of the exported vehicles (fig. 6), the post shredder disposal options (fig. 7) and the system costs of recycling (fig. 8) are depicted.

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9 For the sake of simplicity wages are not taken into account in the simulation model.

10 Such a realization of this indicator hints to fundamental problems within the recycling sector. Persistent negative amounts imply that the costs have to be carried by one or several of the groups included in the indicator. This may lead (among others) to the following effects: illegal dumping (by consumers) and bankruptcies of firms. In this version of the model, exits of agents are not taken into account yet.
Export price scenario

As we already stated above, foreign demand is an important driver of the existing material flow system. In order to assess the impact of higher prices on export dynamics, the price level paid in foreign countries is increased. As expected this leads to an increase in exports and a consequent flow of cars out of national material flow system under consideration (fig. 6b).

<table>
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<tr>
<th>Scenario:</th>
<th>Base run</th>
<th>Export price</th>
<th>Secondary material prices</th>
<th>Material composition</th>
<th>Regulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Price of end-of-life car on export market</td>
<td>300.</td>
<td>900.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Price of metal</td>
<td>1.</td>
<td>5.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastic content of end-of-life cars</td>
<td>constant</td>
<td>rising (for t&gt;100)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landfilling of ASR</td>
<td>yes</td>
<td></td>
<td></td>
<td></td>
<td>no</td>
</tr>
</tbody>
</table>

Table 1: Scenario parameters.

These outflows occur at two stages: (i) at the stage of the consumers and (ii) the stage of the dismantlers. Both groups of agents use the opportunity to sell more cars in other countries and decrease the number of cars dismantled in the national recycling system. As a consequence the amount of shredder residue treated is reduced (fig. 7b); the most important treatment option for shredder residue, however, remains landfilling. The overall indicator for the price of car treatment stays roughly the same as before. This is mainly due to the fact that the reduced income of the dismantler firms is compensated for by higher returns on the side of consumers. The latter result from a relatively high willingness to pay for these cars in foreign countries.

High metal price scenario

High metal prices have been an important characteristic of the economic development in recent years. Metal prices are important for the material flow system under consideration.
because they constitute the main source of income for shredder firms. In this scenario, a higher metal price is assumed for the whole simulation run. Compared to the reference scenario, higher prices can reduce the material drain: the amount of cars disposed in Germany is higher than in the reference scenario (fig. 6c). Once again, the type of treatment for ASR stays the same while the amount to be treated is higher (fig. 7c). Through the increase of prices the viability of the national recycling system is increased (positive price). The reason for this can be found in the prices that can be paid by the shredder firms (fig. 8c). Overall, exports are less attractive.

Plastic scenario

Another major trend is the decrease of the average metal content of cars. In this scenario, we assume a decrease of the composition of cars starting in time step 100. A higher metal content leads to a reduction in the amount of cars treated in the local material flow system (fig. 6d). The reason can be found in the pricing decisions of shredder firms: they have to charge higher prices which make exports by dismantlers more attractive. Apart from that (and compared with the scenario on export prices), the type of treatment for plastics stays the same- though it is now on a lower level (fig. 7d). The cost is not much changed compared to the base scenario (fig. 8d).

Regulation scenario

Recently, regulators have abolished the option for landfilling of shredder residue that has not been pretreated. This is a problem for the agents as landfilling has traditionally been the least cost option. In this scenario, the effects of such a regulatory change can be studied: as for the treatment of shredder residue we can see that energy recovery is now the most favoured option (fig. 7e). Nevertheless, the increase of cost feeds back into the system (fig 8e). The amount of cars exported is increased and therefore leads to an overall reduction in shredder residue treated within the system (6e).

7. Conclusion

In this contribution it has been shown how the dynamics of material flows can be reconstructed by using an agent-based approach. Such an attempt allows to focus the primary economic drivers for such a dynamics in that behavioural variables of actors (agents) and the
interaction of agents in different but sequentially linked markets are taken into account. This is considered as a prerequisite for a meaningful assessment of regulatory options.

This approach has been exemplified here by analyzing the automotive material flows as regards the different disposal as well as recycling options and by assessing (parts of) the European end-of-life vehicle regulation.

From the point of view of a national recycling system the crucial importance (i) of the export incentives for old cars and (ii) of the raw material prices (especially metal) for the economic impact of such a system has been demonstrated. Furthermore the (unintended) side effects of regulations have been dealt with and shown as an important topic.

Future research will have to tackle firstly the logic of the given model by using sensitivity analysis for different parameter constellations and by checking the influence of stochastic processes for the outcome (Monte Carlo analysis). Secondly, the elaboration presented here is only a starting point if the environmental impacts (in terms of natural resource requirements and/or in terms of emissions as well as waste) are to take into account. This can be done by accomplishing this approach by a dynamic ecological balance sheet method (cf. Beckenbach/Steinfeldt/Voß 2010; Urban/Morgan 2010). Due to the endogenous market driver dynamics for actual material flow dynamics a divergence from the leitbild of industrial ecology can be expected.

Fig. 6a: Reference scenario.
Fig. 6b: Export price scenario.

Fig. 6c: Metal price scenario.

Fig. 6d: Plastic scenario.

Fig. 6e: Regulation scenario.

Fig. 6: National and foreign disposal of end-of-life vehicles (red: nationally treated vehicles, green: export (dismantler stage), blue: export (consumer stage).
Fig. 7a: Reference scenario.

Fig. 7b: Export price scenario.

Fig. 7c: Metal price scenario.

Fig. 7d: Plastic scenario.
Fig. 7e: Regulation scenario.

Fig. 7: Disposal options used for shredder residue (green: landfill, blue: power station, yellow: export).

Fig. 8a: Reference scenario.

Fig. 8b: Export price scenario.

Fig. 8c: Metal price scenario.
Fig. 8d: Plastic scenario.

Fig. 8e: Regulation scenario.

Fig. 8: System costs of recycling.

References


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