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AN AGENT-BASED SIMULATION MODEL FOR THE MARKET DIFFUSION OF A SECOND GENERATION BIOFUEL

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ABSTRACT

Second generation biofuels are widely considered a promising energy alternative to conventional (fossil) fuels. Although they will not completely replace fossil fuels (e.g., due to the limited availability of biomass), these high-quality biofuels can contribute to reducing emissions and strengthening a country's energy autonomy. In Austria, a team at the Vienna University of Technology is developing a biomass-to-liquid technology based on the Fischer-Tropsch synthesis. While the remaining technical obstacles are expected to be overcome in due time, the market introduction of the novel biofuel also requires substantial investments. In this context, we developed an agent-based simulation model that can provide potential investors with forecasts for the biofuel's market diffusion. This paper describes the model and presents simulation results.

1 INTRODUCTION

While radical energy alternatives to conventional (fossil) fuels will eventually be established in the long run (e.g., by means of fuel cell vehicles), substitutes for fossil fuels have to ensure full compatibility with the existing infrastructure in order to become adopted by a considerable share of consumers in the short run. This requirement has already been met by the first generation of biofuels (e.g., biodiesel), which can be blended with fossil fuels. However, the production capacity of first generation biofuels is limited in that they threaten food supplies and biodiversity. Furthermore, their agricultural production (which involves the use of fertilizers) as well as their transportation may even increase greenhouse gas emissions.

Therefore, the focus of research has shifted to second generation biofuel technologies that make use of biomass as basic raw material; this includes residual non-food parts of current crops (e.g., stems, leaves and husks), crops that are not used for food purposes (e.g., jatropha), and also industry waste (e.g., wood chips). Biofuels gained from biomass-to-liquid (BtL) processes based on the Fischer-Tropsch (FT) synthesis, such as the biofuel BioFiT that is currently under development at the Institute of Chemical Engineering at the Vienna University of Technology, constitute a particularly interesting alternative. Not only are they fully compatible with the existing infrastructure (thus eliminating technical barriers to their adoption), but they also provide superior combustion properties, extremely low sulphur-contents, and unlimited miscibility with conventional fuels, leading to enhanced engine performance and lower emissions (Fürnsinn 2007).

These BtL-FT-fuels are expected to become ready for market introduction within the next three to five years. While no investments are required on the consumer side, producers would have to invest in a number of biorefineries. Fortunately, these biorefineries would also work efficiently on a relatively small scale and, thus, could be set up geographically dispersed near abundant sources for biomass (further reducing transport distances). However, even for the smaller biorefineries, large amounts of resources are still at stake (e.g., initial capital expenditure is expected to amount to about €50,000,000 for a plant with a capacity of 20,000 tons of BtL-FT-biofuels per year) and, therefore, investors seek support in investigating the market opportunities and risks involved in introducing such a product. This advance research focuses particularly on the question of whether or not and at what rate the novel BtL-FT biofuel "BioFiT" would be adopted by consumers.

Innovation diffusion research has investigated factors that determine the speed and degree with which new products, practices and ideas propagate through a society extensively (Rogers 2003). In his widely influential contribution, Bass (1969) introduced a mathematical formalization of the innovation diffusion process at the aggregate level and provided a closed formula describing the effects of (external) mass communication and (internal) word-of-mouth communication on the diffusion process. This model has been extended in several respects by various authors. However, one common limitation of these works is that they do not distinguish between the individual characteristics of consumers and thus neglect consumers' heterogeneity with regard to preferences and behavior. By contrast, agent-based models start from the consumer's decision-making and model the diffusion as an aggregate process of individual adoption decisions. The main merit of this approach is that it captures the complex structures and dynamics of diffusion processes without knowing the exact global interdependencies (Borshchev and Fillipov 2004). Furthermore, an agent-based approach also makes it possible to take micro-level drivers of innovation adoption into consideration by modeling how consumers' attitudes and behaviors are effected by, for instance, the perception of product characteristics and/or information exchange in a social network.

In this paper, we discuss the design and implementation of an agent-based model for simulating the diffusion of a second generation biofuel on the Austrian market. Our paper's contribution with respect to methodological advances is threefold. First, our model explicitly takes into account both initial and repeat purchases. While other agent-based diffusion models typically are exclusively concerned with the initial adoption of an innovation, our model widens this focus. This expanded focus becomes particularly relevant when modeling the diffusion of frequently purchased products such as fuel. Second, our model considers multiple rivaling products and, thus, is not limited to applications in which no preexisting substitutes are available. This approach constitutes another innovative feature that is essential for simulating the diffusion of the second generation biofuel at hand. Third, we distinguish two separate channels of obtaining information about a product, namely word-of-mouth communication and personal experience, a factor that is largely disregarded by other agent-based diffusion models. From the application point of view, we provide decision makers with insights into the marketability of an innovative biofuel and enable them to test the effect of various pricing strategies on the diffusion process. Our findings for the Austrian market suggest that opportunity exists for such a product, even at a price that lies clearly above that of conventional fuel. The simulation results also indicate that a considerable market share could already be achieved within the first year following the introduction of such a product.

The remainder of the paper is structured as follows. Section 2 introduces our agent-based model. The design of our simulation study as well as results of our simulation experiments are discussed in Section 3. Finally, in Section 4, we summarize key findings and provide suggestions for further research.

2 AGENT-BASED DIFFUSION MODEL

Agent-based models for simulating the diffusion of innovations such as the novel biofuel dealt with in this paper typically adhere to a discrete time approach in which the simulation horizon is divided into periods that represent atomic temporal entities (e.g., Delre et al. 2007a, Delre et al. 2007b, Schenk et al. 2007, Schwoon 2006). Our model, by contrast, conceptually treats time as continuous and is thus based on a discrete event approach. Important advantages of this approach include the ease of using arbitrary continuous interarrivaltime distributions (e.g. Poisson processes) for events as well as avoiding the need to determine the sequence of events scheduled for the same time period. The approach also allows for more general models without a loss in computational efficiency. In the following, we provide an overview of both relevant model elements and the model behavior (e.g., interactions between model elements) before concluding this section with comments on implementation issues.

2.1 Model Elements

2.1.1 Products

Each product is characterized along multiple dimensions using attributes such as price, quality, or environmental friendliness. We assume that consumers do not generally know "true" product attribute values with certainty, but rather estimate product characteristics based on the limited local information they possess. This information may stem from two separate sources, namely (i) the estimations of other consumers as obtained through communication and (ii) personal experience. The degree to which consumers can draw upon the latter source may, however, be limited for certain attributes due to the fact that not all of a product's characteristics can be easily evaluated by simply using it. For instance, a consumer is hardly likely to be able to determine a fuel's precise combustion properties. In order to incorporate these limitations, we introduce an attribute-specific observability parameter that controls the influence of personal experience on the formation of product attribute estimates.

2.1.2 Consumer agents

Consumers form the pivotal elements of the simulation. In contrast to aggregate diffusion models (based, e.g., on the Bass model), our model perceives consumers as independent entities with heterogeneous preferences and behavior capable of both learning and behavioral change. Since an adequate representation of consumer behavior is crucial, consumer agents are the most complex entities in the model. Each consumer agent is characterized by a number of individual parameters, most importantly partial utility functions for each product attribute and an "innovativeness threshold". The latter parameter is used to incorporate individualized adoption behavior based on the concept of innovativeness (Rogers 2003): some agents are willing to adopt the new biofuel once its utility exceeds that of conventional fuel, while others will not purchase the new product before they are completely convinced that it offers considerable advantages compared to conventional fuel. For the application case at hand, additional parameters were needed to characterize the agent's mobility behavior.

2.1.3 Social network

Agent-based simulation approaches allow for an explicit micro-level representation of social interactions, which play an important role in the spread of innovations across societies (Alkemade and Castaldi 2005, Deffuant et al. 2005). Consumer agents are embedded in a social network that establishes communication links between individual members of the social system. Our simulation tool can generate and simulate scale-free (Barabasi and Bonabeau 2003), random (Erdös and Renyi 1960) and small world networks (Watts and Strogatz 1998). An arrival process is attached to each link in the network and used to generate communication events. We applied a Poisson stream in all our experiments to reflect our assumption of exponentially distributed interarrival times for communication events.

2.2 Model Behavior

This subsection outlines three types of events whose micro-level mechanisms determine the emergent macro-level behavior of the model, namely communication events, need events, and experience events.

2.2.1 Communication events

Communication events are generated and scheduled with respect to the arrival processes attached to each edge in the social network. Whenever two agents communicate, they may discuss several attributes of one or more products. By doing so, agents exchange their respective attribute value estimations, which are themselves based on both information obtained in prior communications and personal experience. In the following, we will call each combination of attribute and product (e.g., "quality of conventional fuel" or "environmental friendliness of the second generation biofuel") a "topic".

Before actually exchanging information, the two agents involved in the communication event have to decide on the number of topics to discuss by randomly choosing from the sets of products and attributes the agents are currently aware of. The selection probability of each topic corresponds to the agents' preferences for the respective attribute, since consumers are expected to be more likely to talk about attributes that are important to them than about those playing only a minor role in their individual purchase decisions. Then, a randomly distributed number of topics is drawn from the union set of the topics chosen individually by each agent to finally establish the set of topics for the communication event. For each of these topics, agents exchange their current estimation (i.e., the expected value based on the information available) of the respective product attribute valuation. The information received is weighted with a credibility parameter, which may vary for different communication partners, and is additionally increased by applying an exponential factor with the effect that the importance of old information gradually decays as new information arrives. Furthermore, consumers learn about new products by communicating with agents that are already aware of these products given that the respective product is chosen as a topic. Finally, when attributes of which an agent was previously unaware of occur in the list of topics, agents widen the set of attributes that they consider when making purchasing decisions. Through this mechanism, we have integrated the effect that innovations may also change the way products are evaluated. As an illustrative example, consider the amount by which the novel fuel increases mileage (i.e., by reducing consumption) as this is not an attribute that is typically considered by consumers of conventional fuel, but may become important as soon as fuels with different characteristics in this respect are available.

2.2.2 Need events

Need events arise whenever a consumer agent requires the supply of a product. Since our diffusion model deals with products that are consumed on a regular basis, such need events can be generated by an arrival process being parameterized individually for each consumer agent. To this end, we take into consideration individual tank size, fuel consumption, and mobility behavior. It is assumed that once a need for fuel arises, it is immediately satisfied by purchasing one of the available fuel alternatives since drivers do not have any other options. Given the relative inelasticity of short-term fuel demand, it is also reasonable to assume that minor variations in price do not cause immediate changes in an agent's mobility behavior (for a discussion cf. Goodwin et al. 2004).

The purchasing process triggered by a need event can be divided into three distinct phases, namely (i) evoked set construction (cf. Narayana and Markin 1975), (ii) calculation of expected utility, and (iii) final purchase decision. In the first phase, a consumer agent selects a subset of products that are considered for purchase based on the agent's (limited) information. For a product to be considered by an agent, it is necessary but not sufficient that the agent is aware of it at the time of purchase. In addition, the expected utility of the new product may be required to surpass that of the highest-valued existing alternative product by an agent-specific amount. This mechanism integrates the concept of innovativeness, which is defined as the "degree to which an individual or other unit of adoption is relatively earlier in adopting new ideas than other members of a social system" (cf. Rogers 2003). In our model, the expected increase in utility required for a new product to be considered for purchase is heterogeneous among the population of agents following Roger's partitioning into five discrete categories: innovators, early adopters, early majority, late majority and laggards. For innovators, who are characterized as venturesome, the new product consideration threshold parameter will be low or even negative (which implies that innovative products are considered by them even though they do not benefit in terms of increased utility). For laggards, by contrast, who are characterized as traditional and suspicious of innovations, this parameter is set to a high value. In the second phase, expected utility is calculated for each product in the evoked set. Based on the agent's current estimate of each product attribute and the individual preferences regarding the respective attribute, partial utilities are obtained for each attribute. While in principle various types of utility functions may be modeled, we used a simple additive form and relied on preference data obtained by means of a conjoint analysis in our experiments (see Subsection 3.1). The partial utility values from the conjoint analysis are interpolated to form piecewise linear utility functions for each attribute. Thus, the total expected utility can be calculated by summing up partial utilities over all of the attributes the agent is aware of. In the third phase, the final purchase decision is made by means of a roulette wheel procedure, in which the selection probability of each alternative corresponds to its relative utility valuation.

2.2.3 Experience events

After each product purchase, one or more events may be scheduled in which personal experience gained during consumption or use of the product affects the agent's notions of the product. In the simulation experiments of our application case, we scheduled a single experience event in the interval between the time of purchase and the next scheduled refueling stop.

Personal experience yields new information regarding the estimated attribute values of the purchased product. The "amount" of information obtained depends on the observability of the respective attribute, since some product characteristics can be estimated more easily and directly than others. Analogously to the credibility factor used for weighting information obtained through word-of-mouth communication, observability is used as a weighting factor for new information obtained through personal experience. The ratio of these two factors therefore determines the proportion of influence of word-of-mouth and personal experience. However, while credibility is defined for each communication endpoint irrespective of attributes, observability is defined on a per-attribute basis.

2.3 Implementation Issues

When we decided to follow a discrete event approach (in contrast to the more common discrete time approach), we were aware of the challenges involved, namely (i) finding a proper software tool that supports the development of time-continuous agent-based models, (ii) potential difficulties in parallelization of the simulation runs, and (iii) potential difficulties in handling and analyzing continuous-time models. However, it turned out that the multi-agent simulation toolkit MASON (cf. Luke et al. 2005) – while requiring considerable experience in Java programming – provides a well-suited library for the problem at hand, and thus allowed us to efficiently simulate even a large number of agents. Parallelization at the simulation level is indeed difficult, but this was not considered a serious issue since multiple runs can be parallelized easily, which proved to be more than sufficient for our purposes. Furthermore, handling and analyzing simulation results was considerably eased by the use of a flexible logging facility (i.e., Apache log4j, <http://logging.apache.org/log4j/>). The implementation of the agent-based model described above is built upon the simulation core provided by the MASON toolkit, makes use of the Java Universal Network/Graph Framework (<http://jung.sourceforge.net>) for representing, visualizing, and analyzing the social network, and relies on the COLT library (<http://acs.lbl.gov/˜hoschek/colt/>) which provides functionality for handling random distributions.

3 SIMULATION RESULTS

In the following, we provide an overview of the empirical design used for obtaining input data for the parameterization and initialization of the simulation runs. Afterwards, results for a sample scenario are presented and findings are discussed.

3.1 Data Acquisition

Data acquisition was kicked off with a thorough discussion with our project partner from the Vienna University of Technology in order to identify potentially relevant product attributes. Our project partner's technical-oriented perspective was then complemented with a consumer-oriented view obtained from participants of a focus group. Afterwards, all attributes were tested by means of a pre-study with a non-representative convenience sample of 1,000 subjects. Finally, we commissioned a market research firm to conduct an online survey with 1,000 consumers who were representative for the Austrian market with respect to demographic characteristics such as age, gender, and geographical dispersion. In order to elicit individual consumer preferences, we performed an adaptive conjoint analysis which involved ten paired comparisons of fuels composed from the following attributes and their respective levels: (i) quality (standard or premium), (ii) environmental friendliness (standard or high), (iii) price (€ 1.0, 1.1, 1.2, 1.3 or 1.4 per liter, with a reference price for the conventional fuel of € 1.0), (iv) fuel brand (no brand or branded fuel), (v) fuel consumption (equal, 5 % less, or 10 % less than the conventional fuel), and (vi) raw material (crude oil or biomass). Utility functions for each of the six product attributes were constructed for each individual respondent using partial utility values obtained via a linear programming (LP) formulation of the choices provided in the conjoint analysis and interpolating them where needed. Furthermore, we used the survey to collect individual consumer data on tank size, mileage, and average range per filling, which were used to set parameter values in the simulation. In order to adequately model interaction in the social network, subjects were also asked about the frequency and interlocutor of communication about fuels. We decided to use a Watts-Strogatz network (Watts and Strogatz 1998) with parameters $N = 4$ and $\beta = 0.2$. Based on the data collected, we initialized a total number of 100,000 agents for each simulation run. To establish a frame of reference and facilitate interpretation of results, we decided to use a scaling where each unit time increase in the simulation represents one day, and parameterized arrival processes and agent's mileage distributions accordingly.

3.2 Results for Sample Scenario

Our sample scenario starts with a single, conventional fuel available at the market where, as a matter of course, all consumer agents are aware of its existence. When the biofuel is introduced, its existence is initially communicated to only ten "seed agents" (i.e., 0.01 % of agents in the population), each of which receives information about the true attribute values of the product. Furthermore, we assume a price of € 1.2 per liter for the novel biofuel and a price of € 1.0 per liter for the conventional fuel. The time horizon is set to 400 time units, which roughly corresponds to 13 months.

The resulting adoption for a total of 100 runs with varying random seeds is presented in Figure 1. It was obtained by discretizing the continuous-time adoption in intervals of 1 and calculating the average rate of adoption over all runs in each resulting period. The adoption curve exhibits the typical bell shape. In addition, the results of the individual runs are presented as scattered points in the chart. Despite the complexity and the large number of stochastic elements in the simulation, the results obtained are very robust. The takeoff occurs approximately at time $t = 100$. Starting from that time, the rate of adoption increases sharply before reaching its maximum at time $t = 159$. On average, a market share of 19.3 % of the total unit sales volume is reached one year after the market introduction (cf. Figure 2). The lines represent the average values over all simulation runs while the scattered points again indicate the results of single runs. Because of the higher price of the biofuel, this corresponds to a market share of 22.2 % of total sales. After that, market penetration does not increase significantly any further.

While it goes beyond the scope of this paper to discuss potential pricing strategies and their effects on the diffusion process, we would like to point out that the simulation can be used by a decision maker planning the market introduction of a novel biofuel to learn about the effects of various approaches. For instance, the pros and cons of a skimming strategy (i.e., setting a relatively high price first and lower it over time to capture the consumer surplus) versus a penetration strategy

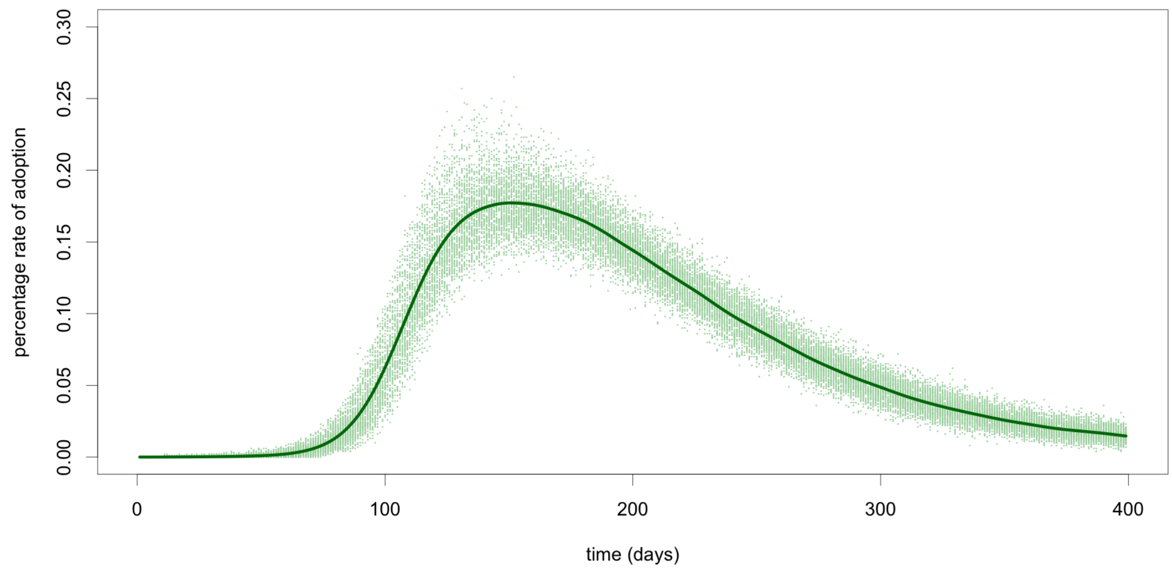

Figure 1: Biofuel adoption curve (line indicates averages, points mark results of single simulation runs)

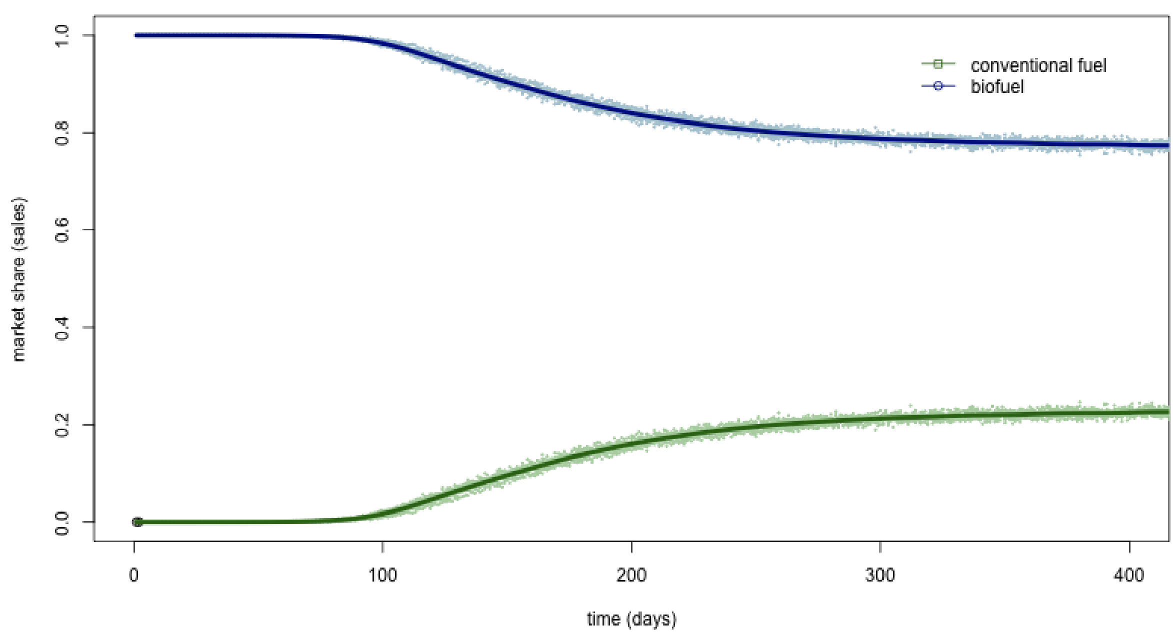

Figure 2: Unit sales volume market share (lines indicate averages, points mark results of single simulation runs)

(i.e., setting a low initial entry price to accelerate the diffusion process) can be easily assessed by means of the simulation.

Furthermore, various energy market scenarios and their impact on the competitiveness of alternative fuels can be simulated while incumbents' potential reactions to the innovation's introduction may also be considered.

4 CONCLUSIONS

In this paper, we have introduced an agent-based model for simulating the diffusion of a second generation biofuel. The model takes into account consumer-related characteristics (e.g., preferences, mobility behavior) and incorporates social interactions that typically play a major role in the propagation of innovations among (potential) consumers. While this can also be achieved by means of other agent-based diffusion models, our approach distinguishes itself by taking into account several product attributes, allowing for the modeling of competitive products and – in addition to the initial purchase decision – also taking repurchases into consideration. These features are particularly worthwhile for our application case. The results of our simulation should be of value for decision makers when planning the market introduction of such a biofuel. For instance, our findings suggest that there should be significant market potential for a high-quality second generation biofuel on the Austrian market even at a comparatively high price.

Further research in the near future will be conducted in two directions. On the one hand, we will put additional effort into properly incorporating the spatial dimension into our model. This is of relevance since production capacity will be quite limited (at least when introducing the biofuel), which makes it necessary to choose the (initial) points of sale (i.e., gas stations) while taking into account both rich sources of biomass and the geographic concentration of consumers. On the other hand, we plan to model various types of promotional activities, which would enable decision makers to simulate the effects of various communication strategies on the diffusion process.

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