International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2013): 6.14 | Impact Factor (2013): 4.438

Agent-Based Modeling for Simulating Eco-Innovation Diffusion: A Review on the case of Green Mobility

Martin Zsifkovits[1]

[1]Universität der Bundeswehr München, Faculty of Informatics, Institute for Operations Research, Werner-Heisenberg-Weg 39, 85577 Neubiberg, Germany

Abstract: ***Modeling the diffusion of eco-innovations is a very challenging task, as there are various influencing factors to consider. The problem gets even more severe when the considered eco-innovation is of high technological complexity and comes along with the need of a supplementary good such as infrastructure. This is the case for alternative mobility concepts such as electric vehicles or hydrogen powered vehicles, where the technology is very innovative and unknown to the consumers and the need of infrastructure leads to a chicken-and-egg problem on the market. In literature various models and methodologies are presented that might tackle this problem. Thereby, Agent-Based modeling turned out to be one of the most promising approaches as it allows for considering various influences on the adoption on a micro level. However, the existing Agent-Based models differ strongly in their architecture and their settings and therefore also differ in their predictive power and their conclusions. For example, several models do not specifically consider the interconnection between consumers and fuel stations operating on the market, hence they ignore the initial chicken-and-egg problem. The technological progress over time is ignored in most of the models, which might also bias their predicting power. The majority of the models does not consider the complex interactions of different market players on the mobility market among each other. Another well-known problem is the pro-innovation bias that is caused by neglecting innovation resistances. This article aims for giving a general overview on the existing models, comparing them and finally identifying the research gap on the field which might lead to new models giving new insights into the diffusion process.***

Keywords: agent-based modeling, simulation, innovation diffusion, hydrogen mobility

1. Introduction

According to Rogers [1,2] innovation diffusion contains four different aspects: (i) the need for an innovation (which might be an idea, practice, or object that is perceived as being new by an individual or another relevant unit of adoption) (ii) that is communicated through certain channels (iii) over time (iv) among the members of a social system. Innovation diffusion is therefore a social phenomenon involving several people making (sometimes independent) choices. These persons do not behave, act, and react mechanically such as molecules, but rather think before acting [3]. Especially in the field of eco-innovations the need for innovation is severe and communicated intensively in society. Therefore, the forecasting of adoption rates is of great interest for decision makers.

However, the traditional mathematical diffusion models allow only a few structural influences to be considered at a time and their need for mathematical solvability may lead to strong assumptions. Furthermore, their aim is solely the reproduction of empirical diffusion processes or optimization and (endogenous) managerial decision-making is not considered [4]. Simulation approaches are able to overcome these shortcomings. For instance, by taking multiple relevant feedback loops on a macro level into account, System Dynamics allows for improving the understanding of involved complex and dynamic structures [4]. Understanding or even predicting adoption rates on a macro level seems less complex than predicting adoption decisions of individual consumers. However, focusing only on the macro view neglects effects that emerge from the micro-level such as social interactions (neighbor effects) or the individual preferences of consumers. Therefore the micro view needs to be considered more deeply in order to understand the mechanism that leads to specific emergent patterns on a macro level [5].

Agent-Based modeling is a bottom-up simulation approach, in which heterogeneous agents interact with each other repetitively and therefore give insight into the outcome on the macro level [6]. For the adoption and diffusion of alternative mobility technologies, agent-based simulation allows for the inclusion and interactions of various market players like consumers, vehicle manufacturers introducing different vehicle technologies, the government, fuel stations and/or fuel producers at the same time. Additionally, the availability of the required complementary good with respect to time and space (e.g. hydrogen fuel, electricity) can be explicitly considered. This might not be of the same importance for all fuel technologies (e.g. bio fuels) as in some cases complementary goods do not play an important role as existing infrastructure can be used (e.g. [7]).

When comparing Agent-Based models on the diffusion of alternative vehicles one can see that literature has to be divided into models dealing with the diffusion of single products, just like alternative vehicles such as electric hybrid vehicles, where the rest of the system (e.g., infrastructure) stays unchanged, and models dealing with the diffusion of vehicles and complementary infrastructure. The reason is that infrastructure models are more complex in the model structure and in general consider more agent types. Therefore the paper at hand is divided into a section of alternative fuel or vehicle diffusion and an alternative mobility market diffusion section, where the alternative market stands for the need of supplementary goods in addition to distributed fuels, such as vehicles or new infrastructure. In the end, the article concludes the major findings from the review conducted and gives implications for future modeling approaches on the topic.

Authors	Consumer	Manufacturer	Vehicle	Government	Fuel Station	Fuel Producer
Stephan and Sullivan, 2004	✗				✗	
Schwoon, 2006	✗	✗			✗	
Schwoon, 2007	✗				✗	
Schwoon, 2008	✗	✗			✗	
Chunjie et al., 2012	✗				✗	
Van der Vooren and Alkemade, 2012	✗		✗		✗	
Shafiei et al., 2013	✗		✗			
Cantono and Silverberg, 2008	✗			✗	✗	
Köhler et al., 2009	✗					
van Vliet et al., 2010	✗					✗
Günther et al., 2011	✗					
Zhang et al., 2011	✗	✗	✗	✗		
Tran, 2012	✗					
Stummer et al., 2015	✗				✗	
Zsifkovits and Günther, 2015	✗	✗		✗	✗	

Table 1: Overview of analyzed models

Table 1 gives an overview of the analyzed models and their considered market players. The analysis shows that only Zhang et al. [10] and Zsifkovits and Günther [21] consider the complexity of several interactions on the market. A further analysis of the articles follows in section two, where the models considering explicitly the technology diffusion of alternative vehicle technologies are described, and section three, that presents overall diffusion models of technologies and complementary infrastructures at once.

2. Technology Diffusion Models

In this section, models are described that concentrate on the diffusion of a technology without considering the shift in the market including updated infrastructure demands or other market adaptions. Thereby the models differ in application cases from technologies without the need of major changes in infrastructure (e.g. [7, 8, 9, 12]) and models where infrastructure changes are not consider in order to reduce complexity (e.g. [10, 11]).

Cantono and Silverberg [8] model the diffusion of eco-innovations, without specifying or defining them. However, based on the model design it can be assumed that also alternative fuels or vehicles can be seen as such eco innovations. The authors created a model, in which consumers have to decide on the adoption of a new technology that was brought to the market. The consumer agents' decision depends on the choice of his neighbors and his own willingness to pay for the new product. This means that the consumer is only willing to purchase if at least one of his neighbors has purchased before (imitation), and his reservation prize is smaller than the market prize, where the market prize can be influenced by the subsidies. The only modeled effect on a macro level is represented by the learning curve of consumers on the market. The study's major finding is that "the introduction of a subsidy policy seems to be highly effective for a given high initial price level only for learning economies in certain range" [8].

Van Vliet et al. [9] designed a supply side diffusion model for alternative fuels, in which they assume that no changes in the infrastructure or vehicles are needed. Thus, the model shows the interactions of fuel producers and motorists. Therefore, two sub-models were created, a supply sub-model and a demand sub-model. In the supply sub-model a progressive series of discrete wheel-to-tank chains of fuel are implemented for modeling the supply options, differentiating between the source location and the different feed stocks (e.g., coal, biomass, crude oil). The decision for or against the production of a special fuel type is only based on the financial rates of return, thus it is a pure economic decision. Costs of fuels are estimated to decrease over time due to learning effects and depletion mechanisms, such as fuel performance increases (e.g., highest possible speed of the vehicle with the used fuel). In the demand sub-model consumers have fixed driving behavior with fixed annually driven distances and are using either gasoline or diesel powered vehicles, were this does not change over the whole simulation. It is expected, that the replacement of vehicles does not change the consumers' attitude in this context. Thus, he always decides either between gasoline and its substitutes or diesel and its substitutes. The decision is based on the costs, emissions and the performance (e.g., speed or acceleration). The interaction between consumer agents is modeled indirectly due to the influence of every consumer's decision on the reputation and popularity of a (alternative) fuel type [9].

Günther et al. [7] created an Agent-Based model to analyze the impact of several marketing strategies on the diffusion process of an innovation. The sample application is the diffusion of a novel biomass fuel, while the introduced model captures social interactions on a micro level in terms of word of mouth as well as marketing activities on a macro level. Consumer agents use all communication channels to increase their information level about offered fuel types. The choice is between conventional fuel and a novel biomass-based fuel. Consumers do consider in their individual utility the price of each fuel type, the information level available about the fuel types, the perceived fuel quality, and the willingness not to purchase the normally purchased fuel. Spatial effects are considered in the model for network effects [7].

Zhang, Gensler and Garcia [10] developed a model, in which the interactions between vehicle manufacturers, consumers and the government were considered. The vehicle manufacturers have to choose between several vehicle variants differing in their design, fuel type, engine power and aluminum content. For modeling-specific reasons they introduced the additional vehicle agent. So the different vehicle types with the varying parameters can be simulated on the market, where consumers purchase based on their individual preferences and the government influences manufacturers and consumers with its policies. Thus, the three mechanisms, technology change, consumer interactions, and regulatory policies on the diffusion process are considered. Technology change here means that the combination of several characteristics can be changed by the manufacturer, depending on the demand on the market [10].

Tran [11] introduced an Agent-Based model to simulate network effects in the diffusion process of green products. The sample-application used in the paper is the market for electric vehicles and hybrid electric vehicles. The model considers only consumer agents that decide on the basis of their individual preferences for several attributes. In the experiments several network settings were tested to test also the difference between direct and indirect network effects. One of the article's major findings is that the influence of the larger population through indirect network effects can have an even larger influence on single consumers' decisions than direct network effects such as word of mouth (WOM) [11].

Stummer et al. [12] model the diffusion of a second generation biofuel and concentrate in their model on three aspects, (i) repeat purchase decisions, rather than only initial adoption of consumer durables, (ii) interactions among multiple products, rather than a fixed market potential for the fuel, and (iii) the spatial dimension of the diffusion. The model is parameterized with empirical data on the case and tests for product launch strategies on the Austrian market. Thereby, several scenarios are analyzed but no optimization of the ideal policy is done.

3. Mobility Market Models

As explained above, the diffusion of several technologies such as hydrogen powered vehicles demands for a change in the infrastructure and therewith comes along with the need of a novel complementary good. This is another challenge for modeling the diffusion process. The models described in this section do consider this effect additionally to other diffusion aspects.

Stephan and Sullivan [13] introduced the first overall Agent-Based model in the field of hydrogen powered mobility. It captures two types of agents, vehicle owners and fuel suppliers. The model's aim is to find the influences of initial distributions of stations in a metropolitan area, in which only short distances are driven by motorists. Initially, some drivers are set up to be hydrogen vehicle drivers, meaning that the chicken-and-egg problem is not tackled in the model at all. The driving behavior depends on some special routes that motorists drive daily, and some random chosen destinations they sometimes travel to. Drivers and fuel station owners both have utility functions they want to maximize. The filling station owner thereby observes the monthly hydrogen fueled traffic around his station and decides to install a hydrogen facility if the weighted sum of vehicles exceeds a threshold. The vehicle drivers' utility function contains his benefit by driving a hydrogen powered vehicle, the distance traveled, the public opinion about the vehicles, fixed costs and the worry about refueling the car [13].

Schwoon [14] implemented an extensive market model to simulate the influence on the diffusion of fuel cell vehicles (FCVs) by several external influences, such as tax policies, the availability of vehicles and their technological conditions, and the availability of fuel on the market. The fuel availability is measured as the percentage of stations offering hydrogen fuel compared to the overall number of stations operating. The problem concerning the infrastructure is considered to be easily solvable through a special taxation policy. In the model consumers decide based on an individual utility function and, to some extent, on imitation behavior. The utility function covers the consumers' preferences relative to the price. Vehicle producers invest in their technologies (CV and FCV) and bring the technology to the market, which promises higher revenues; thus, every producer has only one technology on the market at the same time. Once the alternative technology is produced, the vehicle manufacturer does not consider the possibility of changing the produced technology. Producers act as price setters with limited market power. Filling station owners react to the distribution of new technology on the market, analyzing the total sales of vehicles and increasing the stations offering additional hydrogen fuel if the number of vehicles increases [14].

In a further development of his model, Schwoon pictured the consumers' purchasing decision of FCVs based on the frequency of hydrogen refueling opportunities on long distance trips. In contradiction to prior studies, the initial distribution is not focused on the fast access for all residents but on fast access to potential FCV adopters. Special regions with particular demographics are estimated to be more promising in terms of having potential adopters. These areas should be satisfied with initial infrastructure and small access at first. Nevertheless, sufficient initial distribution of infrastructure also requires enough refueling possibilities along long distances. Based on the German trunk road network, an Agent-Based model was set up. The focus of initial stations is set on cities because these areas are more likely to adopt the new technology. The model considers additionally to the model of Stephan and Sullivan (2004) long distance trips. Here a gravity model considers the possibilities of traveling from one city to another with random probabilities. Drivers start to worry about the refueling starting from a critical distance they have to cover. The vehicle-purchasing decision of consumers is based on the availability of fuel and individual benefits, such as being a technological precursor or showing ecological awareness. Moreover, reduced taxes are estimated for such alternative vehicles. The filling station owners add a hydrogen-pump if there is sufficient demand for it on the market [15].

In another approach based on the initial model from 2006 [14], Schwoon [16] simulated the adoption of fuel cell vehicles based on learning effects in the vehicle production. The underlying experience curve concept is well known in energy system modeling and tries to forecast increasing attractiveness of renewable energies through price reductions. In the model learning by doing (LBD) is characterized by "…work specialization, enhanced methods, new production processes, better performance from production equipment, and changes in the resource mix" [16]. Due to the major limitation of the experience curve concept that costs can fall infinitively, the lower price level is in a side condition assumed to be the price of conventional vehicles. However, problems with the parameterization of the experience curve are also mentioned in the publication [16].

Köhler et al. [17] developed a transition model for sustainable mobility, which is not a classical Agent-Based model but follows in general a hierarchical System Dynamics structure. The model is based on transition theory and shows an environment with two kinds of agents, a small number of complex agents with an internal structure representing a sub-system and a larger number of simple agents. In the model the simple consumer agent supports the complex agents in her geographical vicinity. The complex regimes are representing the dominant transportation technology of internal combustion engine (ICE) and its alternatives, represented by ICE/electric hybrid cars, biofuel cars and fuel cell vehicles (FCVs). The consumers change their location in the geographical area based on their preferences [17].

Based on the case of natural gas vehicles in Shanghai, Chunjie et al. [18] designed a technology/infrastructure diffusion model. The case study's findings were used for parameterizing an Agent-Based model on the topic. The model considers two main actors, the vehicle drivers and the fueling station owners. Vehicle drivers have special driving behavior and check to see if there is the possibility of refueling the car before they decide if they should purchase a CV or a NGV. In the utility function for purchasing one or the other technology, they also consider the fixed (not dependent on mileage) and variable (dependent on mileage) benefit of driving the vehicle type, public opinion about the technology as well as the technology's maturity and security. The fueling station operator decides to offer the alternative fuel based on the needed investment and the operating costs, market demand and her risk attitude. The main finding of the article is that most fueling stations are willing to offer the alternative fuel on frequently traveled routes or central business districts. An additional implication and conclusion is given in the case study [18].

Van der Vooren and Alkemade [19] introduce an Agent-Based model of several low emission vehicle technologies and the competition between them. Here they picture four different agent types in their model, the consumer agent, the vehicle technology agent (vehicle manufacturer), the infrastructure agent (fueling station), and the policy maker agent. Consumers base their decision exclusively on past experiences and have no expectations about the future. Thus, they do not take into consideration consequences of their behavior. They do have individual preferences about several vehicle characteristics, a budget constraint and infrastructure requirements. The authors assume that there are at least a limited number of stations offering the supplementary fuel to the vehicles on the market as soon as a technology is launched. Therefore the chicken-and-egg problem is not tackled in the model. The policy maker has two different mechanisms available to influence the market, a carbon tax on vehicles and a technology-specific support like subsidies on vehicles or the initial infrastructure. The technological parameters of the different vehicle types do change over the simulation runs. Nevertheless, according to the simulation results the diffusion of hydrogen fueled vehicles is not successful. The reason seems to be that the more incremental innovations meet the historically oriented demand of consumers better [19].

Shafiei et al. [20] introduced a model to simulate the diffusion of conventional internal combustion engines (ICEs) and electric vehicles (EVs). Consumer agents in the model decide which technology to purchase based on the vehicle price, fuel consumption, length, acceleration and luggage capacity. The availability of recharging stations is considered as a linearly correlated proportion function to the EVs operating on the market. The greater the number of recharging stations is, the lower the agents' worries are concerning this matter. The model is parameterized with data from a case study from Iceland and pictures several scenarios in which tax and subsidy policies, fuel prices, and electricity prices differ [20]

Zsifkovits and Günther [21] identified the lack of considered barriers to the innovation of hydrogen powered vehicles and therefore created a model that concentrates on the resistances in the consumers' adoption decision. Figure 1 shows the modeled resistances. The resistances are thereby split into functional barriers and psychological barriers, influencing the perceived value (VALUE) of the technology or the real value of total costs (TC) coming with its adoption. All modeled barriers to adoption are thereby based on the uncertainty of real values due to a lack of knowledge or (first-hand) experience. Therefore, the resistances can be tackled via marketing, word-of-mouth communication and first-hand experience. This means, that with an increase of information gained through different channels the uncertainty decreases.

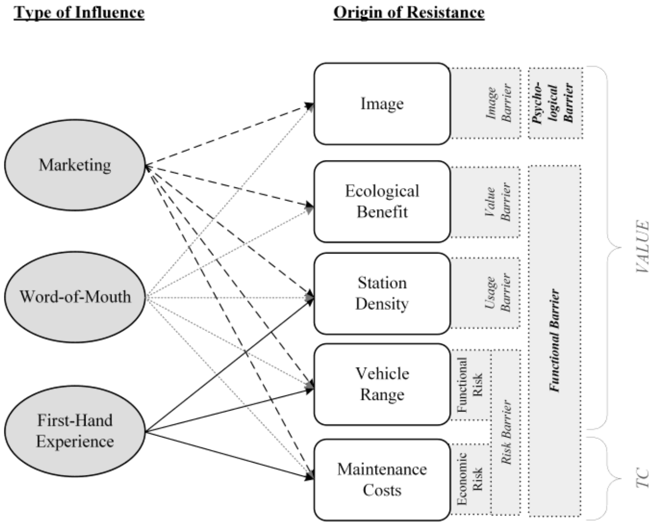

Figure 1: Modeled resistances in [21]

The model generally considers consumers, vehicle manufacturers, fuel station providers and the government as agents and analyses several interactions among them. Another novelty in the model is that technological change in the vehicle technology is considered (such as in [10] but based on progress instead of simple change). Thereby the vehicle manufacturer invests into research and development in order to improve the technology's parameters. In their analysis several public policies including financial subsidies and information campaigning are considered. The main finding is that due to the resistances to adoption only financial incentives are not sufficient for a successful diffusion of the innovation on the market. Also effort is needed in the communication on the market in order to decrease the uncertainties of consumers and therewith overcome barriers to adoption.

4. Conclusion

The analysis of existing models on the diffusion of hydrogen powered vehicles shows that Agent-Based modeling is definitely an adequate approach for modeling the diffusion of eco-innovations in general and alternative mobility in special. It allows for the individual consideration of consumers' preferences and interactions among market players. Based on the case to be considered, models can be kept simpler in the overall structure and the number of considered market players but should be extended to suppliers of complementary goods when technologically needed. However, there is still a research gap in some extends of the existing models. For example, so far no overall market model considering various market players and technological progress of fuel cell vehicles was set up in a real life environment (using a GIS map) with real driving behavior instead of random driving behavior. This might also allow for optimizing the spread of fuel stations in different locations, as it was done in other models without consideration of additional diffusion aspects such as barriers to adoption. Furthermore it is not clear at all if all relevant adoption barriers for the case at hand were modeled so far. This implies the need of an extensive market survey on real behavior on chosen markets. Technological progress over time was already modeled in two cases. However, the progress is based on strong assumptions regarding the technologies' future potentials. Overall, Agent-Based modeling allows for detailed analysis of the field of adoption behavior and diffusion research. The case of hydrogen powered vehicles is well analyzed in various models and is shown to be a promising technological solution for future mobility markets. Existing models are thereby able to support the decision making process strongly. This support might be expanded based on the findings of the article at hand.

References

[1] Rogers EM "New product adoption and diffusion" Journal of Consumer Research, 2, pp.290–300, 1976.
[2] Rogers EM, "Diffusion of innovations" Free Press, Simon & Schuster Inc, New York A., 2003.
[3] Geroski PA, "Models of technology diffusion" Research Policy, 29, pp. 603–625, 2000.
[4] Meier FH, "New product diffusion models in innovationmanagement: a system dynamics perspective" System Dynamics Review, 14(4), pp. 285–308, 1998.
[5] Ostlund LE, "Perceived innovation attributes as predictors of innovations" Journal of Consumer Research, 1, pp. 23–29, 1974.
[6] Garcia R "Uses of Agent-Based Modeling in Innovation/New Product Development Research" The Journal of Product Innovation Management, 22, pp. 380-398, 2005.
[7] Günther M, Stummer C, Wakolbinger LM, Wildpaner M "An agent-based simulation approach for the new product diffusion of a novel biomass fuel" Journal of the Operations Research Society, 62, pp. 12–20, 2011.
[8] Cantono S, Silverberg G "A percolation model of eco-innovation diffusion: the relationship between diffusion, learning economies and subsidies" Technological Forecasting and Social Change, 76(4), pp. 487–496, 2008.
[9] van Vliet O, de Vries B, Faaij A, Turkenburg W, Jager W "Multi-agent simulation of adoption of alternative fuels" Transportation Research Part D, 15, pp. 326–342, 2010.
[10] Zhang T, Gensler S, Garcia R "A study of the diffusion of alternative fuel vehicles: an agent-based modelling approach. Journal of Product Innovation Management, 28, pp. 152–168, 2011.
[11] Tran M "Agent-behavior and network influence on energy innovation diffusion" Communication in Nonlinear Science and Numerical Simulation, 17, pp. 3682–3695, 2012.
[12] Stummer C, Kiesling E, Günther M, Vetschera R "Innovation diffusion of repeat purchase products in a competitive market: an agent-based simulation approach" Euro Journal of Operations Research, 245(1), pp. 157-167, 2015.
[13] Stephan C, Sullivan J "An agent-based hydrogen vehicle/infrastructure model" Contributions to the congress of evolutionary computation, Dearborn, MI, USA, pp. 1774–1779, 2004.
[14] Schwoon M "Simulating the adoption of fuel cell vehicles" Journal of Evolutionary Economics, 16, pp. 435–472, 2006.

[15] Schwoon M “A tool to optimize the initial distribution of hydrogen filling stations” Contributions to the research unit sustainability and global change, Hamburg, Germany, 2007.
[16] Schwoon M “Learning by doing, learning spillovers and the diffusion of fuel cell vehicles” Simulation Modelling Practice and Theory, 16, pp. 1463–1476, 2008.
[17] Köhler J, Whitmarsh L, Nyvkvist B, Schilperoord M “A transitions model for sustainable mobility” Ecological Economics, 68, pp. 2985–2995, 2009.
[18] Chunjie C, Tieju M, Fujin N “Technology/infrastructure diffusion of natural gas vehicles: the case of Shanghai” International Journal of Energy Sector Management, 6, pp. 33–49, 2012.
[19] Van der Vooren A, Alkemade F “Managing the diffusion of low emission vehicles” IEEE Transactions on Engineering Management, 59, pp. 728–740, 2012.
[20] Shafiei E, Stefansson H, Asgeirsson EI, Davidsdottir B, Raberto M “Integrated agent-based and system dynamics modelling for simulation of sustainable mobility” Transportation Review, 33(1), pp. 44–70, 2013.
[21] Zsifkovits, M., Günther, M. “Simulating resistances in innovation diffusion over multiple generations: an agent-based approach for fuel-cell vehicles” Central European Journal of Operations Research, 23, pp. 501-522, 2015.

Author Profile

Martin Zsifkovits received the Master degree in Business Administration and the Ph.D. degree in Economics from the University of Vienna. Currently he is employed as an Assistant Professor at the “Universität der Bundeswehr” in Munich, Germany on the chair of Operations Research. Martin Zsifkovits is Research Director at COMTESSA Munich and specialized on public decision making based on Operations Research.