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.

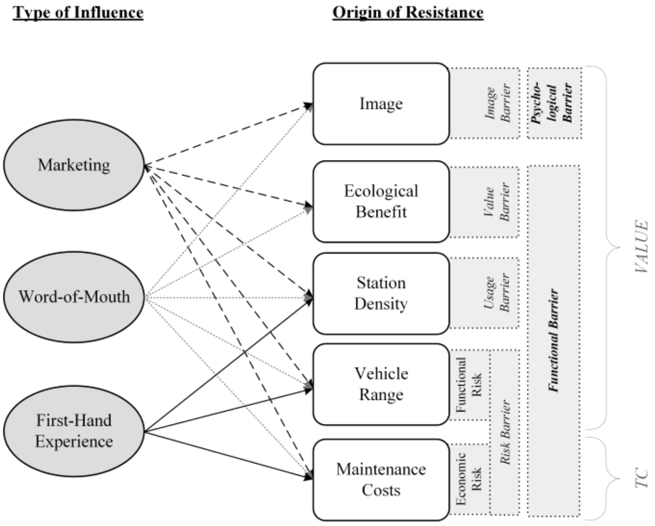

Figure 1: Modeled resistances in [21]

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.

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