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Using empirical data to build an agent-based model of innovation diffusion

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Abstract

There seems to be a wide gap between empirical studies of the acceptance of innovations and the simulation of innovation diffusion. In this paper, an approach to bridge this gap is described that uses specifically surveyed data to build an agent-based model of innovation diffusion for water-use appliances. The empirical data stem from a standardised written questionnaire as well as from telephone interviews. The theoretical background is threefold: Insights from social psychology, innovation diffusion and sociology are combined. The outcomes (mainly derived from structural equation modelling) are implemented into a spatially explicit agent-based model. First simulation results indicate that a close linkage between empirical data and agent-based modelling is a fruitful and promising approach.

1 Introduction

One can distinguish research on innovation diffusion based upon the methodology used. On the one hand there are numerous empirical studies that do not lead to methodologically advanced modelling, and on the other hand, various simulation models have been implemented without recurring to data gathered specifically to inform the model building process.

The empirical studies relate to the acceptance of innovations, especially in IT (information technology) research. At least three approaches can be identified here:

First, the diffusion of innovations via social networks is analysed. Thresholds, critical mass as well as relational and structural connections are used as explanations for innovation diffusion (see Valente, 1995, for an overview).

Second, another set of studies investigate how characteristics of the innovation itself influence the decision to adopt it. In this research, characteristics like the ease of use or the relative advantage of using an innovative product are the independent variables explaining the adoption by individuals.

Third, personal characteristics influence the adoption time of an individual. Rogers (2003) gives a summary.

Various scientific disciplines are involved in these empirical studies. Therefore one can find different methods and theoretical backgrounds in these studies. Most of them focus on one innovation at a time, and only few longitudinal studies have been conducted.

The simulation models found in the literature are implemented on various levels of abstraction:

On the macro-level diffusion models reproduce the S-shaped curve of adoption. The Bass-model (Bass, 1969) and its refinements are derived from the field of epidemics. The coefficients in the model's differential equation are interpreted as the influence of mass-media (external influence) and face-to-face communication (internal influence).

The diffusion in social networks takes place on the meso-level. For each node of an artificially generated network, a utility function is computed. The utility function of a node integrates the behaviour or the opinion of the communication partners of this node into the decision process (e.g. Abrahamson and Rosenkopf, 1996).

Microanalytical simulations aggregate the demand of individuals with regard to some innovative product. They include neoclassical models that assume rational and fully-informed consumers as well as evolutionary models of innovation diffusion that relax some of these assumptions (ground breaking Nelson and Winter, 1982).

Agent-based models of innovation diffusion finally are on the one hand grounded in economics (see Arthur and Lane, 1993, and Weisbuch et al., 1996, for models of information contagion). On the other hand diffusion models are based upon theories of social psychology (e.g. Jager, 2000).

Both empirical research on innovation diffusion and simulation models include a wide variety of variables to explain innovation diffusion, e.g. characteristics of the innovations and of the adopters or communication. The gap between empirical research and simulation models to be noted here is the different level of abstraction: While empirical research has a relatively detailed view on these variables and explicitly analyses specific innovations, simulation models tend to oversimplify matters when treating all innovations as equal and using abstract but highly interpreted variables with only loosely referring to reality.

In the following sections, a PhD-thesis[1] is described which aims at bridging the gap between empirical studies and simulation of innovation diffusion by connecting specific research on innovation characteristics, personal characteristics and situational constraints to agent-based modelling. Its topic is the diffusion of environmental innovations, specifically water-use devices for households.

The PhD-thesis is part of the project GLOWA-Danube. Its aim is to develop a decision support system for the Upper Danube basin to facilitate integrated water resources management under conditions of global change, using scenarios computed by 16 coupled process models from the natural, engineering, and social sciences. The project's geographic area of investigation is sketched in Figure 1. It has an extension of approx. 76,000 km², and about 11 million people are living there. The spatial unit for the data representation and their exchange between the models of the decision support system was defined to be 1 km².

In the context of this project, households' water use and water related perceptions play an important role. Innovation adoption comes into play with regard to the diffusion of innovative water-use technologies. It is the major purpose of the study reported here to simulate innovation diffusion as realistically as possible. The agent-based approach allows for integrating transparent decision algorithms of acting entities. Therefore this methodology has been chosen for building our innovation diffusion model.

[1] As the PhD-thesis is work in progress, only preliminary results are discussed.

Figure 1: The investigation area of the GLOWA-Danube project is the Upper Danube basin. Munich lies in the middle of the area, and in the South it is confined by the Alpine ridge.

In order to build a theory-driven and empirically founded agent-based model, a stepwise approach is used that includes theory-building, gathering specific empirical data for the decision process, and deriving, implementing and validating an agent-based model. Therefore, the text is organised as follows: First the theoretical framework of both the empirical study and the agent-based model will be described. Second, the empirical study concerning water-use innovations will be sketched, followed by an outline of the agent-based model of innovation diffusion. Finally, conclusions will be drawn and an outlook will be given.

2 A theoretical framework for investigating and modelling innovation diffusion

This study combines three theoretical approaches, which will be discussed in the following sections.

2.1 Theory of Planned Behavior

The Theory of Planned Behavior (TOPB) (Ajzen, 1991), which stems from social psychology, serves as a theoretical framework for the work presented here. The TOBP states that the behaviour of an individual is solely determined by his or her intention to perform that behaviour. Attitudes, social norm and perceived behavioural control each influence the intention. Within the TOPB, attitude comprises all emotions and cognitions concerning a behaviour; social norm is the pressure on an individual because his or her peers expect him or her to perform a certain behaviour. Perceived behavioural control is the degree to which a person believes he or she is able to perform a behaviour. This includes financial resources and infrastructure as well as personal capabilities.

The TOPB was applied to innovation diffusion by numerous authors (see Venkatesh et al., 2003, for an overview). It has a broader view as for example the Technology Acceptance Model (TAM). This model (Davis, 1989) is based upon the Theory of Reasoned Action, an earlier version of the TOPB. In the TAM, the perception of ease of use and usefulness influence the intention to adopt an innovation.

2.2 Innovation characteristics

Empirical research of the acceptance of (mainly IT) innovations has led to a set of innovation characteristics influencing a product's adoption. Moore and Benbasat (1991) developed a frequently used instrument to measure such innovation characteristics. Their set of Perceived Characteristics of Innovations (PCI) contains eight innovation characteristics: ease of use, result demonstrability, relative advantage, voluntariness, compatibility, image, visibility and trialability. According to this approach, the decision whether to adopt or refuse an innovation is solely influenced by the perception of these characteristics. In this study, the PCI-scale is adapted and replenished.

2.3 Innovativeness

The innovativeness of a person is another key factor for predicting individual adoption times. Rogers (2003) groups adopters according to their individual time of adoption (and therefore according to their innovativeness) into innovators, early adopters, early majority, late majority, and laggards. These adopter categories differ concerning the socio-economic status, personality values, and communication behaviour.

Grouping people according to their opinions and values is the main purpose of the so-called lifestyles. The concept of lifestyles has been derived by sociologists (a classic: Bourdieu, 1984). It is assumed that – since the second half of the 20th century – social classes (e.g. upper, middle and lower class) no longer provide a useful discrimination, because people with similar socio-demographic background (e.g. income and education) do behave differently according to their attitudes, values, and their general conception of life. Consequently, sociologists have derived new typologies based upon attitudes and values of individuals that complement socio-demographic data.

The study presented here assumes that sociological lifestyles and Rogers' adopter categories match to a certain extent. Lifestyles provide the basis for a typology of agents in our diffusion model.

2.4 The decision process

The TOPB states which variables influence a one-shot behaviour of a person but is not explicit when it comes to the decision process. Nevertheless, the TOPB is used as a blueprint to combine innovation characteristics and social influence. Figure 2 depicts the theoretical framework for the decision process on innovation diffusion.

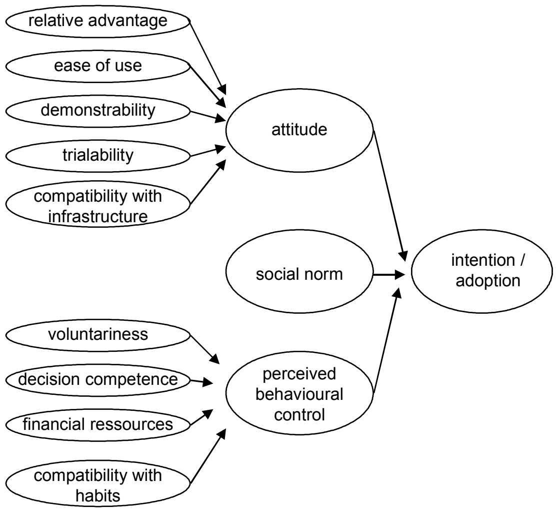

Figure 2: The theoretical framework for the decision process in innovation diffusion for a certain lifestyle. It combines the Theory of Planned Behavior and innovation characteristics.

The relationship is transformed into a decision algorithm which is based upon rational choice. The decision process relies on two factors: On the one hand, the innovations have several characteristics, and on the other hand, these characteristics are of different importance for the individuals. The utility of an innovation is then computed as follows: The importance of a characteristic is multiplied by the value of that characteristic, and all these weighted characteristics are summed up. More on the process oriented extensions to the theory will be described in the modelling section below.

3 An empirical study of the acceptance of water use innovations

To empirically substantiate the decision algorithm, several questions need to be addressed:

1. How are different innovations perceived with respect to their characteristics? [Technically: Which

values shall be implemented as characteristics of the innovations?]

2. Which factors are relevant for acceptance? Are different factors relevant when considering different innovations? [Technically: Which values shall be implemented as weights of importance for the agents?]

3. When and why do people evaluate innovations? [Technically: When shall the decision process be triggered in the model?]

3.1 Development of a questionnaire

In order to answer these questions, a standardised questionnaire as well as telephone interviews are conducted concerning four water-use innovations:

- water-saving shower heads (reducing the water flux per minute for showering),
- rainharvesting systems (using rain water for toilet and washing mashine),
- hydromassage showers (several nozzles spraying in the shower) and
- dual-flush toilets (two keys on the toilet tank easily providing different water quantities).

In the written questionnaire, respondents are asked to evaluate several innovation characteristics. For example, one item concerning the demonstrability of results is: "The results of using a water-saving shower head are apparent to me." Whenever applicable to water-use innovations, the questions in the questionnaire were taken from the PCI-scale of Moore and Benbasat (1991) and translated. Otherwise, own questions were developed and tested.

Furthermore, items concerning general values and attitudes were included in the questionnaire in order to classify respondents according to their lifestyles. The present study uses the instrument of Sinus Sociovision, a leading German marketing company. Sinus Sociovision divides the German population into ten so-called Sinus-Milieus® (www.sociovision.com). Each milieu is described with general values, typical behaviour patterns as well as sociodemographic data. Microm, a marketing company cooperating with Sinus Sociovision, provides spatially explicit data for the Sinus-Milieus in Germany. These data are used for the agent-based model.

A pilot study for testing and refining the standardised, written questionnaire was conducted in July 2005; the main study is carried out in winter 2005/2006.

A small telephone survey using a semi-standardised questionnaire will provide insights of how and when individuals are triggered to evaluate the innovations and give some hints on the functioning of the decision process. This survey will be conducted in spring 2006.

3.2 Data analysis

The mean scores of innovation characteristics in the questionnaire are used as values for the attributes for the corresponding innovation. The results of the pilot study already indicate that there exist statistically significant differences in the perception of the innovations. E.g. respondents rated hydromassage shower lowest concerning result demonstrability, and rainharvesting systems only slightly higher. The results of using dual-flush toilets and water-saving shower heads are perceived as highly demonstrable.

The importance of innovation characteristics as well as attitudes, social norms and perceived behavioural control is computed using structural equation modelling. Structural equation modelling is a statistical method for testing causal models. Usually one begins with specifying a model, which is tested against the empirical evidence. The output consists of data concerning the overall model fit as well as weights for each path that has been specified in the model. In our study, the weights of these paths are interpreted as the relative importance of a variable. To reduce the agent-based model to a reasonable size, only statistically significant variables will be included into the final simulation model. The overall results of the pilot study show that relative advantage, compatibility with habits and ease of use are important for the attitudes. Concerning perceived behavioural control, the variables decision competence and compatibility with infrastructure seem to be relevant.

Furthermore, there is evidence that – for different innovations – attitude, social norm and perceived behavioural control themselves have different weights in the decision process. In case this trend could be confirmed in the main study, then different weights for the innovation characteristics and the variables in the TOPB will be included in the agent-based model. It is a major task of the main study to detect if there are differences between lifestyles as well: It is assumed that people belonging to different lifestyles assess the evaluation criteria differently, e.g. when attributing importance to the price of an innovation. This assumption will be tested with data of the main study.

4 First steps towards an agent-based model of innovation diffusion

4.1 Overview

Based upon the theoretical assumptions sketched above, the agent-based model of innovation diffusion has the following elements:

There are several innovations which have different innovation characteristics.

According to the concept of lifestyles there are different types of agents. Each type of agent has its own preferences with regard to the attributes of an innovation: The agents vary in their perception of the importance of the various variables in the decision process.

The agents are located on a spatial grid that is based on a GIS representation of the Upper Danube region. They are parametrised according to the spatially explicit data for the distribution of Sinus-Milieus. The spatial unit is 1 km² with one agent representing all households of the same Sinus-Milieu on that km². One agent thus stands for a type of household and not for a person. This makes sense because water-use innovations are rather bought once per household and thus the household can be regarded as the natural decision unit.

The agents use a rational choice algorithm based on the TOPB and the relevant innovation characteristics to decide upon the innovations. The decision process is triggered once a (modelled) month. As one agent represents all households of a lifestyle on 1 km², the result of the decision process is not simply a yes or no. The outcomes are rather percentage values of adoption for the innovations (e.g. 76% of all households represented by an agent adopt innovation A).

The agents are linked via a static social network. It is generated using spatial proximity (von Neumann neighbourhood) as well as randomly selected agents further away on the grid. The connecting nodes of an agent's network are determined to a large extend by its lifestyle, because social contacts are mostly made within one's own milieu. Thus, depending on the Sinus-Milieu the agent belongs to, different algorithms are used when generating the network.

4.2 A preliminary model of innovation diffusion

4.2.1 Concept and algorithms

A first version of the model presented here has been implemented for testing and experimenting with the algorithms. It possesses

- two types of agents: Post-Materialists (typical characteristics: young families with middle to high income and modern values) and Traditionals (mostly elderly, conservative women with low income),
- two innovations: standard shower head and water-saving shower head,
- three variables in the decision process, representing each of the three basic variables in the TOPB: environmental impact (attitude), behaviour of peer group (social norm), and price of the innovation (perceived behavioural control).

In the model, 2% of the population decide about buying a new shower head in each time step. The replacement rate is calculated assuming a life span of approx. eight years for a shower head as well as replacement due to removals or buying a new house. Depending on the results of the telephone survey, additional triggers of the decision process will be implemented.

At the moment, the innovations are evaluated as follows: Each agents computes a utility for each innovation:

$$\mathrm{util}_i A = \sum_{n=0}^{m} (\mathrm{imp}_i(n) * \mathrm{char}A(n)), m \in \mathbb{N}$$

with

- $\mathrm{util}_i A$: utility of innovation A as perceived by agent i,
- $\mathrm{imp}_i(n)$: importance of innovation characteristic n for agent i,
- char A (n): innovation-specific value for innovation characteristic n and
- m: number of innovation characteristics.

The percentages for the innovations as adopted by an agent are computed as follows:

$$\mathrm{perc}_i A = \frac{\mathrm{util}_i A}{\mathrm{sumUtil}_i A}$$

with

- $\mathrm{perc}_i A$: fraction of innovation A adopted by agent i and
- $\mathrm{sumUtil}_i A$: sum of utilities of all competing innovations as perceived by agent i.

4.2.2 Implementation

The agent-based model has been implemented using a spatially explicit framework developed for the project GLOWA-Danube. The framework is programmed in Java and described in more detail in Ernst et al. (2005). It comprises of a model class which integrates the agent-based model into the overall decision support system. The main part of the model is the actor class. The agent takes decisions about the choice and instantiation of plans. Specific sensors relating to other agents and the environment lay the ground for the decision algorithms defined by the respective models.

The innovation diffusion model reifies the abstract base classes provided by the framework. The concrete model is called HouseholdModel, the plans of the agents (the HouseholdActors) relate to the adoption of the two different shower heads mentioned above. All agents share the same decision making core, but have different attributes for the importance of environmental issues, price and behaviour of peers. The class is instantiated for each inhabited km² and within each km² for each Sinus-Milieu. Therefore the innovation diffusion model so far consists of 18,230 agents (with 9,115 inhabited km² and two milieus of agents). The agents communicate via their sensors: In each time step, the agents import the percentages of standard and water-saving shower heads of their peers. The preliminary model thus assumes a perfect visibility of an innovation within the agent's social network.

A UML-Diagram of the basic classes of the innovation diffusion model and the underlying framework is given in Figure 3.

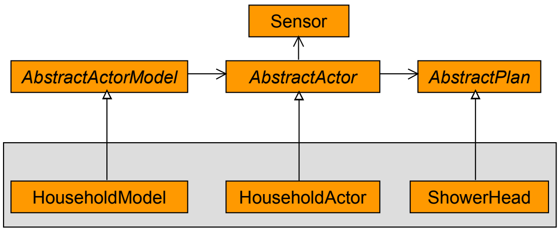

Figure 3: UML diagram of the innovation diffusion model and the underlying framework.

4.3 Simulation results

First simulation runs were computed in order to test the model. Starting values for adoption were 0% for both agent types.

4.3.1 Aggregated results

After 50 simulated years (600 time steps equalling simulated months), in average 95% of Post-Materialist agents possess a water-saving shower head (minimum 83%, maximum 99%, depending on their geographical position).

The pattern of diffusion among Traditionals differs from Post-Materialists. After 50 simulated years, 41% of Traditionals in average have bought a water-saving shower head, but the range is quite large: the minimum for water-saving shower heads among Traditionals is 30% and the maximum 64%.

A plot of the aggregated adoption percentages over time is given in Figure 4.

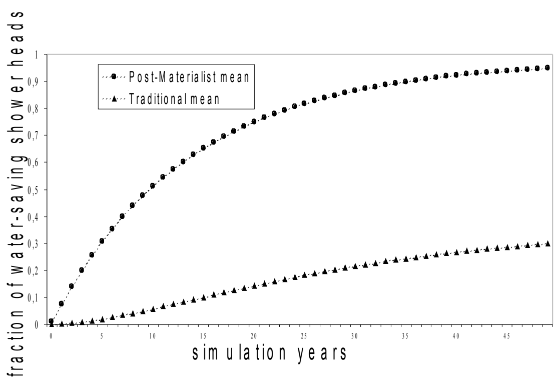

Figure 4: Aggregated results for both Post-Materialist and Traditional agents. The lines show mean percentages of adoption of water-saving shower heads among the respective agents.

4.3.2 Spatially results

Figures 5a to c present first spatially results for both agent milieus.

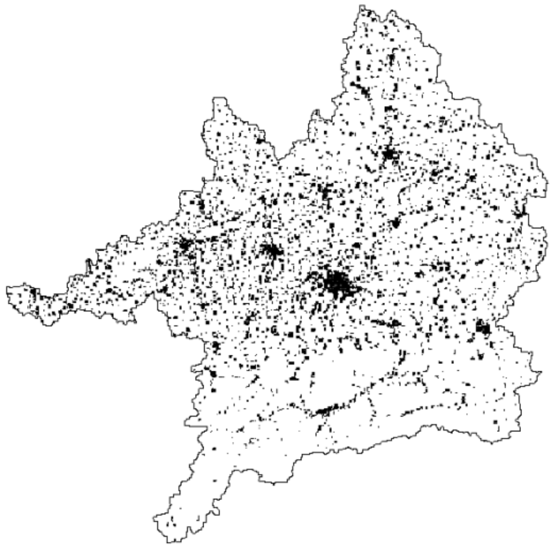

Figure 5a: Spatially explicit results (1 km² spatial resolution) for the diffusion of water-saving shower heads among the Post-Materialist agents (percentage after 50 simulated years).

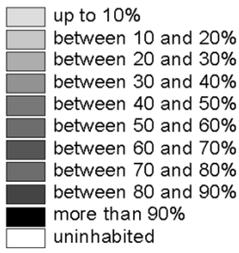

Figure 5b: Legend for spatially explicit results.

Figure 5c: Spatially explicit results (1 km² spatial resolution) for the diffusion of water-saving shower heads among the Traditional agents (percentage after 50 simulated years).

The figures show clearly the population distribution in the Upper Danube basin. One can easily distinguish the bigger cities (like Munich in the middle of the area) and the more sparsely populated areas. Contrasting both maps, one notes that Post-Materialists reach a higher overall level of innovation adoption than the Traditionals, which relates to the graph given in Figure 4.

4.3.3 Discussion

The quick diffusion of water-saving shower heads among Post-Materialist agents is due to the missing social influence for Post-Materialists: It is assumed that for Post-Materialists the behaviour of their peers is not that important when compared to e.g. innovation characteristics. On the other hand, environmental issues are very important for people belonging to this lifestyle. Hence the Post-Materialist agents are innovators or early adopters in this diffusion model and buy water-saving shower heads independently of the behaviour of others.

As environmental issues are not very important for Traditional agents, the diffusion of water-saving shower heads among them is mainly due to the behaviour of peers. Therefore, water-saving shower heads diffuse quite slowly among Traditionals and do not reach saturation within the 50 modelled years.

So far, the diffusion model does not replicate the well-known S-shaped curve of innovation diffusion (Rogers, 2003). Up to now, only two lifestyles are represented, who are supposed to be innovators or early adopters on the one hand and late majority or laggards on the other hand. The S-shaped curve is typically found for whole populations. Therefore, we suppose that the S-shaped curve of innovation diffusion will be approximated when integrating all lifestyles into the diffusion model. Special attention will also be given to the social networks of different lifestyles and their function in the diffusion process.

Furthermore, the influence of model parameters on the diffusion process will be investigated using systematic sensitivity analysis.

5 Conclusions and outlook

The approach introduced in this paper demonstrates that a close linkage between empirical evidence and modelling is feasible, if not necessary. By gathering specific empirical data, it is possible to build a theory-driven and empirically founded model. Agent-based models lend themselves nicely to modelling innovation diffusion according to the desired innovations, because one can explicitly formulate the rules of the decision process.

The agent-based model described above is aimed at simulating diffusion of water-use innovations in a spatially explicit way. It will be extended according to empirical findings in spring 2006 and sensitivity analysis will be conducted. Furthermore empirical data are sought for validation of the model.

During development and testing, the model will be coupled with the other models within the GLOWA-Danube project. In a later stage of the project, it will be investigated in how far the model presented here, which is aimed at modelling the diffusion of water-use technologies, can be extended and generalised to modelling the diffusion of water saving behaviours as well.

Acknowledgements

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