# TOWARDS AN AGENT-BASED MODEL ON CO-DIFFUSION OF TECHNOLOGY AND BEHAVIOR: A REVIEW

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## ABSTRACT

In this paper we propose an agent-based modeling study to assess policy options towards technological interventions to energy consumption behavior, in particular products also known as ‘Transformational Products’. They are novel domestic heating energy efficiency enabling devices, designed to change heating behavior of their users. Innovative behavior can then trigger social learning, i.e. propagation of changed behavior from users to their peers. Arguing that effects of such domestic technology needs to be assessed beyond the household scale, we state the following requirements for a simulation model: it should be an agent-based model considering co-diffusion of behavior and technology. Bottom-up, it should base upon households of certain lifestyles, which are connected in social networks. Model rules should be rooted in socio-psychological theory. Model validation should be feasible. We conduct a literature review on modeling studies, evaluating to which extent these meet these stated requirements, and conclude: (1) an agent-based modeling study meeting all these requirements is not found, suggesting that it does not exist yet; (2) a combination of existing models would meet the stated requirements. A use case for the proposed simulation model for policy makers is enabling strategic decisions by comparing the effects of technology that addresses heating behavior with technology which automizes heating.

## INTRODUCTION

To combat climate change and to deal with the depletion of fossil resources, increased energy-efficiency in heating is urgently needed. Domestic heating may play a key role in the energy transition, as it provides for roughly 28% of energy consumption in the EU-15 (Balaras et al. 2007). Of various possible approaches to decarbonize heating, change in domestic heating behavior is appealing due to its low expected investment costs, its resource-efficiency and broad applicability in the housing sector. The potential for energy savings of households by behavior change of ca. 30% is significant (Peschiera et al. 2010). Additionally, change in heating behavior additionally bears the potential to spread via social learning. In this paper we are exploring ways for assessing the effects of efficiency enabling devices more holistically.

Effects of technological interventions to domestic heating behavior are commonly investigated on the scale of households, which leaves spatial up-scaling to a larger area as an open challenge (Ernst 2014). However, crucial factors to the intervention potential lie beyond the household level: (1) the technology diffusion process (e.g. adoption rates, product market shares, ideally specified for societal groups) between consumers and (2) behavior diffusion, (e.g. innovative behavior stimulated by such devices) which can spread in social networks via social learning. We coin the combination as *co-diffusion of technology and behavior* in socio-technical systems. This emergence of diffusion suggests that investigating efficiency appliances on the household scale is not sufficient. Rather, their impact should be assessed dynamically and on a societal scale.

To realize the energy saving potential of heating efficiency enabling devices, policy options for their diffusion need to be evaluated. Existing knowledge regarding policy impact on diffusion (see Tao Zhang and Nuttall 2011) may be transferred to the co-diffusion of efficiency products and the behavior changed by these. We need to understand co-diffusion of behavior and technology, i.e. heating efficiency enabling devices, and the opportunities for policy to manage that diffusion. In this paper we aim to find out if and which simulation models are suited for this task. Therefore, we review relevant modeling studies.

The structure of this paper is as follows. First, the potential role of heating efficiency enabling devices is described. From this, requirements for a simulation model assessing their potential are derived. Second, a literature search for simulation models meeting these requirements is conducted, starting separately with models on diffusion of energy efficient behavior and efficiency technology. Thereafter, underlying assumptions of the key publications in this realm are examined. Finally, implications for policy makers and stakeholders are given, followed by conclusions and an outlook on further research.

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## THE POTENTIAL ROLE OF HEATING ENERGY EFFICIENCY ENABELING DEVICES

Here, established paradigms of heating efficiency enabling devices are presented, using Transformational Products as a case technology. Finally, requirements for a simulation model assessing their possible effects are derived.

Behavior theory widely accepts the fact that routinized behavior (or 'bad habits') is a key barrier to more sustainable heating practices (Jackson 2005; Jaeger 2003). Transformational Products particularly address 'bad habits' by causing *friction* to create *situative awareness*, which enables the user to make choices where, otherwise, routinized behavior would take place. As a comprehensive example, Laschke et al. (2011) present the 'never hungry caterpillar', a caterpillar-like device that is supposed to be placed next to a TV. If the TV is switched to stand-by, it twists and thus symbolizes discomfort, which creates awareness on the waste of energy. Thus, awareness is created just in time and can immediately be translated into action. Enabling choice can further be combined with 'nudging' (Thaler and Sunstein 2009) towards more sustainable behavior. As soon as the TV is turned off completely, the caterpillar stops and thus stops showing unease. Like this, Transformational Products have the potential to support behavior change by *unfreezing* routines (see Lewin 1951) and to close the gap between consumers' intentions and actions. Afterwards, refreezing new routines is possible, given a sufficient frequency of the new action and strength of reinforcement (Jager 2003). Figure 1 illustrates the functioning of Transformational Products, including the potential of behavior diffusion.

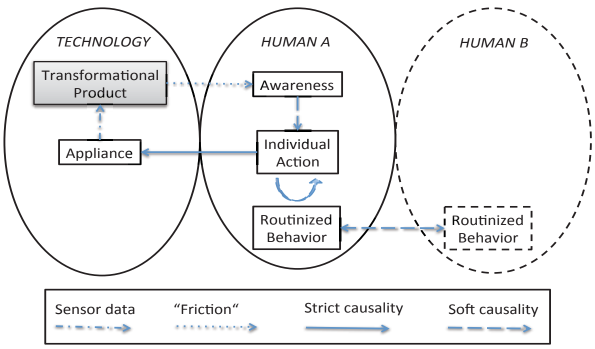


Figure 1: Effects of Transformational Products (partly based on Wood and Newborough 2003, fig. 4)

As the concept of Transformational Products is novel, prototype testing intervening in heating routines is just starting. Results on their energy saving potential are expected for the first quarter in 2015. Again, because Transformational Products address heating behavior, energy savings for adopters can yet be estimated as up to 30% (see Peschiera, Taylor, and Siegel 2010), as for similar interventions.

### Difference from other efficiency enabling devices

Transformational Products are designed to solve the shortcomings of the technological paradigms *automation* and *persuasion by information*.

*Automation* is aimed at ruling out behavioral deficits and making users obsolete, e.g. with programmable thermostats. A drawback is that consumer behavior often interferes with automation systems, e.g. by opening windows while heating. Also rebound effects are a common consequence of automation systems, e.g. programmable thermostats can cause longer heating times and consequently higher energy consumption, compared to manual control (Guerra-Santin and Itard 2010). Finally, automation only works where installed, e.g. heating at home do not benefit from automated heating at work.

*Persuasion by information* emphasizes the pivotal role of users, intending to change their behavior by presentation of information, e.g. via a Smart Meter display. This can include normative comparison to peer consumption (see *Watt's Watts* device at Gulbinas et al. 2014). Persuasion uses the successive steps *monitoring*, *visualization* and *user awareness* (Laschke et al. 2011). Unfortunately, awareness alone does not effectively translate into behavior change – particularly not on the long run (Wood and Newborough 2003). Presumably, this is caused by persistence of routines. Thus, if not addressed repetitively and with the right timing, learning of different heating routines might be of low success (Jager 2003).

Transformational Products attempt to address the drawbacks of both. First, they address consumer behavior instead of eliminating it. Second, they aim at changing behavior routines situatively. Behavior change is therefore likely to be quicker and more persistent. Persistently changed heating routines could thus be more transferable, e.g. beyond the time of product usage and between locations.

### Requirements for Agent-based Modeling of Transformational Products

Because Transformational Products are currently in the prototyping phase, their performance is only observable for small sample sizes of households. Simulation modeling would enable exploring their possible effects already before market launch. Perfectly predicting 'the future' is not the primary focus, because of high uncertainty of future product diffusion at market initialization (Rogers 2010), uncertain future consumer preferences and the complexity of socio-technical interactions. Instead of predicting, a simulation model can be useful for exploring possible futures.

For this purpose, a good choice for exploring emergent system behavior resulting from complex socio-technical interactions is agent-based modeling (Chappin 2011). This is because processes of product diffusion among cognitive agents cannot be solved analytically (Schwarz 2007), and diffusion of technology and changed behavior is an emergent process, which is naturally analyzed bottom-up, based upon the final units of empirical assessment, i.e. in this case households. Furthermore, when giving policy advice with a simulation model, this should consider human behavior (Sopha et al. 2011). To this, an advantage of social simulation to estimate policy effects to technology diffusion is to gain valuable time for decision making. Agent-based modeling in particular has the advantage to explicitly model agents' heterogeneity (Grimm et al. 2006), which can be used to reveal heterogeneous effects of a technology throughout society.

Consequently, we propose analyzing the diffusion of Transformational Products and heating behavior with an agent-based model. The purpose of an according study should be to explore potential future alterations of domestic heating behavior by this technology. Such a simulation model should allow assessing policies supporting the diffusion of Transformational Products. This would enable decision makers to decide on policy as soon as possible. The suggested simulation model should meet the following design requirements: it should be (1) an agent-based model, (2) households should be its focal units of analysis, i.e. its agents, including (3) lifestyles to address the 'up-scaling problem' (see Ernst 2014). (4) It should consider social networks. (5) Assumptions on model rules should explicitly base on acceptable socio psychological theory. (6) Validation should be addressed with respect to the applicability of such models for policy makers to decide on policies to enable Transformational Products to flourish and be effective. Such an analysis would benefit if (7) co-diffusion of technology and behavior as an important underlying mechanism is included.

## EXISTING DIFFUSION MODELS

A literature review is conducted in order to, first, investigate if the here proposed modeling study is novel, i.e. whether an existing agent-based modeling study yet could describe the co-diffusion of both Transformational Products and sustainable heating behavior. The second aim is to guide modeling decisions of future work. Thus, successes and limitations of the reviewed fields are assessed. An additional output of this is identification of suiting approaches for *TAPAS validation, i.e. "tak(ing) a previous model and add(ing) something"* (Frenken 2004; Windrum et al. 2007). With TAPAS validation, existing models can potentially be used as 'ingredients' for building the proposed model.

To find relevant papers, we select publications meeting several of our model requirements. Publications being cited by or citing this set, according to SCOPUS and Google Scholar are first reviewed for closeness to the proposed agent-based model. If this is the case, their undirected citation network is explored, too. The only exception to this is made for reviewing the Consumat framework (see Jager and Janssen 2012), which we do generally, instead of for all its applications.

### Agent-based Modeling Studies

We separately present agent-based modeling studies on diffusion of behavior and technology. Each study is scored to the above stated requirements (see table 1).

*Behavior Diffusion*.
Zhang et al. (2011) model the diffusion of energy saving awareness. The purpose is to compare the potentials of improving technology and behavior. Agents interact in a 'small-world' network, representing social structure in an office building. However, model rules are not transparently stated. Thorough analysis of the provided model code would be needed to get this information. Model calibration and validation bases on (patterns of) quantitative data. Potential shifts in consumer behavior are not dynamically described over time. Furthermore, individual assumptions are debatable, e.g. that e-mail communication is the main pathway of behavior diffusion.

Azar and Menassa (2014; 2010; 2011) model consumer diffusing practices in order to understand changing energy consumption behavior in groups. At their latest work, they apply the of theory of Relative Agreement by expressing agents' energy consumption by its mean and variance. Including the latter is a simple psychologically-based approach to consider strength of habits: the weaker a consumption habit, the greater its variance, the greater the potential for change. Simulations converge against an equilibrium, i.e. modeled behavior freezes eventually. This conflicts with the empirical finding of the frequent relapse pattern of consumers after interventions (see Peschiera, Taylor, and Siegel 2010). The outcomes are not validated against an empirical case.

Chen et al. (2012) model the effect of *peer-feedback devices* on energy efficient behavior in order to understand the influence of social network characteristics on diffusion of behavior in social groups. The model is empirically-based on the case study by Peschiera et al. (2010). Behavior is modeled as 'energy consumption', underlying a drift towards the consumption level of peers. The empirical 'relapse pattern' of increased energy consumption after an intervention is not reproduced by this model which is, according to the authors, due to insufficient mechanistic understanding. The model assumes complete penetration of *peer-persuasion technology* in the social network, which is a best case scenario. Successive market diffusion of technology would have been more realistic.

Anderson et al. (2014) investigate the influence of types of social networks on diffusion of consumer practices in a generic agent-based model. In simulation experiments, the effect of *environmental champions* (change agents) is assessed. Model validation is only conducted structurally. Like at Azar and Menassa

(2014), simulations converge towards a steady state which could be problematic for validation (see above).

We argue that the modeling methods given at Chen et al. (2012), Anderson et al. (2014) and Azar and Menassa (2014) are each particularly suited to be developed further in a TAPAS approach for the above proposed modeling study. Chen et al. (2012), though validated, tailor their model to peer-persuasion technology. Anderson et al. (2014) and Azar and Menassa (2014) both describe behavior diffusion without specific technological interventions in mind. This could make them applicable to a broader range of efficiency technology, including Transformational Products. The latter captures habits, an important element for describing change to repetitive behavior (Jager 2003).

*Technology Diffusion.*

Schwarz (2007) and Schwarz et al. (2009) model the diffusion of domestic water saving technology. The social network is based on lifestyle groups, yet with household agents each representing all households of each lifestyle for each $km^2$. The modeling choices are based on surveys. The degree of aggregation can be seen as appropriate for yet established product innovations and at intermediate stages of diffusion (see Rogers 2010). For initial diffusion however, a smaller resolution could possibly be more appropriate.

Sopha et al. (2013; 2011) investigate the spread of wood pellet heating systems in Norway. Agents are representing 270 households investigated with a survey. Thus, decisions on model structure, calibration and validation are data driven. For translating empirical findings into the model, three clustered lifestyle groups are used. The study adds weight of evidence to the initial assumption that agent-based models on technology diffusion in social networks can have predictive power. However, adoption of wood pellet stoves could be significantly different from adoption of Transformational Products, thus direct transfer may not be justified.

Kroh et al. (2012) model the diffusion of green electricity. Choice of an electric utility is modeled on household level and is linked to lifestyle groups in a spatial social network. Network construction bases on Holzhauer et al. (2013), which leads to higher connectivity within lifestyle groups. The LARA framework, a psychologically based decision model, is applied (Briegel et al. 2014). Regarding transferability to domestic heating efficiency appliances, several barriers show: (1) utility choice may not be sufficiently similar to heating efficiency appliances; (2) until today, methods of this study are only published to limited extent.

Zhang and Nuttal (2007) model the potential futures of Smart Meter diffusion in the UK, applying the 'Theory of Planned Behavior'. The focus of their study is to investigate the effect of management strategies and economic regulations on diffusion success. A suggested agent-based co-diffusion model could at one point be tested for similarity in sensitivity to these policies.

Jager and Janssen (2012) propose the Consumat framework as a meta framework for social simulation. It has been applied in several technology diffusion studies, e.g. for modeling market introduction of green products (Janssen and Jager 2002). The Consumat applications regarding technology diffusion focus on the competition of products (e.g. the diffusion of green products among established grey products). The applicability of this framework seems proven for competing alternative products. It is yet uncertain, however, to which extent it is applicable to novel products like Transformational Products, for which no established market exists. Nevertheless, we acknowledge that the Consumat framework is a highly adaptable meta model. Thus, it could in principle be adapted to model behavior diffusion or to include lifestyles of consumers. However, the downside of this high flexibility is twofold. First, a flexible modeling framework may be too general to a particular problem, which may limit its applicability to co-diffusion of technology and behavior. Furthermore, flexibility comes with a higher number of parameters, which increases empirical work needed for parameterization (see Jager and Janssen 2012). Concluding, the Consumat framework is useful for developing a model on co-diffusion of technology and behavior in the way that it can provide input for the structure of the model, rather than for detailed model parts.

Summarizing, among the reviewed technology diffusion models, the ones presented by Schwarz (2007) and Zhang and Nuttal (2011) appear the most suited to become integrated into a model on co-diffusion of technology and behavior. Others, e.g. the Consumat framework, might serve more indirectly by means of modeling guidance and structural validation.

*Applied Diffusion Theories.*

In this subsection, we discuss socio psychological theory applied in the reviewed studies. Because modeling co-diffusion of technology and behavior should neither build upon conflicting nor arbitrary grounds, it is important to make sound and explicit modeling decisions.

The larger part of the reviewed studies on technology diffusion use the Theory of Planned Behavior (e.g. N. Schwarz and Ernst 2009; Nina Schwarz 2007; Sopha, Klöckner, and Hertwich 2013; Tao Zhang and Nuttall 2007). This is an acceptable choice for modeling technology diffusion (see Tao Zhang and Nuttall 2011). For modeling behavior diffusion, however, we argue that it is not particularly suited. This is because it frames peer interaction as limited to normative pressure and, implicitly, information (Fishbein and Ajzen 2005). However, persistence of habits (see Jackson 2005; Peschiera, Taylor, and Siegel 2010) is not considered.

The reviewed studies on behavior diffusion refer to ‘peer-pressure’, i.e. normative pressure, for justifying model assumptions on behavior diffusion. However, behavioral norms are potentially of lower relevance for domestic heating behavior, because heating takes place in private, which naturally limits opportunities for normative judgment of heating practices. A promising alternative to the restriction to norms is given by Azar and Menassa (2014), capturing the role of habits.

Despite prevailing disputable theoretical foundations, the reviewed behavior diffusion studies yet partly are successfully validated. This could be explained by the existence of socio-psychological theories that justify their modeling decisions: First, Balance Theory states that people prefer consistency not just in their own attitudes, motivations and behaviors, but also in their interpersonal relationships. This implies that consumers change their behavior if it is not ‘in balance’ with their peers. Second, Social Learning Theory states that peers are a source for constant learning, implying that consumers do reproduce their peers’ heating behavior (Jackson 2005). Both behavioral theories are supported by the findings of Peschiera et al. (2010) and, furthermore, justify the reviewed diffusion models. Most importantly, they underscore the relevance of behavior diffusion in social networks. As maybe the only major shortcoming, behavioral relapse after interventions, as observed by Peschiera et al. (2010), is not captured by the reviewed agent-based modeling studies. This could be regarded as a blind spot.

Table 1: Reviewed Modeling Studies Compared to Design Requirements (see text). Signs +, - and ~ Represent ‘meets requirement’, ‘does not meet requirement’ and ‘meets to requirement to some extent’, Respectively

| **Authors** | **ABM** | **Household** | **Lifestyle** | **Social Netw.** | **Theory** | **Validation** | **Co-Diff.** |
|---|---|---|---|---|---|---|---|
| Zhang et al. (2011) | + | - | - | + | +/- | - | - |
| Azar and Menassa (2014; 2010; 2011) | + | - | - | + | +/- | - | - |
| Chen et al. (2012) | + | + | - | + | +/- | + | - |
| Anderson et al. (2014) | + | - | - | + | +/- | - | - |
| Schwarz et al. (2009) | + | + | + | + | + | + | - |
| Sopha et al. (2013) | + | + | + | + | + | + | - |
| Kroh et al. (2012) | + | + | + | + | + | + | - |
| Zhang and Nuttal (2007) | + | + | - | + | + | - | - |
| Jager and Janssen (2012) | + | ~ | ~ | + | + | ~ | ~ |

We draw three conclusions concerning applied diffusion theories. First, we regard Theory of Planned Behavior appropriate for describing technology diffusion. Second, Balance Theory and Social Learning Theory complement and support modeling assumptions on reviewed behavior diffusion models. Third, the concept of behavior relapse should be included into future models of behavior diffusion.

*Conclusions on Reviewed Models.*
None of the reviewed modeling studies meets all of the above stated requirements. In other words, no modeling study inter-linking diffusion of technology and behavior to a co-diffusion is found by this review. This suggests that an agent-based model on co-diffusion of technology and behavior concerning heating energy efficiency might not exist yet. However, modeling studies on diffusion of technology and behavior, which partly meet the stated requirements, do exist (see Table 1). Regarding the stated criteria, in both fields of application, modeling studies can be found which represent households with agents. Lifestyles and social theory are applied to less extent in the modeling studies on diffusions of behavior. Even though none of these modeling studies explicitly represents heating behavior, all refer to energy and resource conservation behavior. Thus, we see potential to apply these to heating behavior.

## DISCUSSION: LESSONS LEARNED FOR BUILDING A DECISION SUPPORT MODEL

So far, we have explored simulation studies and theories that could be used to model effects of Transformational Products on a societal scale. Stressing that a combination of these models could meet all requirements, we are briefly outlining the design of such a joint simulation model. To achieve this, TAPAS validation provides an accepted methodological basis for building a new model on the basis of an existing one. This way, even the validation properties of an initial agent-based models could partially be transferred to a joint model (Frenken 2004; Windrum et al. 2007).

Such a model could contain two modules, which combined could meet all given criteria. First, technology diffusion of Transformational Products could be modeled for instance based upon the technology diffusion model by Schwarz (2007). Second, behavior diffusion could be modeled on the basis of e.g. Azar and Menassa (2014). Finally, a link between these modules would be established. This link would capture the effect of Transformational Products on heating behavior in households.

Even though linking existing agent-based models is possible, we expect it not to be trivial. A challenge will be matching them in degree of aggregation. E.g. scales in existing models differ for aggregation of agents: in most of the reviewed technology diffusion studies these are 'super-households', representing numerous entities. In contrast, behavior diffusion is modeled for individual persons, i.e. small households. A matching scale will have to be found when joining the two fields.

Having outlined a possible agent-based model on the effect of Transformational Products, we are describing how such a model could assist policy makers. Co-diffusion of this technology and the behavior it supports, though being a complex process, structurally is a *diffusion process*. Thus, existing knowledge on policy options to diffusion (see Tao Zhang and Nuttall 2007) can potentially be transferred to it. However, future research has to show if this combined diffusion leads to qualitative difference or if transferability stays intact.

In combination with knowledge on sensitivity of diffusion to policy, the proposed simulation model can be put to use in several ways: first, ideal policy mixes could be identified to manage the diffusion process 'towards' multiple aims, e.g. energy efficiency, social justice (see Chawla and Pollitt 2012) and ease of policy implementation. Second, insight could be gained into possible futures of diffusion of Transformational Products. Third, a simulation model would enable us to suggest empirical research for filling key knowledge gaps. Fourth, the proposed agent-based model would be a theoretical contribution to the understanding of co-diffusion of technology and behavior. These applications can be particularly meaningful when tailored to a case area. Proposed policy mixes can be fitted to local actors and their competences. Potential effects of Transformational Product could be differentiated for district or street level. Finally, case studies would tie links to empirical research and support empirical studies.

In this setting, the proposed agent-based diffusion model would structurally be capable of answering, among others, the following questions: (1) Which market introduction strategy would reach which social groups, e.g. such that are prone to energy vulnerability? (2) Regarding the expected potential of Transformational Products in changing routinized behavior and triggering of behavior diffusion: what is the performance of a marketing strategy of *lending* compared to *owning*? (3) Under which conditions can Transformational Objects, addressing behavior, exceed automatizing appliances, e.g. Smart Meters, in fostering energy efficiency? Though prone to uncertainty, these questions are particularly difficult to asses without a simulation modeling.

## CONCLUSIONS

Technological interventions to domestic heating behavior, e.g. so-called Transformational Products may prove valuable for increasing domestic energy efficiency. We have discussed the literature on agent-based models on diffusion of technology and behavior, respectively, that could describe the effects of Transformational Products in society and the potentials of policy to diffusion governance. Important modeled aspects of agent-based modeling in this respect are diffusion of (1) technology and (2) behavior. Individually, these are well established, but from the various models that have been found, none can directly tackle the co-diffusion of technology and behavior. Nevertheless, they provide ingredients. We conclude that from developing a model for Transformational Products we can expect (1) results that identify a good policy mix to governance the co-diffusion of Transformational Products and sustainable heating behavior, (2) results that enable exploration of possible futures, (3) results that support empirical research in this field, and (4) theoretical contributions to the body of knowledge on co-diffusion. These results become particularly meaningful when applied to a case study, e.g. an urban area.

## FURTHER RESEARCH

Future research should extend the search for exiting co-diffusion models, e.g. to other types of simulation models than agent-based models or beyond application to the energy sector. Furthermore, when developing the proposed simulation model, it should be linked to future empirical research on Transformational Products.

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