ODD+D protocol for agent based simulation model PVact

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1. Overview

1.1. Purpose

1.1.1. What is the purpose of this study?

Cities and regions are dynamical systems involving many different actors in complex relationships. Their development is influenced both exogenously through external factors and endogenously through internal processes. Many approaches to investigate these systems, however, do not recognize the limits of municipal authorities to actively determine infrastructure transformation and fail to represent actors with a direct influence on infrastructure deployment and their decision structures. In order to develop infrastructure successfully, autonomous decisions of property owners need to be integrated with the logic of utilities in order to reduce conflicts in sustainable development of central infrastructure.

In this context, the following agent-based simulation (PVact) has been developed to simulate and explore the diffusion of rooftop photovoltaic systems among Consumer agents in a temporally and spatially explicit manner.

1.1.2. For whom is the model designed?

The underlying goal of the model is to develop relevant decision support structures in order to foster strategy development of municipal utilities with regards to increasing requirements. The model and the connected framework IRPact is aimed at supporting the design and management of municipal and regional transformation processes by utilizing computerized instruments.

The model is intended for researchers in municipal sustainable infrastructure transformation in order to gain insights, explore assumptions and evaluate policy instruments. The evaluation results aim to be useful to policy managers and decision makers in these contexts.

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1.2. Entities, state variables and scales

1.2.1. What kinds of entities are in the model?

Agents in PVact represent households occupying a spatial unit such as a city or a region. For each residential address within the spatial unit, one agent is defined. They are referred to as *consumer agents* in the following. Consumer agents are derived from consumer agent groups (CAGs), which group similar agents; in this case the 10 Sinus® milieus of Germany in 2021. The product of interest are rooftop photovoltaic systems, referred to as *PV* or *product*. However, these don't represent full PV systems, but instead a unit product with a capacity of 1kWhp.

1.2.2. By what attributes (i.e. state variables and parameters) are these entities characterised?

For the technical overview of all parameters, their dimensions and reference values see appendix table 37.

Consumer agents

Consumer agents are characterized by 5 state variables that are dynamically changing throughout the simulation (environmental concern, novelty seeking, uncertainty, interest level and process stage) and a set of 15 parameters. Of these 10 (street address, zip code, owner type, number of households, income, rooftop orientation and inclination, x and y-centroid, initial product adopter) are set directly, whereas 5 (milieu, network size, affinities, rate communicate and rate rewire) are inferred from the CAG.

Product

The product is characterized by 19 parameters. Of these, 4 are parameters that are relevant to initialize the consumer agents (initial product awareness, initial product interest, initial product adopter, number initial product adopter), 3 are relevant in the process model of consumer agents (interest threshold, adoption threshold, financial threshold) and global parameters, and 12 are parameters used to calculate the net-present value (NPV) of a 1kWpeak PV system under different rooftop inclinations and orientations (investment cost, electricity reference price, price increase factor, feed-in tariff, module efficiency, performance ratio, solar irradiation per inclination, adjustment factor per orientation, interest rate, investment horizon, self-consumption ratio and degradation). Of the parameters used to calculate the NPV, solar irradiation per inclination and adjustment factor per orientation are part of the physical model described below. 6 of the 12 parameters are changing per year (investment cost, electricity price, feed-in tariff, module efficiency, performance ratio, interest rate), and one is depending on the spatial unit under consideration (solar irradiation).

Global

The model furthermore employs global parameters that are defined by the user and applied in the modelling procedure across all consumer agents. For the households, construction and renovation rates are integrated. In the process model, consumer agents collect interest points before they begin to evaluate the product. To this end, the parameters adopter influence, interested agent influence and aware agent influence are defined. The relative agreement algorithm ([8]) is used to model opinion dynamics, and requires the following parameters: speed of convergence, attitude gap, chance neutral, chance convergence, chance divergence, extremist rate, moderate uncertainty, extremist uncertainty. To model the passive peer effect, a haversine-based distance filter with a user defined distance (default case 2km) is employed (section 1.2.4). Lastly, weights for the components of the utility function are defined as global parameters - weight NPV, weight social pressure, weight local pressure, weight novelty seeking and weight environmental concern.

1.2.3. What are the exogeneous factors/drivers of the model?

Model variables that can not be influenced by model processes are all global, product and consumer agent parameters. One exemption is the consumer agent parameter owner type, as consumer agents can change owner type to private if they are assigned a construction measure by chance, based on the construction rate.

1.2.4. How is space included in the model?

Spatial data is included through the integration of GIS data. Agents are associated with their addresses and building parameters and are influenced by other agents in spatial proximity. In initialization, agents are assigned to addresses and initial adopters are distributed proportionally to the post codes.

Spatial relationships are utilized to model passive (local) peer effects. For this purpose, a haversine-based distance filter is employed. The haversine distance d (equation 1) between two agents is calculated using the agent's position, consisting of x-centroid (= longitude λ) and y-centroid (= latitude ϕ). Based on the earth's radius r, the distance can be calculated in meters or kilometers.

$$d = 2 * r * \arcsin \sqrt{\frac{1 - \cos(\phi_2 - \phi_1) + \cos\phi_1 \cdot \cos\phi_2 \cdot (1 - \cos(\lambda_2 - \lambda_1))}{2}} \tag{1}$$

The passive peer effect is then applied to agents within a given haversine distance of the principal agent (in the default case 2km).

1.2.5. What are the temporal and spatial resolutions and extents of the model?

PVact draws on georeferenced data for the simulated region including address-specific consumer agent data. Distances between consumer agents can be determined within the model, using the distance metric.

PVact is based on years. Defined in the discrete time model, the time unit of PVact are weeks, and the time units per step are 1, resulting in 52 timesteps per year.

1.3. Process overview and scheduling

1.3.1. What entity does what, and in what order?

Consumer agents move through phases of a process plan over time. The process plan is depicted in Figure 1. Within one timestep, agents behave according to the rules of the respective phase. The agents are synchronized through the framework Jadex and proceed synchronously before the next time step is simulated.

Figure 1: The automatically created process plan guiding agents through the simulation.

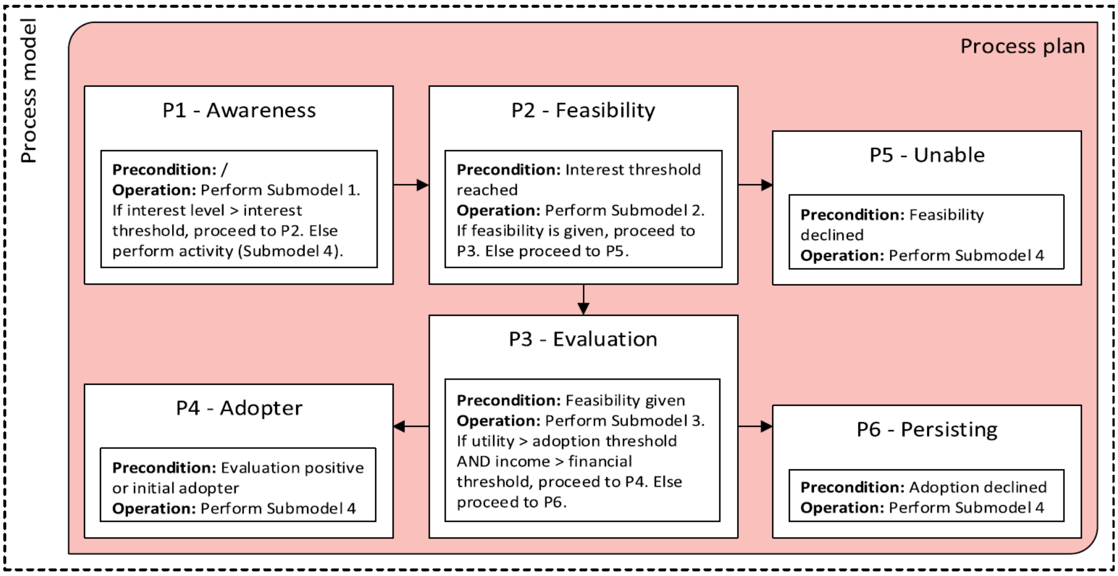
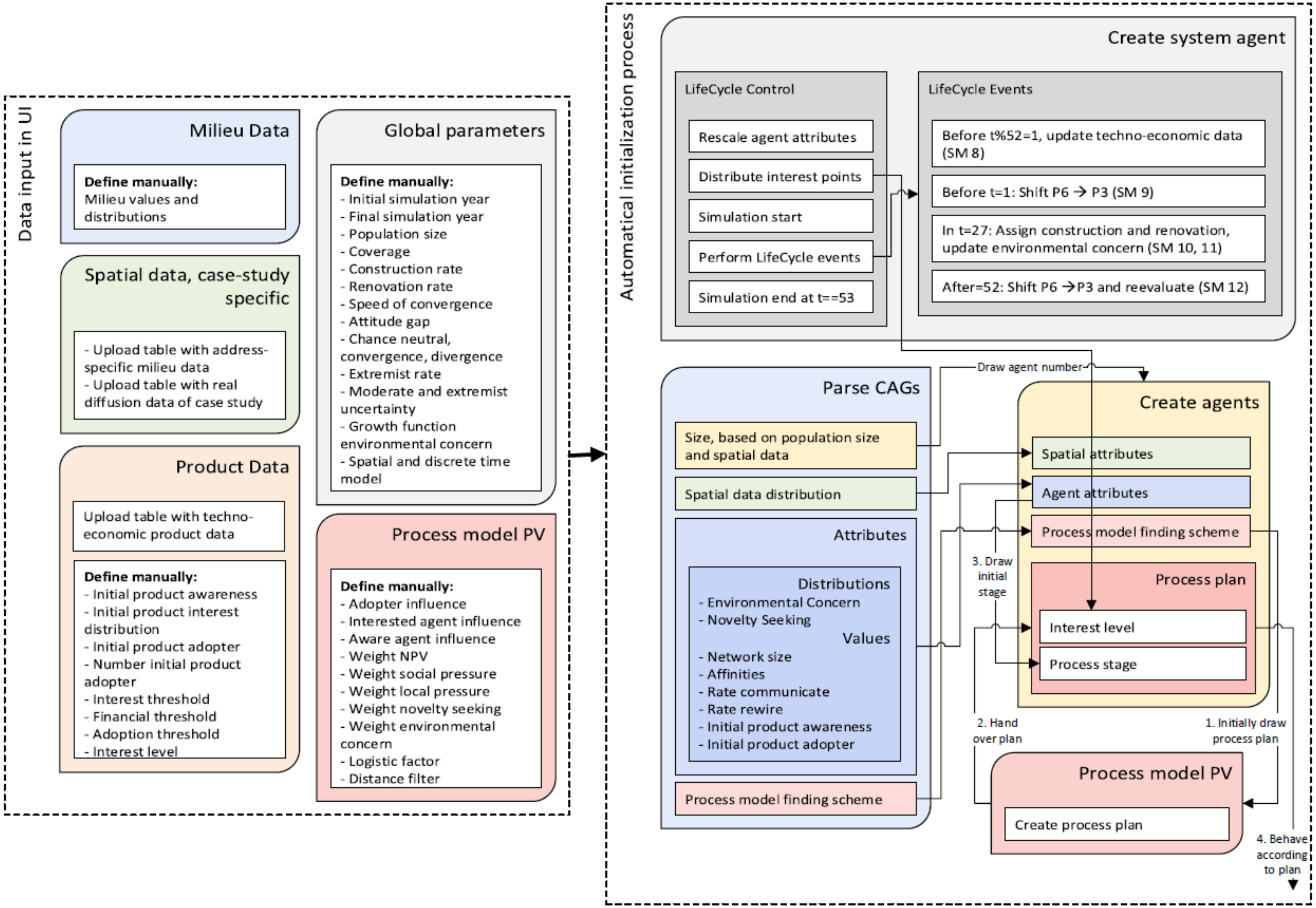


Figure 2: Data input in user interface and automatical initialization process in PVact



Process overview Figure 2 gives an overview of the processes in PVact, including data input in the user interface and the automatical initialization process, in which the system agent, the process model and the consumer agent groups (cags) are created and parsed from the input data, and individual agents are derived from the cags and put in their initial state. In the following, the phases and submodels of the model are described. For a detailed description see section 3.4.2.

- Initialization: system agent and process model are generated, and cags are parsed from the input data. Consumer agents are initialized based on the population size and the pre-defined cags, and allocated to an address. All agents are aware of the product (initial product awareness = 1). Depending on the real-world number of adopters before the initialization year in the modelling region, and the distribution of initial adopters among zip codes in said region, consumer agents are defined as initial adopter. Social networks are defined. Agents begin the simulation in phase 1 (aware) or phase 4 (adopter) of the process plan (see figure 1).
- Begin simulation in t==1
- Phase 1 - Awareness: Perform Submodel 1. If interest level is greater then interest threshold ($int(i) > IT$), proceed to P2. Else perform activity (Submodel 4).
- Phase 2 - Feasibility: Perform Submodel 2. If feasibility is given, proceed to P3. Else proceed to P5.
- Phase 3 - Evaluation: Perform Submodel 3. If utility $\geq$ adoption threshold AND income $\geq$ financial threshold, proceed to P4. Else proceed to P6.
- Phase 4 - Adopter: Perform Submodel 4
- Phase 5 - Unable: Perform Submodel 4
- Phase 6 - Persisting: Perform Submodel 4
- Submodel 1 - Interest test: Comparison of interest level and interest threshold
- Submodel 2 - Feasibility test: Test if owner type = 1 (private) AND households = 1 (single or two family house)
- Submodel 3 - Evaluation: Calculate weighted utility of the product and check against the adoption threshold to check if the agent will adopt

- Submodel 4 - Activity: Stochastic performance of communication based on rate communication (Submodel 5) OR rewire based on rate rewire (Submodel 6) OR no activity (NOP)

- Submodel 5 - Communication: Draw unlocked[1] agent from social network, sense interest level and process stage. Add interest points according to interest level and process stage of other agent. Perform Submodel 7.

- Submodel 6 - Rewire: Delete random edge in social network, add new edge according to affinities

- Submodel 7 - Relative Agreement: Communicating agents both sense environmental concern, novelty seeking and respective uncertainties, update own values according to relative agreement algorithm (see section 3.4.2)

LifeCycle Events

- Submodel 8 - Product development: Before $t_{start\_of\_year}$[2], update techno-economic data of product based on input data (see table 3).

- Submodel 9 - Re-evaluation 1: Before $t_{start\_of\_year}$, shift all agents from P6 to P3

- Submodel 10 - Construction and renovation: In $t_{mid\_of\_year}$[3], assign construction and renovation events to random agents based in the construction and renovation rates

- Submodel 11 - Increase of environmental concern: $t_{mid\_of\_year}$, increase environmental concern of all agents according to pre-defined linear function

- Submodel 12 - Re-evaluation 2: After $t_{end\_of\_year}$[4], shift all selected agents from P6 to P3 and perform Submodel 3

[1]Agents can perform only one action (phase, activity) per timestep. NOP is not defined as activity. Communicating counts as activity for both agents.

[2]$t_{start\_of\_year}$ describes the simulation step at the beginning of each year.

[3]$t_{mid\_of\_year}$ describes the simulation step in the middle of each year.

[4]$t_{end\_of\_year}$ describes the simulation step at the end of each year.

2. Design Concepts

2.1. Theoretical and Empirical Background

2.1.1. Which general concepts, theories or hypotheses are underlying the model's design at the system level or at the level(s) of the submodel(s) (apart from the decision model)? What is the link to the complexity and the purpose of the model?

Following the purpose of the model to simulate the diffusion of residential PV systems temporally and spatially explicitly, the fundamental model design is based on the Diffusion of Innovation Theory [25], and the Theory of Planned Behavior [2]. Model fundaments are developed based on [28]. The model is implemented in the modeling framework IRPact ([14]).

The process plan of PVact reflects the general idea that decision-making is a goal-directed process, whose six phases can vary in length among agents and can reoccur (c.f. [4, 25]). Agents can adopt a PV system only once. Thus, if an agent reaches the adopter phase (P4), it remains in the phase for the rest of the simulation period. This is plausible, given that PV systems are typically utilized for at least 20 years and we assume a modeling horizon of at most 20 years.

Similar to other ABMs [19, 26], agents are assumed to have social networks, communicate and adjust their network from time to time (Submodel 4). In the Diffusion of Innovation Theory, innovations are assumed to diffuse through communication channels over time [25], emphasizing the paramount importance of communication among individuals for innovation diffusion. Consequently, agents require a certain amount of information before an evaluation can take place. This is reflected in the interest level of agents, which increases if an agent communicates. Communication with agents having experience with PV systems increases interest in the product to a larger extent than communication with interested agents or agents that are just aware (Submodel 5). Only if the interest level exceeds the interest threshold, can an agent proceed to P2. It is furthermore widely acknowledged that individuals affect each others opinions, and various researchers have intended to simulate these dynamics (e.g. [7–9]). The Relative Agreement Algorithm by [9] is a solution that has been employed in the realm of agent based models for PV adoption, e.g. by [26] and [19]. Thus, the algorithm and extensions following the recommendations of [7] has been employed in Submodel 7.

Lastly, Submodel 2, performed in P2 is built on the assumption that residential PV adoption is performed by households living in 1-2 family houses owned by the household. This assumption is reflected in numerous surveys, in which the population is defined accordingly (c.f. [20, 31]) and is motivated by the fact that PV adoption requires decision authority about the roof which only building owners have. Model such as tenant electricity are excluded from the model.

2.1.2. On what assumptions is/are the agents' decision model(s) based?

The decision model draws on the fundamental idea that the evaluation of a product is the result of a subjective assessment of its advantages and disadvantages in which the decision-makers "broad dispositions may influence how an innovation is perceived" [33]. Based on the analysis in [28, 29] and the availability of data in the model, the evaluation includes a behavioral barrier, two indicators of social norm and three attitudinal variables, namely environmental concern, novelty seeking and the agent- and time-specific net present value (NPV) of a PV system. A weighted utility function was chosen to represent the individual evaluation based on utility theory. All agents use the same weights, assuming that the decision structure is equal across the population. The weights were derived empirically through a large-scale survey (survey II, N=1799), as described in [27].

In line with the Theory of Planned Behavior [2], the behavioral barrier can impede adoption. Building on the finding of [12] that a low income impedes adoption, agent income is compared to an empirically determined financial threshold (see [27]). The agent only proceeds if household income is above the financial threshold. Social norm, relating to both, social pressure in the social network [1, 15], and the passive peer effect [18, 22, 24] has been found to affect PV adoption. Agents thus sense the total amount of potential and actual adopters in their social and spatial environment. Moreover, the general personal motivations, environmental concern and novelty seeking positively affect PV adoption [3, 32], and are included as two separate components in the utility function. It is assumed that novelty seeking biases agents towards interest, awarding agents a given starting interest based on the strength of their innovativeness. Additionally, an increasing environmental consciousness is assumed in the agent population. Due to this, an agents environmentalism increases (linearly) each simulation year (see section 3.4.2 for more details). Lastly, as the adoption of a PV system is a high-investment decision [17, 23], or can also be seen as an investment with positive financial outcomes [13], the financial outcome for the deciding agent, taking into account rooftop orientation and inclination and the approximate solar irradiation in the investigated spatial unit is calculated, and accounted for in the utility function. The financial outcome is expressed as NPV, as also done in the models of [6, 26], and put in perspective with the average NPV of PV systems across the simulation period based on a logistic function (see section 3.4.2).

2.1.3. Why is/are certain decision model(s) chosen?

A utility function was chosen because it is an adequate tool to account for the multi-faceted considerations individuals make preceding PV adoption. Moreover, it reflects the statistical approach to explain adoption intentions or decisions with linear regression models, as standardized regression weights can be used as component weights to adjust the relevance of the components relative to one another.

2.1.4. If the model/submodel (e.g. the decision model) is based on empirical data, where do the data come from? At which level of aggregation were the data available?

The model is based on and works with different data sources that will be briefly described and illustrated through summarizing tables in the following paragraphs. As an exemplary case the city of Leipzig was chosen; a technical description of these data within this local context is available in the appendix

- Spatial data: appendix section 3.1
- Techno-economic product data: appendix section 3.2
- PV diffusion data: appendix section 3.3

to provide readers with a formatted template suited for PVact. Furthermore, appendix table 37 provides n complete overview of all PVact parameters.

Empirical data

In the model, empirical data is used to characterize agents, determine the financial threshold and component weights in the utility function, and the global parameters construction and renovation rate.

In PVact, agents are drawn from consumer agent groups (CAGs) that are created based on a survey conducted in collaboration with the Sinus® institute, using the German Sinus® Milieus of 2021. Sinus® Milieus describe groups of like-minded people that resemble each other in terms of lifestyle, socio-demographic variables, values and visions [30]. With the means of a large scale survey (survey II, N=1799), the 10 CAGs were characterized regarding the following parameters: environmental concern, novelty seeking, network size, affinities, rate communicate and rate rewire. Whereas the latter four are milieu-specific values, environmental concern and novelty seeking are milieu-specific distributions. Agents of one milieu thus have the same network size, affinities, and communication and rewiring rates, but vary in the expression of environmental concern and novelty seeking, reflecting the milieu-specific distribution of values / time-series. In addition, the distribution of initial adopters across milieus (initial product adopter) is derived from an initial survey (Survey I, N=1165).

Furthermore, the German-wide survey II was used to estimate the financial threshold by comparing the incomes of high-intention respondents (43,464 €/a) with the incomes of low-intention respondents (42,000€/a) with the means of an ANOVA, revealing a highly significant income difference ($p=.001$). Because incomes in the model context Leipzig are 4,636 €/a below the German mean, 38,827 €/a, the central value between low- and high-intention respondents minus the income difference between Leipzig and Germany is used as financial threshold.

Lastly, a linear regression with the five components of the utility function was performed to estimate component weights ($R^2 = 0.3996$). To this end, scales for environmental concern (c.f. [10, 11]), novelty seeking (c.f. [16]), and a financial evaluation, and the amount of previous adopters in the spatial and social environment were regressed on the dependent variable adoption intention. Rescaling the standardized regression weights to sum up to 1 leads to the component weights presented in Table 1.

The annual construction and renovation rate for the federal state of Saxony has been calculated based on data drawn from the platform Destatis[5].

Spatial Data

The model uses spatial data to allocate and further specify agents, using the Sinus® milieus as an interface between empirical and spatial data. To this end, the input data file Datensatz_210322.xlsx was created, containing data for the respective spatial unit (here: Leipzig, Germany) in a predefined structure. Table 2 presents the column names, the respective parameter name, a description and the data source. A formal file description can be found in appendix section 3.1. The final input data set for the city of Leipzig covers 69,64% of all residential addresses in Leipzig and contains 47,731 complete entries.

Techno-economic product data

In PVact, residential PV systems are described in the techno-economic input file Barwertrechner.xlsx. Table 3 presents sheet and column names, the respective parameter name and a description. Information on data sources can be found in the attached input file. A formal file description can be found in appendix section 3.2.

Diffusion data

As the model initially aims to simulate real diffusion data, the diffusion process of privately owned PV systems in the selected region (Leipzig, Germany), had to be reconstructed. The input file PV_Diffusion_L.xlsx

[5] https://www-genesis.destatis.de/genesis/online
[6] https://www.bdew.de/service/daten-und-grafiken/strompreis-fuer-haushalte/
[7] https://www.photovoltaik.org/photovoltaikanlagen/solarmodule/degradation-von-solarmodulen
[8] https://www.solaranlage-ratgeber.de/photovoltaik/photovoltaik-voraussetzungen/standortbedingungen
[9] Fraunhofer ISE, Aktuelle Fakten zur Photovoltaik in Deutschland 26.03.2020, S.8/99
[10] https://www.bdew.de/service/daten-und-grafiken/strompreis-fuer-haushalte/
[11] https://de.statista.com/statistik/daten/studie/152973/umfrage/eeg-umlage-entwicklung-der-strompreise-in-deutschland-seit-2000/
[12] https://de.statista.com/statistik/daten/studie/202295/umfrage/entwicklung-des-zinssatzes-fuer-spareinlagen-in-deutschland/
[13] Fraunhofer ISE 2018, Stromgestehungskosten
[14] Fraunhofer ISE 2020, Aktuelle Fakten zur Photovoltaik in Deutschland
[15] https://www.photovoltaik.org/wissen/performance-ratio

Table 1: Description of empirically determined model variables

Parameter	**Description**	**Values**	**Aggregation level**	**Source**
novelty seeking	agents attitude towards new products	0-1	milieu-specific distribution	survey II
environmental concern	agents attitude towards the environment	0-1	milieu-specific distribution	survey II
network size	number of edges in the social networks of milieu members	11-17	milieu-specific value	survey II
affinity	composition of the social networks of milieu members	0 - 53 %	milieu-specific vector (for each other milieu)	adapted from survey II and [19]
rate rewire	probability to delete and create a new edge in the social network of a milieu member	0.25 - 1 %	milieu-specific value	adapted from [19]
rate communicate	probability of a milieu member to seek an agent in the social network to communicate with	14.5 - 21.6 %	milieu-specific value	survey II
initial product adopter	determines the distribution of initial adopters across milieus	2 - 19 %	milieu-specific value	survey I
financial threshold	adoption is impeded for agents with income below the financial threshold	38827.44 €	municipal (model case Leipzig)	survey II
weight novelty seeking	component weight in the utility function	0.3371	product specific	survey II
weight environmental concern	component weight in the utility function	-0.0997	product specific	survey II
weight finance	component weight in the utility function	0.5934	product specific	survey II
weight social pressure	component weight in the utility function	0.0101	product specific	survey II
weight local pressure	component weight in the utility function	0.1591	product specific	survey II
construction rate	annual construction rate of 1-2 family houses, based on total residential building stock	0.3 - 0.5 %	state-wide (model case Saxony)	Destatis
renovation rate	annual renovation rate of total residential building stock	0.3-0.4 %	state-wide (model case Saxony)	Destatis

Table 2: Description of the input data file Datensatz_210322.xlsx

Column name	Parameter name	Description	Source
ID	id	serial number	
Addresse	address	street and house number	INSPIRE
Zip code	zip code	zip code of the address	INSPIRE
Owner type	owner type	type of owner of the property	Flurstücke der Stadt Leipzig
Private owner	private owner	binary indicator indicator of whether the property is private	
Households	households	number of households registered at address	microm
Small household	small household	binary household indicator whether the household is small ((semi-)detatched house)	
Income	purchasing power	income in €	microm
Milieu	milieu	dominant Sinus® Milieu	microm
Rooftop orientation	rooftop orientation	assumption gabled roof, 90°=North/South, 0°=East/West	LoD2
Rooftop inclination	rooftop inclination	assumption gabled roof, 0°=vertical, 90°=horizontal	LoD2
Area		base area of the building polygon	Gebäudelayer der Stadt Leipzig
X-Centroid	x-centroid	longitude in WGS84	Gebäudelayer der Stadt Leipzig
Y-Centroid	y-centroid	latitude in WGS84	Gebäudelayer der Stadt Leipzig

Table 3: Description of the techno-economic input data file.

Column name	Parameter name	Description	Source
p	price increase	average annual increase in electricity prices between 2006 and 2020	bdew[6]
D	degradation	average annual degradation of PV systems	photovoltaik[7]
SC	self-consumption ratio	average self-consumption ratio	online research
t_{FIT}	investment horizon	calculation horizon, based on 20 years guaranteed feed-in tariff	
Rooftop inclination	rooftop inclination	angle of inclination of a surface, 0°=vertical, 90°=horizontal	
Solar irradiation	solar irradiation per inclination	average annual global radiation in kWh per $6m^2$ area with inclination N at south orientation; calculated based on monthly values of the years 2010-2016 in Leipzig.	
Rooftop orientation	rooftop orientation	orientation of a surface, 90°=North/South orientation (optimal), 0°=East/West orientation	solaranlage-ratgeber[8]
Adjustment factor	adjustment factor	factor for reduction of the amount of radiation by deviation from south orientation	
Year	year	year of calculation	
Investment cost	investment cost	price per kWpeak in €	Fraunhofer[9]
Electricity price	electricity price	electricity price per kWh in €	bdew[10]
Feed-in tariff	feed-in tariff	feed-in tariff for small plant in €	statista[11]
Interest rate	interest rate	interest rate for risk-free savings deposits in Germany	statista[12]
Module efficiency	module efficiency	average efficiency under laboratory conditions (laboratory efficiency)	product information
Performance ratio	performance ratio	factor for reduction of efficiency due to shading, pollution, maintenance, conduction, etc. (real efficiency)	various[13,14,15]

presents both, the running total of new private installations per postal code, and the absolute number of new private installations per postal code for the years 1993 to 2020. Data had been drawn from the Marktstammdatenregister[16], a central registry for all renewable energy production plants in Germany. In the registry, data had been filtered with the following settings: Commissioning date of the unit before 01.01.2021; Energy source equals solar energy; Municipality key equals 14612000[17]; Name of the plant operator (only org.) contains "natürliche Person" (natural person).

Until the end of 2020, 2132 privately owned PV systems have been put into use in Leipzig.

2.2. Individual Decision-Making

2.2.1. What are the subjects and objects of the decision-making? On which level of aggregation is decision-making modelled? Are multiple levels of decision making included?

The subject of decision-making are agents which model the decision unit of a representative household at the residential address. The object of decision-making are the decision for a (non-particular) rooftop photovoltaic system. In the decision process, interested agents first assess whether they have decision power over their rooftop (owner type = 1 (private) and households = 1 (1-2 households)) by checking their owner type and the number of households at their address. Thereafter, they check whether they have the financial capacities to invest in a PV system by comparing their income to the financial threshold. Lastly, they determine their utility of a PV system and test whether the utility exceeds the adoption threshold (see section 3.4.2).

2.2.2. What is the basic rationality behind agent decision-making in the model? Do agents pursue an explicit objective or have other success criteria? How do agents make their decision?

The basic rationality is that agents must have sufficient knowledge of PV systems to be interested, be owners of a 1-2 family house, have enough financial resources to purchase a PV system, and derive a sufficient utility from the PV system to make the decision to invest. Only if they are feasible and have enough income and the utility exceeds the adoption threshold, agents adopt. Agents thus pursue the objective to move through the phases of the process model.

[16] https://www.marktstammdatenregister.de/MaStR

[17] The official municipality key (amtlicher Gemeindeschlüssel, "AGS" for short) is a numerical key assigned to each municipality in Germany to uniquely identify it

2.2.3. Do the agents adapt their behaviour to changing endogenous and exogenous state variables? And if yes, how?

While the rules according to which agents behave do not change over time, a number of endogenous variables used in the decision process change over time and thus affect agent behavior.

First, agents collect interest points when they communicate with interested agents or adopters, raising the interest level quicker or slower in dependence upon the behavior of their social network. Also, each communication event potentially affects an agents environmental concern and novelty seeking through the relative agreement algorithm. Both variables affect the utility agents perceive when investing in a PV system. Moreover, the values of the social and spatial components of the utility function gradually increase, as more potential adopters in the social network and the spatial environment become actual adopters. Furthermore, agents draw annually changing information on the product to calculate the NPV of a PV system on their rooftop, affecting the perceived utility. Attitudes shift based on opinion dynamics and increasing environmental awareness of households. Overall, all five components of the utility function are subject to change over time, resulting in varying utilities over time. Additionally, the social network for the agents is modeled in a dynamic fashion. Agents can engage in new connections (and delete old ones in exchange) and the influence they receive from other agents changes with the status of these agents as well.

Lastly, the exogenous variables renovation and construction rate affect behavior in that they shift agents automatically to the feasibility or the evaluation phase. In the case of construction, the agent attributes owner type and household both change to 1 (private, 1 or 2 households), ensuring that the randomly chosen agent constructs a private 1-2 family house and thus becomes feasible for adoption.

2.2.4. Do social norms or cultural values play a role in the decision-making process?

Social norms play a role in the decision-making process based on active and passive peer pressure. Fundamentally, both social components of the utility function draw on the idea of social norms: the injunctive and the descriptive social norm [21]. Both components moreover account for the variety of social norms across social milieus. On the one hand, social networks are rather homogeneous than heterogeneous in terms of socio-economic status and worldview, with the majority of the social network being from the agents own milieu, and the remainder from "adjacent" milieus. On the other hand, agents are allocated in space according to the actual milieu distribution in the modelled region. Thus, the model considers differences in settlement types and income differences, making some areas more prone to adoption than others.

Cultural values are reflected in the model through the integration of Sinus® Milieus as consumer agent groups and the individual attitudes of their derived agent. For environmental concern, dynamicity is added reflecting increasing environmental consciousnous throughout the population (c.f. [5]).

2.2.5. Do spatial aspects play a role in the decision process?

Spatial aspects play a two-fold role. On the one hand, the simulation takes place in a specific region with specific irradiation values affecting the NPV of PV systems. On the other hand, agents are located in space following real-world data about the spatial distribution Sinus® Milieu in the respective case study. In this way, both structural and socio-demographic differences between neighborhoods can be mapped realistically, and each agent is characterized with realistic building information. Moreover, the spatial component is used through normative pressure based on spatial proximity; for this, the fraction of adopters in a pre-determined radius around the evaluating agent contributes to the overall utility.

2.2.6. Do temporal aspects play a role in the decision process?

Temporal aspects play a role in that the state variable interest level increases over time, the state variable process stage changes over time, and that scheduled events externally affect the process stages of agents. Moreover, the state variables environmental concern and novelty seeking evolve over time (relative agreement), and the average environmental concern increases per year. Lastly, in the financial component, the individual agents NPV is put in relation with the average NPV across the years 2008 to 2019. Thus, agents are assumed to know whether investing in a PV system is relatively feasible compared to the past and the future.

2.3. To which extent and how is uncertainty included in the agents' decision rules?

Uncertainty is not integrated directly in the agents' decision rule. However, the initial distribution of adopters is based on the milieu; furthermore, an agents' uncertainty about their attitudes is used in opinion dynamics.

2.4. Learning

2.4.1. Is individual learning included in the decision process? How do individuals change their decision rules over time as a consequence of their experience?

Learning is not modeled in an explicit fashion. However, interest in PV is built up by communicating with other agents about their experiences, which can be interpreted as a form of learning. Furthermore, agents influence each other based on their attitudes through the relative agreement algorithm (see section 3.4.2) and agents increase in environmental attitude over time, both of which can be interpreted as learning.

2.4.2. Is collective learning implemented in the model?

Collective learning is only included in an indirect fashion through converging attitudes and increasing environmental awareness.

2.5. Individual Sensing

2.5.1. What endogenous and exogenous state variables (of which other individuals) are individuals assumed to sense and consider in their decisions? Is the sensing process erroneous?

Agents are assumed to sense the endogenous state variables interest[18] and adoption state, novelty seeking and environmental concern of agents they communicate with (Submodel 5), and the absolute number of potential and actual adopters in their social and spatial environment during the evaluation of the product (Submodel 3). Moreover, they sense the product parameters to calculate the NPV of a 1kWpeak PV system, and the average NPV of all possible rooftop inclination and orientation combinations over the years 2008-2019 within Submodel 3. Perceptions are not modeled explicitly, agents have perfect information and the sensing process is not erroneous with current assumptions.

2.5.2. What is the spatial scale of sensing?

Sensing is limited to the social network, the spatial environment determined by a radius, and the product information. The scale of sensing thus is context dependent; spatial restrictions for sensing don't technically exist, however.

2.5.3. Are the mechanisms by which agents obtain information modelled explicitly, or are individuals simply assumed to know these variables?

The opinion dynamics between agents in each communication event concerning novelty seeking and environmental concern are modelled instantly and explicitly in Submodel 5. Agents are assumed to simply obtain all other sensed information.

2.5.4. Are the costs for cognition and the costs for gathering information explicitly included in the model?

Agents can perform only one phase per timestep (52 per year). However, they gather information instantaneously and are only restricted in their phase transition and performed actions.

[18]Interest states comprise unaware (not used in PVact), aware (agent is aware of the technology), interested (interest points meet or exceed interest threshold), adopted (agent already adopted the technology). The default option for PVact is awareness and it assumes that every agent is aware of the PV technology option.

2.6. Individual Prediction

2.6.1. Which data do the agents use to predict future conditions?

Agents don't predict future conditions, but assume that the FIT will be guaranteed to be paid for 20 years.

2.6.2. What internal models are agents assumed to use to estimate future conditions or consequences of their decisions?

Agents don't predict consequences.

2.6.3. Might agents be erroneous in the prediction process, and how is it implemented?

Agents don't predict.

2.7. Interaction

2.7.1. Are interactions among agents and entities assumed as direct or indirect?

Interactions among agents in communication events are direct and both-sided (Submodel 5).

2.7.2. On what do the interactions depend?

The interactions depend on the likelihood of communication of the agent and its social network, as agents can only interact with agents that are not locked (agents are locked if they perform an action or a phase transition, or if they are addressed by an other agent. They are not locked if no action (NOP) was performed). The agent to seek communication with is chosen randomly from the social network of the agent at the time of communication.

2.7.3. If the interactions involve communication, how are such communications represented?

Within a communication event, information is exchanged and state variables are updated accordingly (see Submodel 5 in section 3.4.2). This includes the convergence or divergence of attitudes and gathering interest about the product of adoption.

2.7.4. If a coordination network exists, how does it affect the agent behaviour? Is the structure of the network imposed or emergent?

There is no coordination network, all interactions arise from individual behavior.

2.8. Collectives

2.8.1. Do the individuals form or belong to aggregations that affect and are affected by the individuals? Are these aggregations imposed by the modeller or do they emerge during the simulation?

Initially, CAGs, representing Sinus® milieus are imposed by the modeller, and individual agents are derived from them. Additionally, agents have social networks that emerge. Individual social networks are sub-graphs of the social graph of the model. Networks are initialized in the initialization stage according to the agent parameters network size and affinities to every other agent group (milieu). They then evolve during the simulation according to the agent parameter rate rewire. Each agent has its own outgoing edges, forming its own social network. At the same time, agents are targets of edges of other agents, and are thus part of other agents social networks. Networks are directed, and agents can approach other agents for communication only within their own social network. The social environment which is sensed in the evaluation phase includes all agents linked with an edge.

2.8.2. How are collectives represented?

CAGs are represented as collections of agent attribute distributions or scalar parameters. Agents are derived and initialized from these groups (in the case of PVact milieus) and they serve to describe agents belonging to different groups during initialization. Social networks are represented as edges in the social graph.

2.9. Heterogeneity

2.9.1. Are the agents heterogeneous? If yes, which state variables and/or processes differ between the agents?

In PVact, state variables and parameters differ across agents, whereas processes don't differ across agents. Instead, all agents follow the same process plan.

Agents belong to one of 10 CAGs. Across agents within CAGs, the state variables environmental concern and novelty seeking differ, as the individual values are drawn from a milieu-specific truncated normal distribution—. They moreover evolve during the simulation. Additionally, the household parameters income, street, number, zip-code, x- and y coordinates, owner type, rooftop inclination and orientation and households differ across all agents, as each agent is allocated to one address with its' respective data. Across CAGs, but not across agents within one CAG, the agent parameters network size, milieu affinities, likelihood rewire, likelihood communicate and share of initial adopters differ. The state variables interest level and process stage differ across all agents, because each agent moves through the processes at its own pace.

2.9.2. Are the agents heterogeneous in their decision-making? If yes, which decision models or decision objects differ between the agents?

No, all agents follow the same process plan.

2.10. Stochasticity

2.10.1. What processes (including initialization) are modelled by assuming they are random or partly random?

The initial values of the state variables environmental concern and novelty seeking are determined partly at random by a truncated normal distribution pre-determined for each milieu. For each initialized agent, a value is drawn. Also the combination of the initial values of the state variables environmental concern and novelty seeking and the spatial allocation of the agent is partly random (see section 3.2 for more on initialization). The location of an agent is restricted to addresses with the agents' milieu, but selected randomly out of all milieu-addresses. What agents are initial adopters is determined partly random as well. Per postal code, the accumulated number of installations in the year before the simulation starts (number initial product adopter) is distributed among agents in the postal code, using the parameter initial product adopter as weight. Before previous installations are distributed, they are rescaled, considering the coverage of the spatial dataset of the total amount of residential addresses in the modeled region and the number of agents in the simulation.

Edges in social networks are established partly randomly, guided by a pre-determined network size and affinities. For a consumer agent, let cag be its consumer agent group and e_{cag} the corresponding network size. To determine the edges in the social network, a weighted sample is drawn from the consumer agent population without the agent itself (no self-reference). The sample size is equals to the network size e_{cag} and the affinity vector $[a_{cag,cag_j}], j \in$ milieu is used as sampling weights. For example, if $a_{cag,cag_m} = 0.5$, (up to) 50% of the agents in the sample belongs to milieu m. If a milieu does not have enough agents, agents from other milieus are added to the sample instead (based on the weighting). The process attempts to achieve the required network size.

Whether communication takes place within Submodel 4 is determined by a pre-determined likelihood. With whom the agent communicates is determined by the social network and the availability of agents. Whether rewiring takes place within Submodel 4 is determined by (1) whether communication took place (only one action allowed) and (2) a pre-determined likelihood. Which edge is deleted in the social network is random and what consumer agent group a new edge points to is determined by affinities. Which agents renovate or construct is determined by a global likelihood.

2.11. Observation

2.11.1. What data are collected from the ABM for testing, understanding and analyzing it, and how and when are they collected?

In PVact two types of data are collected. First, during the whole simulation an automatically generated event log file is created, whose granularity can be adjusted by the user. This file is mainly used for testing and to verify the correct workflow.

The second type of data is application-specific. The customizability of PVact allows users to observe, collect and store data changes at different stages during the simulation. Users can also decide which parameters are collected. The following analyses can be performed (and respective files created):

- Values at the end of a simulation year (appendix section 3.4)
- Quantile analysis (appendix section 3.7)
- Bucket analysis (appendix section 3.8)

In addition to the customizable data, there is data that is always collected during the simulation made available to the user in processed form. This includes:

- PV adoption data
- Development of interest (appendix section 3.13)
- Process model phase changes (appendix section 3.12)
- Agent communication (appendix section 3.9)
- Social graph (appendix section 3.5)

PV adoption data is processed in various ways. There is a general overview over each adoption event (appendix section 3.6) and two different visualizations. The first compares the annual adoptions of the simulation with the real ones (appendix section 3.10). The second also compares the simulation adoptions with the real ones, but at zip code level (appendix section 3.11).

The collected data can be visualized in the user interface, or made available for download. The default configuration of PVact collects data for all major components of submodel 3.4.2 (environmental concern, novelty seeking, local pressure, social pressure, finance and utility). The table 2.11.1 shows an overview of all created files (and thus collected data) for this configuration.

Table 4: Overview of collected data. Most file names can be specified by the user. The images "X_Quantile.png", "X_Buckets.png" are based on "X_End_Of_Year_Logger.xlsx" and "Annual_Adoptions.png", "Annual_Adoptions_ZIP.png" are based on "Adoption_Overview.xlsx".

File name	How	When	Where
Environmental_Concern_-End_Of_Year_Logger.xlsx	customizable logger	at the end of each year	Download area
Environmental_Concern_Quantile.png	-	-	User interface
Environmental_Concern_Buckets.png	-	-	User interface
Local_Pressure_End_Of_Year_Logger.xlsx	customizable logger	at the end of each year	Download area
Local_Pressure_Quantile.png	-	-	User interface
Local_Pressure_Buckets.png	-	-	User interface
Novelty_Seeking_End_Of_Year_Logger.xlsx	customizable logger	at the end of each year	Download area
Novelty_Seeking_Quantile.png	-	-	User interface
Novelty_Seeking_Buckets.png	-	-	User interface
Fiance_End_Of_Year_Logger.xlsx	customizable logger	at the end of each year	Download area
Fiance_Quantile.png	-	-	User interface
Fiance_Buckets.png	-	-	User interface
Social_Pressure_End_Of_Year_Logger.xlsx	customizable logger	at the end of each year	Download area
Social_Pressure_Quantile.png	-	-	User interface
Social_Pressure_Buckets.png	-	-	User interface
Utility_End_Of_Year_Logger.xlsx	customizable logger	at the end of each year	Download area
Utility_Quantile.png	-	-	User interface
Utility_Buckets.png	-	-	User interface
Communication.xlsx	customizable logger	at each communication event	Download area
Neighbourhood.xlsx	post processing	at the end of the simulation	Download area
Adoption_Overview.xlsx	customizable logger	at each adoption event	Download area
Annual_Adoptions.png	-	-	User interface
Annual_Adoptions_ZIP.png	-	-	User interface
Process_Model_Phases.png	customizable logger	at each phase change event	User interface
Interest_Development.png	fixed logger	at the end of each year	User interface

2.11.2. What key results, outputs or characteristics of the model are emerging from the individuals? (Emergence)

Key result of the simulation model PVact is the zip-code (aggregated) and agent-specific (disaggregated) diffusion over time of the product. It emerges from individual agent behavior and shows the adoption patterns of the agent population.

3. Details

3.1. Implementation Details

3.1.1. How has the model been implemented?

The model was implemented in Java 11 as a command line tool within the agent-based modeling and simulation framework IRPact[19] [14].

3.1.2. Is the model accessible, and if so where?

The implemented model is accessible on github[19].

3.2. Initialisation

3.2.1. What is the initial state of the model world, i.e. at time t = 0 of a simulation run

As mentioned in section 2.10, agents are initialized based on the pre-defined consumer agent groups (milieus) and allocated to an address. All agents are aware of the product (aware stage = 1). Depending on the number of adopters in the initialization year in the modelling region, the number of initial adopters is defined and the agents parameter probability initial adopter is derived for each post code. From this distribution, initial adopters belonging to the respective post code are drawn. Then social networks are defined. Agents begin the simulation in phase 1 (aware) or phase 4 (adopter). The exact parameterization can be found in the as *Reference value* or *Characterstic* in appendix table 37.

3.2.2. Is the initialisation always the same, or is it allowed to vary among simulations?

While the initialisation process is always the same, the initial state of the world (3.2.1) depends on the input configuration and the stochastical rendition derived from it and may differ among simulations. Random variables are derived based on the random seed of the simulation. Idential configurations lead to the same initial state; if the simulation is run in a single process, identical runs with the same seed lead to the same results.

3.2.3. Are the initial values chosen arbitrarily or based on data?

The large majority of values is based on empirical (table 1) or spatial data (table 2), drawn from related literature. Many parameters are specified by random distributions (see *distribution* type parameters in appendix table 37). These are initialized stochastically by drawing from these distributions. Free parameters

[19] `https://github.com/IRPsim/IRPact`

are interest threshold, adoption threshold, logistic factor in financial component, interest points, financial threshold and spatial environment size (local distance), which are set by the modeller according to the investigated scenarios or individual model runs or which can be set through model calibration.

3.3. Input Data

3.3.1. Does the model use input from external sources such as data files or other models to represent processes that change over time?

- Spatial data (appendix section 3.1)
- Techno-economic product data (appendix section 3.2)
- Real adoption data (appendix section 3.3)

Milieu data is used directly in model parameterization and is endogeneous to the model, but sufficiently modular to change.

3.4. Submodels

3.4.1. What are the model parameters, their dimensions and reference values?

An overview over all model parameters can be found in appendix table 37.

3.4.2. What, in detail, are the submodels that represent the processes listed in 'Process overview and scheduling', how were the submodels designed or chosen, and how were they parameterised and then tested?

The processes mentioned in section 1.3 are further described in detail. In general, all submodels were tested on special toy-configurations which encapsulated the appropriate functionalities.

Submodel 1 - Interest test

What: The interest test is performed in the awareness phase (P1). It compares the interest level $int(i)$ of agent i with a global interest threshold IT, which is determined through calibration or used in ensemble tests.

Submodel 2 - Feasibility test

What: The feasibility test is performed in the feasibility phase (P2). It tests whether an agent i has decision power by checking whether it is a homeowner ($ot(i) = 1$) of a 1 or 2 family house ($h(i) = 1$). This was chosen since it was assumed that these agents have decision authority over their roof.

Submodel 3 - Evaluation

What: The evaluation for the product by agent i is performed in the evaluation phase (P3). The result of the decision is a binary adoption value based on comparing if the overall $U(i)$ exceeds the adoption threshold AT. $U(i)$ is the weighted utility of the five partial utility components $U_f(i), U_s(i), U_l(i), U_{ec}(i), U_{ns}(i)$. The values of components differ between agents and change over time, whereas the component weights are similar for all agents and stable over time.

$$U(i) = w_f * U_f(i) + w_s * U_s(i) + w_l * U_l(i) + w_{ec} * U_{ec}(i) + w_{ns} * U_{ns}(i) \tag{2}$$

The partial utilities relate to financial ($U_f(i)$), social ($U_s(i)$), local ($U_l(i)$), environmental ($U_{ec}(i)$) and novelty considerations ($U_{ns}(i)$). The sum of all weights w_f, w_s, w_l, w_{ec}, w_{ns} is 1.

For the environmental and the novelty components, agent i's values of the state variables environmental concern and novelty seeking are drawn.

$$U_{ec}(i) = ec(i) \tag{3}$$

$$U_{ns}(i) = ns(i) \tag{4}$$

with $ec(i)$ being the agents environmental concern and $ns(i)$ the agents novelty seeking.

For the spatial component agent i calculates the relative diffusion of PV systems across potential adopters in a circular environment around it. The distance is determined through the distance filter (max_2) based on the $\text{haversine}_{\text{km}}$ metric.

$$U_l(i) = \frac{\text{Actual adopters}_{spatial}}{\text{Potential adopters}_{spatial}} \tag{5}$$

In this, the potential adopters are all agents with decision authority over their roof (feasible agents) that fall within the spatial radius around the respective agent.

The social component works similar to the spatial component. An agent i calculates the relative diffusion of PV systems across potential adopters in their social environment, including all agents linked with an edge.

$$U_s(i) = \frac{\text{Actual adopters}_{social}}{\text{Potential adopters}_{social}} \tag{6}$$

In this, the potential adopters are all agents with decision authority over their roof (feasible agents) that are part of the social network of the respective agent.

The evaluation of the financial component is the most complicated partial utility and is calculated in several steps. First, the net-present-value of a 1 kWpeak PV system on agent i's rooftop ($NPV(t_0, E(t_0, roof_i(i), roof_o(i))))$ is calculated, using data for the respective year from the input file Barwertrechner.xlsx, and the agent-specific annual yield of the system $E(t_0, roof_i(i), roof_o(i))$.

$$NPV(t_0, E(t_0, roof_i(i), roof_o(i))) = -p_{invest}(t_0) + \sum_{t=0}^{t_{FIT}=20} \frac{(FIT(t_0) * (1 - SC) + p_{elec}(t_0) * (1 + p_{esc})^t * SC * E(t_0, roof_i(i), roof_o(i))}{(1 + r_{int}(t_0))^t} \quad (7)$$

with $-p_{invest}(t_0)$ being the investment cost, $FIT(t_0)$ the feed-in tariff, $p_{elec}(t_0)$ the retail price and $r_{int}(t_0)$ the interest rate in the year of the evaluation, SC the self-consumption ratio, p_{esc} the average annual price increase and t the time.

The annual yield of the system $E(t_0, roof_i(i), roof_o(i))$ is calculated as follows:

$$E(t_0, roof_i(i), roof_o(i)) = solar(roof_i(i)) * adj(roof_o(i)) * \eta(t_0) * (1 - D)^t * pr(t_0) \quad (8)$$

with $solar(roof_i)$ being the annual solar irradiation on 6m^2 on a surface oriented to south with agent i's rooftop inclination $roof_i(i)$, $adj(roof_o(i))$ the adjustment factor for agent i's rooftop orientation $roof_o(i)$, D the annual degradation, and $\eta(t_0)$ the module efficiency and $pr(t_0)$ the performance ratio in the year of the evaluation.

The financial utility $U_f(i)$ is gained by inserting $NPV(t_0, E(t_0, roof_i(i), roof_o(i)))$ in a logistic function to assess the relative feasibility of the system in the unit interval $[0, 1]$. In the first step, the NPV is normalized between 0 and 1.

$$NPV(t_0, E(t_0, roof_i(i), roof_o(i)))_{norm} = \frac{NPV(t_0, E(t_0, roof_i(i), roof_o(i))) - NPV_{min}}{NPV_{max} - NPV_{min}} \quad (9)$$

NPV_{min} and NPV_{max} are the min/max NPV values across the years 2008 to 2019 over all potential combinations of inclinations and orientations. In the next step, $NPV(t_0, E(t_0, roof_i(i), roof_o(i)))_{norm}$ is inserted in a logistic function.

$$NPV(t_0, E(t_0, roof_i(i), roof_o(i)))_{logistic} = \frac{1}{1 + e^{(-1*(NPV(t_0,E(t_0,roof_i(i),roof_o(i)))_{norm}-0.5))}} \quad (10)$$

In the final step, $NPV(t_0, E(t_0, roof_i(i), roof_o(i)))_{logistic}$ is rearranged to $[0, 1]$ as financial utility $U_f(i)$. The rearrangement is necessary, since $NPV(t_0, E(t_0, roof_i(i), roof_o(i)))_{logistic}$ is in $[logistic_0, logistic_1]$ with:

$$logistic_0 = \frac{1}{1 + e^{(-1*(0-0.5))}} = \frac{1}{1 + e^{0.5}} = 0.3775 \quad (11)$$

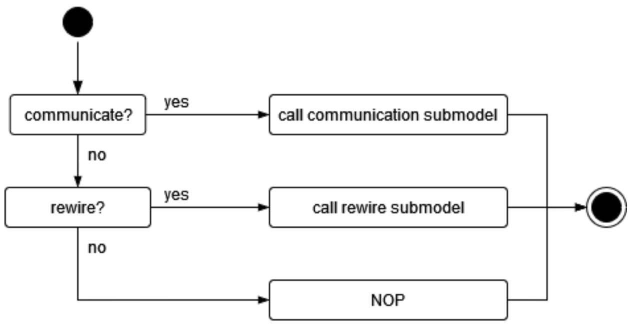
$$logistic_1 = \frac{1}{1 + e^{(-1*(1-0.5))}} = \frac{1}{1 + e^{-0.5}} = 0.6225 \quad (12)$$

$$U_f(i) = \frac{NPV(t_0, E(t_0, roof_i(i), roof_o(i)))_{logistic} - logistic_0}{logistic_1 - logistic_0} \quad (13)$$

$$= \frac{NPV(t_0, E(t_0, roof_i(i), roof_o(i)))_{logistic} - 0.3775}{0.2450} \quad (14)$$

Submodel 4 - Activity

Figure 3: Activity submodel

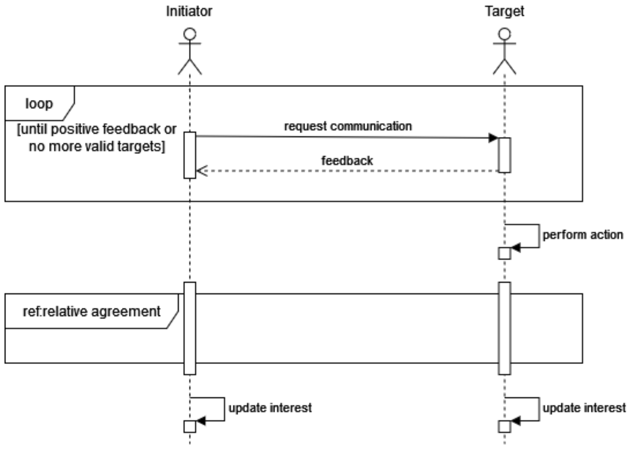


What: The activity submodel is a sequence of actions (other submodels) performed in different process stages. In figure 3 the detailed submodel in PVact is shown. First, it is tested whether communication (submodel 5) should be performed, using the agent parameter rate communicate (r_{com}). If not, rewiring (submodel 6) is tested, using the agent parameter rate rewire (r_{rew}). If both were rejected, no action is performed (NOP). Only the first stochastically chosen activity will be executed.

Submodel 5 - Communication

What: Communication is an activity. The general process is shown in the sequence diagram in figure 4. First, the communication initiator agent i searches for a target within his social network and sends a request

Figure 4: Communication submodel



message. If the target j can still perform an action in this step, it sends a positive feedback. Now the relative agreement submodel is called for both agents i and j and interest points are added according to the phase of the opposing agent (adopter influence ai = (P4), interested agent influence iai = (P5, P6), and aware agent influence aai = (P1)). If the agent already acted in this time step, a negative feedback is returned and the initiator i searches for another agent. This process is repeated until a valid communication partner is found or the network is exhausted.

Participating in communication counts as activity for both agents. Consequently, the (passive) communication partner can no longer perform any action in this time step.

Submodel 6 - Rewire

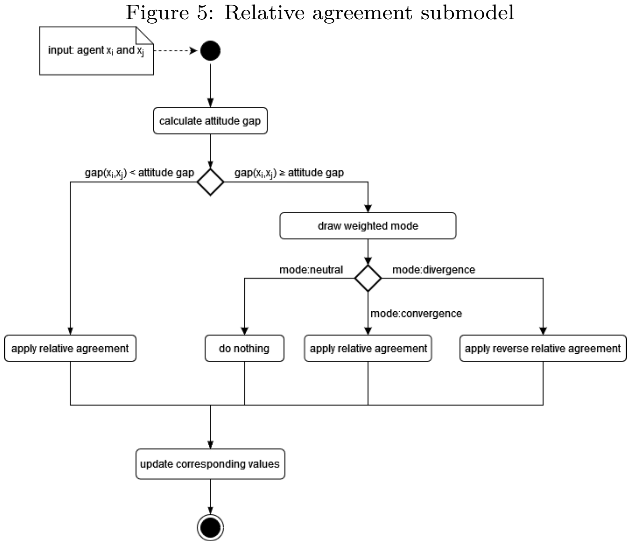
What: Rewiring is an activity and a two-step action. First agent i removes an existing edge in his social network. In the second step a new random communication edge is added. The target node is a random node of the target milieu not connected to the agent yet. The respective milieu is determined by the milieu-specific affinities.

Submodel 7 - Relative Agreement

What: The relative agreement algorithm is applied to model opinion dynamics concerning the state variables environmental concern and novelty seeking. An overview of the relative agreement submodel is shown in figure 5. The submodel is performed independently for the communicating agents values of environmental concern and novelty seeking.

In the following, the algorithm is described using the terms opinion opi_i and opi_j for the communicating agents i and j's values on the state variables environmental concern and novelty seeking, and unc_i and unc_j

Figure 5: Relative agreement submodel



for the respective uncertainty.

In the algorithm, the communicating agent's opinions opi_i and opi_j and the respective uncertainties unc_i and unc_j are used to update the opinions. Afterwards, the uncertainties are updated.

First, the attitude gap $ag_{i,j}$ between the communication partners i and j is calculated.

$$ag_{i,j} = |opi_i - opi_j| \tag{15}$$

If the attitude gap $ag_{i,j}$ is smaller then the attitude gap threshold AGT ($ag_{i,j} < AGT$), the standard relative agreement algorithm is applied. Otherwise, a weighted mode is selected. In the neutral case ($c_{neut} = 0.5$), nothing is changed. In the convergence case ($c_{con} = 0.25$), the standard relative agreement algorithm is applied. In the divergence case ($c_{div} = 0.25$), the reverse relative agreement is applied and agent i's and agent j's values move further apart.

The relative agreement algorithm works as follows:

The overlap ($h_{i,j}$) of agent i's and agent j's opinions is defined as

$$h_{i,j} = \min(opi_i + unc_i, opi_j + unc_j) - \max(opi_i - unc_i, opi_j - unc_j) \tag{16}$$

The non-overlapped width of the opinion of agent i influencing agent j is defined as

$$2\,unc_i - h_{ij} \tag{17}$$

With the overlap $h_{i,j}$, the agreement $agree_{i,j}$ of the agents can be calculated for both agents:

$$agree_{i,j} = h_{i,j} - (2\,unc_i - h_{ij}) = 2(h_{ij} - unc_i) \tag{18}$$

Then, the relative agreement $ragree_{i,j}$ is

$$ragree_{i,j} = \frac{2(h_{ij} - unc_i)}{2\,unc_i} = \frac{h_{ij}}{unc_i} - 1 \tag{19}$$

Only if $h_{i,j} > unc_i$, the update of opi_j is

$$opi_j = \begin{cases} opi_j + \nu \left(\frac{h_{ij}}{unc_i} - 1\right)(opi_i - opi_j) & \text{— standard case} \\ opi_j - \nu \left(\frac{h_{ij}}{unc_i} - 1\right)(opi_i - opi_j) & \text{— reverse case} \end{cases} \tag{20}$$

and the update of unc_j is

$$unc_j = \begin{cases} unc_j + \nu \left(\frac{h_{ij}}{unc_i} - 1\right)(unc_i - unc_j) & \text{— standard case} \\ unc_j - \nu \left(\frac{h_{ij}}{unc_i} - 1\right)(unc_i - unc_j) & \text{— reverse case} \end{cases} \tag{21}$$

Otherwise, opinions remain stable.

After the opinion update, the agents both sense whether they belong to the most extreme agents (defined through the extremist rate r_{ext} as the 6,25% agents with the lowest, and 6,25% with the highest opinion). If they belong to the group of extremists, their uncertainty is defined by unc_{ext}. Otherwise, their uncertainty is unc_{mod}.

Submodel 8 - Product development

What: In the model, the techno-economic development of PV systems is accounted for. To this end, the input table 3 for techno-economic data is used to update product parameters at the beginning of each year.

Submodel 9 - Re-evaluation 1

What: In the first timestep of each year, all agents who are in the persisting phase (P6), i.e. that they have evaluated the product negatively at previous times, are forced to re-evaluate the product (P3). The submodel had been integrated for analytical reasons: A positive decision in the first timestep can be explained with the new techno-economic data, as the same group of agents was forced to re-evaluate as well after $t_{end\_of\_year}$ (submodel 12). This reflects a change of opinion based on changed information on the product involved.

Submodel 10 - Construction and renovation

What: Since households frequently discuss different building adaptation options during building construction or renovation, these events are seen as a trigger for PV adoption decisions. In PVact, non-adopting agents are selected randomly for these events based on the r^{year}_{const} and r^{year}_{reno} parameters that correspond to (state-level) construction and renovation rates. In the time step $t_{mid\_of\_year}$, agents are randomly selected to construct or renovate according to these rates. If construction is assigned, owner type and household are updated to 1 to guarantee feasibility. If renovation is assigned, the agents' interest level is updated to the interest threshold to guarantee interest and foster the decision process.

Submodel 11 - Increase of environmental concern

What: In Germany, a general trend of increasing environmental concern could be observed over the last decades. This development is accounted for in PVact. In $t_{mid\_of\_year}$, the state variable environmental concern of all household agents is updated according to the following rules.

The overall increase of environmental concern in Germany [5] follows the linear function

$$y = 0.006 * x - 11.46 \tag{22}$$

In the initialization, each agents EC_{init1} is rescaled with

$$ec^{init}(i) = ec_{parameter}(i) * t_n * 0.994 \tag{23}$$

to $ec^{init}(i)$, which is the value the agent starts the simulation with.

Within the simulation, at $t_{mid\_of\_year}$, $EC_{t_{mid\_of\_year},old}(i)$ is updated with

$$EC_{t_{mid\_of\_year},new}(i) = EC_{t_{mid\_of\_year},old} * 1.006 \tag{24}$$

to $EC_{t_{mid\_of\_year},new}$.

Submodel 12 - Re-evaluation 2

What: After the last timestep of each year, all agents who are in the persisting phase (P6) are forced to re-evaluate the product (P3). Being in this phase means that agents have evaluated the product at least once at an earlier time, but its utility was below the threshold. The submodel was integrated for analytical reasons: A positive decision after the last timestep can be explained with changes in the agents environmental concern, novelty seeking, or the local or social component.

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