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Spatial Agent-Based Modelling and Simulation to Evaluate on Public Policies for Energy Transition

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Abstract. The manuscript describes the development of a spatial Agent-based Simulation to model the effect of public policies on private houseowner's decisions concerning their heating system. The methodology utilized comprises of an empirical survey to determine the (location-based) behavior and motivation of homeowners. In addition, spatial data on the houses can be used to implement renovation and thermal refurbishment in the simulation. In addition, the system is able to model and simulation the effect of public policies on the actions of homeowners. Hence, based on their decisions the system can estimate the carbon footprint of the houses over the simulation period. Hence, decision makers can select the best policy (e.g. funding, motivation) to reduce the carbon footprint of communities.

Keywords: Agent-Based Modeling, Geoinformatics, Actor Decisions

1. Introduction and Motivaton

Our energy system is undergoing rapid change. New technologies and opportunities such as electromobility, digitization, energy communities or low-temperature heating networks are entering the market, which must be reconciled with societal demands for greater sustainability and political commitments such as the Austrian heating strategy with the goal of decarbonizing the heat supply for buildings by 2040. This poses a high level of complexity for decision-makers in politics, energy supply and business.

An energy-efficient and climate-friendly heat supply of the future now requires planned action, the modernization of the existing building stock, a sustainable orientation of new buildings, and the conversion of the heating and cooling supply to renewable energy sources. Not only will infrastructure and technology change, but the use of buildings will also be transformed by digitalization, and administrative as well as planning processes must do justice to this system complexity. In addition to the spatial dimension of energy supply and demand, increasing importance must also be attached to the social dimension of the energy transition in planning and decision-making processes. The behavior and decision-making patterns of central actors (politics, public administration, planners, investors, energy supply companies, population), each with their own specific roles, needs and values, are highly relevant to planning in the context of heat and energy transition, but are, if at all, hardly considered in current processes.

This combination and integration will be addressed in the project ABM4EnergyTransition complementing existing (spatial) planning approaches and spatial Agent-based Modelling (ABM) approaches (see Figure 1). Classical modelling and planning approaches of the heating and energy transition primarily focus on the techno-economic aspects of energy demand and provision. In doing so, they not only neglect the spatial dimension, but also complex interactions between technology, business and politics and their influence on the decision-making behavior of key players in our energy system. Agent-based modelling and simulation (ABMS) is an ideal tool to make such complex interactions understandable from the bottom up and in a spatial context [1, 2]. Using ABM, different actors in a system can interact with each other and with their environment as autonomous agents, each with different properties, differentiated decision-making behavior and the ability to learn. This makes ABM particularly useful when considering and analyzing complex, multilevel problems with very heterogeneous influencing factors, as represented by an energy system. ABMs are widely used to simulate social, economic and environmental problems [3, 4]. More recently, ABM has also been used increasingly in the field of energy transition research, in particular with a focus on the electricity sector [5] or to investigate the dynamics in the development of the building stock [6, 7].

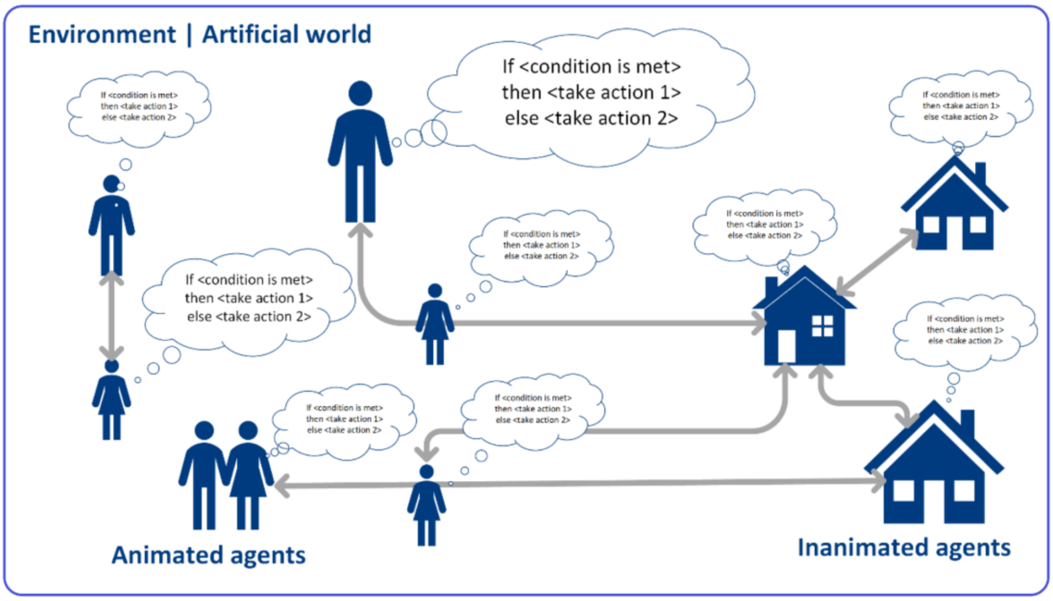

***Figure 1**: Schematic structure of an ABM, which consists of an environment and the agents acting in it and their interactions. Adapted from [1].*

The objective of ABM4EnergyTransition is the development and demonstration of a novel simulation approach based on ABM for the spatial analysis and assessment of pathways for the municipal heat and energy transition. The ABM methodology considers both spatial information to describe the energy system of a study area (buildings, grid-based energy infrastructure such as natural gas or district heating networks, renewable potentials, population structure) and parameters to describe the behavior of actors (agents), like homeowners, investors, or policy makers. In addition, the simulation system considers demographic and socio-technical parameters such as income and state of education. The methodological approach represents an extension of existing energy planning approaches and helps to better assess the impact of public policies on the achievement of climate and energy goals. The methodology of the project is of an interdisciplinary character, and involves Spatial Analysis, Spatial ABM and Simulation, Energy Planning, as well as Software Engineering and a Social-technical empirical approach. Based on a large survey that was sent out to households in the Province of

Styria (Austria), we are able to accurately model the behaviour of people with different socio-economic backgrounds in varying geographical contexts accurately using ABM technology.

2. Methodological Background and Approach

2.1 Spatial Agent-based Modeling and Simulation

Agent-based modeling is a method to simulate dynamic processes involving autonomous agents [8]. Agents are independent entities that can interact with each other, but also with their environment. Such agents could be, for example, people, buildings, cars or animals. While the behavior and individual actions of agents are defined on the micro level, the resulting model is able to show patterns and behaviors on the macro level that were not explicitly defined, but rather evolved during the execution of the model ("bottom-up" approach) [1, 2, 3, 4, 5, 8, 9]. By using GIS data, ABMs are able to incorporate real world geospatial data into the simulation to define the area in which the agents can move and act within [10]. Such an environment could consist of spatial grids, continuous spaces, or networks. According to [1] and [2], agents themselves may also be spatially explicit, which means that they have a location in the model space assigned to them. They can also be spatially implicit when their location is irrelevant in the context of the simulation.

2.2 Collection of Model Parameters and Actor Decisions

For the initialization of the agent-based model various information is needed. This includes **spatial input data** which is necessary to describe an energy system within its defined boundaries in the context of the intended ABM (e.g., buildings, grid-based energy infrastructure, renewable energy potentials, population structure), **input variables** (parameters, e.g., renovation rate) which are necessary to set the scenario constraints for the spatial agent-based simulation, as well as **output variables** (state variables, e.g., heating energy demand) that describe the state of the system or an entity in that system (e.g., building) at any time during a simulation [6, 7, 8, 9].

Next to the technical parameters, the collection and specification of the **parameters for actor decisions** is also crucial for the model. For this, a conceptual model was developed in order to operationalize homeowner's decision-making process for building renovations based on the diffusion of innovations theory [11] as well as psychological models and theories, i.e. Theory of Planned Behavior [12], Value-Belief-Norm Theory [13] and the Model of Justified Behavior [14, 15, 16, 17]. Second, to gather empirical data on homeowner's renovation behaviour, a quantitative survey was designed in accordance with the conceptual framework. The survey comprised the following sections: (i) characteristics of implemented building construction measures in the last ten years (renovation, refurbishment and new building); (ii) characteristics of intended building construction measures; (iii) triggers and information variables for implemented measures; (iv) household characteristics, building characteristics and life events; and (iv) personal attitudinal factors. The corresponding online survey was released in June 2023 and targeted homeowners of single and multi-family homes in Styria, who received a subsidy for heating system replacements or consultation for energy refurbishment measures.

3. Experimental Setup of ABM4EnergyTransition Simulation

Together with the technical model parameters and the actor behaviour, the agents, environments, and interactions can be implemented. Furthermore, these parameters are used to model the agent's behaviour in order to be able to simulate the decision-making process of households depending on public policies and the agent's context.

The ABM consists of agents represented by buildings (i.e., building owners) and an environment (administrative border of study area), where the buildings are located. Buildings contain information on their installed heating systems, their heating energy demand, or their CO_2 emissions. The environment contains further entities representing land plots (land use classes), energy infrastructure (district heating and natural gas network), heatmaps corresponding to energy demand and CO_2 densities and energy zones for applicable renewable energy supply technologies. Both energy infrastructure and energy zones as well as heatmaps interact with the building agents in the simulation. An overview of the model setup is shown in **Figure 2**.

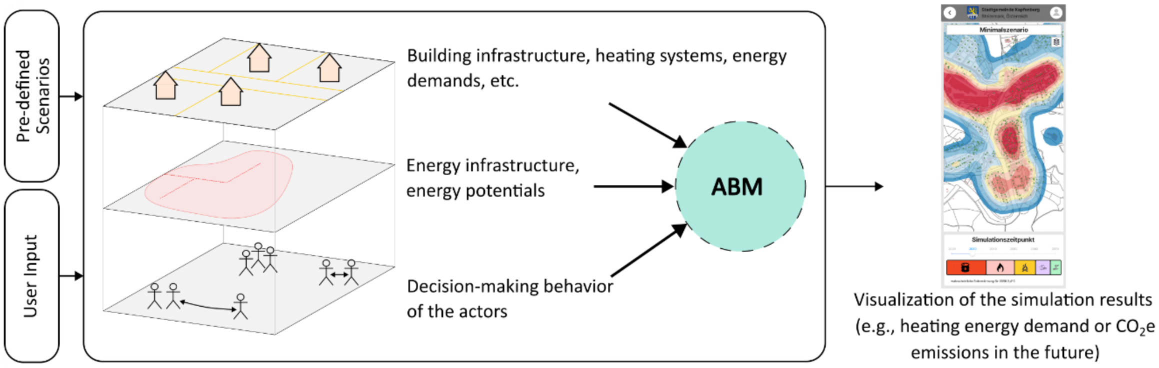

***Figure 2**: Overview of the model setup*

In the course of the energy transition simulated by the ABM, part of the existing building stock will be gradually modernized (thermal refurbishment) or, alternatively, existing buildings will be demolished and replaced by new buildings (with a new, climate-friendly heating system included). In addition to thermal building refurbishment, heating systems attached to existing buildings will also be gradually replaced by more climate-friendly technologies as part of the heat transition. Building refurbishment and replacement of heating systems are not linked to each other (an existing building not being demolished can be either refurbished or equipped with a new heating system or both). The transition of the building stock also affects the development of the grid-based energy infrastructures. For example, the expansion of district heating or gas networks may enlarge or downsize depending on the kind of building heating systems installed over time.

Consequently, the agents are subject to the following processes:

- demolish() demolition of existing building
- build() new construction of building (incl. heating system)
- refurbish() thermal refurbishment of existing building envelope
- replace() replacement of existing heating system
- grow(+ / -) expansion (+) resp. deconstruction (-) of grid-based energy infrastructures (district heating, natural gas) and growing (+) resp. shrinking (-) of corresponding energy zones

The model in its current state does not yet include the decision-making behavior of agents. In the future, however, the model will be extended with the empirical data (i.e., survey results), which will be used to model the decision-making behavior of households.

4. Results

The tangible results are a prototypical map centered web application with a dashboard and the representation of the ABM results. The spatial temporal data in addition with buildings and energy infrastructure are represented best in a cartographic way. The Dashboard allows users from administration and planning to plan possible energy policy and/or technical interventions in the ABM and to display the results (e.g.: Energy and Life Cycle Assessment as well as technology and energy carrier mix in variable spatial and temporal granularity, etc.). In addition, simplified simulation scenarios can also be initialized and visualized by interested citizens in the web application for a playful examination of the topic of heat transition and energy system change (see Figure 3).

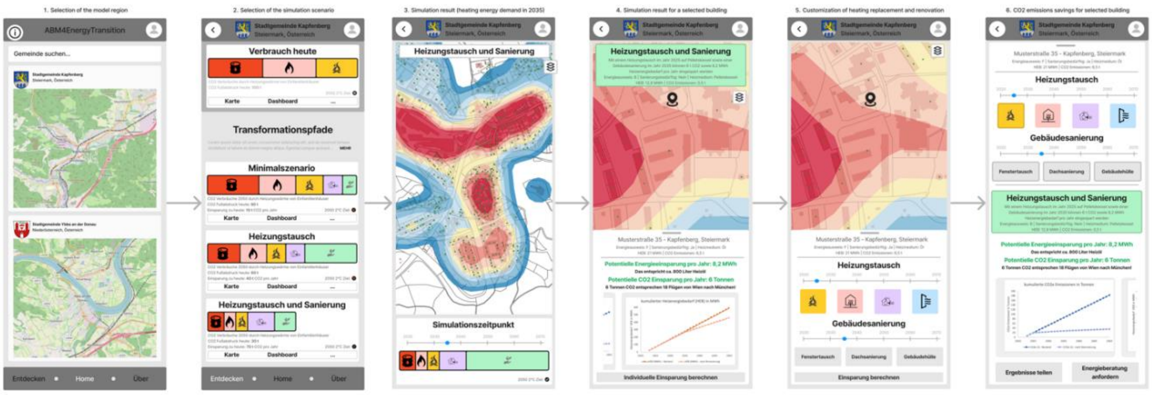

***Figure 3**: Wireframes of the Demonstrator application (Work in progress).*

5. Discussion and Conclusion

This paper presents an approach for the development of an agent-based model for the spatial analysis and assessment of pathways for the municipal heat and energy transition. The proposed agent-based model considers spatio-technical parameters, such as the building stock or energy infrastructure of an area, as well as social factors that influence the decision-making behavior of the actors in the simulation. Over the course of the simulation, processes, such as thermal refurbishments or heating system changes, are applied to the building stock. This extended simulation approach should help to better assess the impact of public policies on the achievement of climate and energy goals.

The project is currently ongoing, with the ABM still under development. Upon completion, users will be able to access the simulation through a web application to plan potential interventions as part of the energy transition.

Author contributions

G.W. wrote the original draft, and is conducting the implementation of the ABM, S.L.C. and M.A.H. did conduct the empirical study and analysis, F.K. is implementing and designing the wireframes, R.B., M.A.H., S.L.C., J.S. J.N. reviewed and edited the draft.

Competing interests

The authors declare that they have no competing interests.

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