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An agent-based model framework for understanding the decisions of households and exploring bottom-up effects on housing sustainability

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Abstract. Housing plays a crucial role in the transition towards sustainability. Zero-energy or low-carbon housing solutions are key, but their success depends on their acceptance by the users. We propose a conceptual and an operational framework for understanding households' residential choices as a base for an agent-based model, using the tenant as basic unit to populate it. We firstly conceptualise the decision-making process of tenants as a system. Secondly, we cluster the synthetic agents populating the model into typologies of dwellings and tenants. Thirdly, we display their actions in the *action arena*, and set-up the test runs. Lastly, we introduce the next steps to follow for the simulation of the bottom-up effects on housing sustainability.

1. Introduction

The residential sector represents a fourth of the CO₂ emissions from fossil fuels in Switzerland [1], and 20% of the energy end use in the world [2]. Based on these numbers, it becomes clear that the housing sector is key for a transition towards sustainability. It has been shown that technical solutions (e.g. improvement in buildings' energy-efficiency) play an important role, but are not sufficient to achieve the transition [3]. The success of these technical solutions depends on how they can be reconciled with the present and future needs of households. In this context, a greater understanding of households' residential preferences is needed.

The driving factors determining households' residential mobility and location choices have been studied in the literature by a multitude of disciplines, but their analysis lacks a systemic approach. Such an approach permits to conceptualize the decision-making process of the tenants. Simulation tools, such as agent-based models (ABM), can support the representation and study of the dynamics of this 'decision-making *system*' [4], by capturing the behavior of tenants at the individual level and understanding their impacts on the systemic level. The operating rules of the agents (or tenants) and their implementation are represented in conceptual and operational frameworks respectively.

This paper proposes a conceptual and an operational framework for understanding households' residential choices as a base for an agent-based model, using the tenant as the basic unit to populate it. The final goal of the ABM is to explore the emerging large-scale bottom-up effects on housing sustainability. We structure the paper as follows: first, we provide an overview of the methods adopted to develop the frameworks. In the second section, we display the conceptual framework, which represents the elements that play a role in the tenants' decision to move and where to move as well as



their relationships. Subsequently, we propose a way of clustering tenants and dwellings in *typologies*. In the third section, we (i) define mathematically the synthetic agents populating the model, (ii) display the operationalization of the framework for the ABM, and (iii) explain the set-up of the test runs. In the last section, we discuss the results obtained, and introduce the next steps to follow for the simulation of the bottom-up effects on housing sustainability.

2. Methods

2.1. System Analysis: Conceptual Framework Development and Validation

Prior to building the agent-based model, we performed a system analysis by following the steps indicated by Nikolic and Ghorbani [5]. Firstly, we elucidated the problem entity through the review of multidisciplinary literature on residential mobility and location choices. Secondly we defined the structure, boundaries and elements of the ‘decision-making system’ under study. Lastly, we conceptualized it (Figure 1). For the conceptualization, relevant theories were combined in a representation integrating two existing frameworks in psychology and environmental sciences [6–8], which encompass the key elements playing a role in the decision-making process of tenants as subsystem of the larger housing system. The conceptual framework was validated during two group discussions in the canton of Vaud and Zurich, involving the tenants of our research partners: two of the largest housing cooperatives in Switzerland and a Swiss insurer and asset manager.

2.2. Model design: Operationalization and Typologies.

Based on the combination of the decision-making elements resulting from the analysis of the group discussions [9], we identified types of tenant-agents and types of dwellings. We then defined these types for the simulations as agents with attached sets of properties, characterized by different intentions to move and to select specific dwellings. The synthetic agents –the ‘tenants’– were used as the basic units to populate the model, whilst the dwellings were considered together with the housing market and other events (e.g., job creation) as the environment of the agents [5]. Lastly, based on the steps abovementioned, we defined the ‘action arena’, encompassing a list of actions the agent may be able to execute (for more details, see MAIA - Modelling Agent systems based on Institutional Analysis [10]). After refining the ontology proposed in the system analysis, we designed this ‘action arena’ as a representative flowchart, which displays the behavior of the artificial entities (Figure 2).

3. Conceptualization

3.1. The Conceptual Framework

Housing systems are defined by supply and demand constraints [11]. The *supply* is the dwelling, characterized by e.g., its design, location, or size; the *demand* is the tenant, characterized by e.g., their socio-economic status. Their interrelationships in the decision-making system are presented in the conceptual framework of Figure 1. The framework combines the structural agent analysis (SAA) framework of Binder [8], which is based on Giddens’ structuration theory [7], with the Theory of Planned Behavior of Ajzen [6]. The SAA conceptualizes the interactions between the social structure (e.g., legislation, culture, and economic system), human action and the natural and technical environment. At the scale of the agent, Ajzen [6] defines the agent’s intention to perform a specific behavior as determined jointly by the *perceived behavioral control* (the ease of performing the behavior), the *attitude towards the behavior* (the evaluation of the behavior) and the *subjective norms* (the perceived social pressure to perform the behavior). Furthermore, we include the *dwelling function* among the determinants of the decision to move and to select a new dwelling. In fact, the *function* of the housing system, similarly to any other system function, is the most crucial determinant of the system’s behavior [12]. These *housing functions*, identified in the literature and displayed in Table 1, have proven to be relevant in the residential choices of tenants [9]. Lastly, in the framework, we show how actions (to move, and to select a dwelling) provide diachronic (dotted lines) and synchronic (full lines) feedbacks to tenants and dwellings (e.g., change in rent following vacancy).

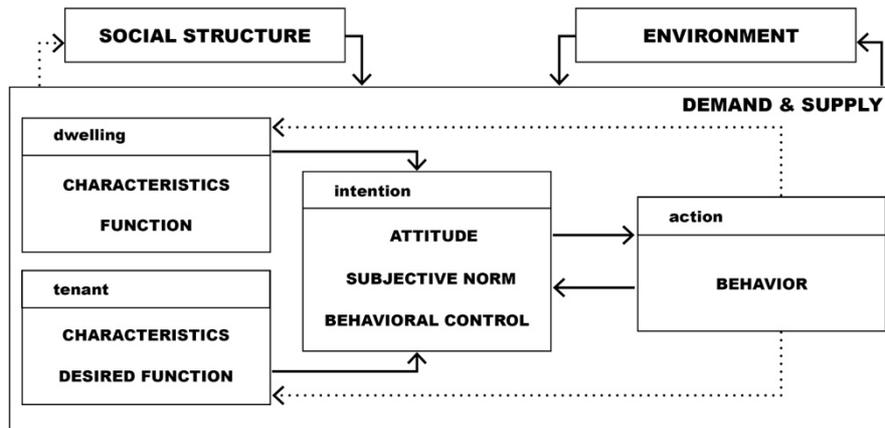


Figure 1. Conceptual framework for the decision of tenants to move and select a new dwelling.

3.2. *Typologies of tenants, typologies of dwellings*

To go from the conceptual to the operational framework, dwelling and tenants are clustered in typologies. These typologies result from the aggregation of (i) agents with similar decision patterns, and (ii) dwellings with similar sets of ‘non-substitutable’ characteristics (e.g., balcony, materials, view) [13] and function (e.g., ‘Status symbol’). More precisely, we define tenant-typologies as a combination of: (i) life-cycle stage [14,15], (ii) lifestyles [16], (iii) desired housing function [9], (iv) desired non-substitutable dwelling characteristics [13], (v) level of satisfaction of the tenant with the dwelling prior to moving, and (vi) past residential experience. The two first include the socio-economic characteristics of the tenants, whilst the latter relate to their preferences. Dwelling-typologies are defined based on the dwelling characteristics and functions as determined by the tenants. We provide a short overview of these typologies in Table 1, which displays three potential types of tenants based on the combination of the elements illustrated above. The three dwelling types correspond to the ‘Function’ and ‘Characteristics’ rows of each tenant type (e.g., Production-Consumption; Well equipped, Compact).

Table 1. Types of tenants and types of dwellings: three examples. The types of dwelling correspond to the combination of the rows ‘Function’ and ‘Characteristics’ for each type of tenant.

	TYPE 1	TYPE 2	TYPE 3
Life-cycle Stage	Young married without children	Married with school aged children	Middle-aged divorced without dependent children
Lifestyle	Adaptive Mainstream	Domestically Centered	Entertainment Seekers
Function	Production-Consumption	Permanence	Status Symbol
Characteristics	Well equipped, Compact	Maintainable, In historic building	Spacious, Modern
Satisfaction	Highly Satisfied	Medium Satisfied	Highly Satisfied
Past experience	Easiness to move	Difficulty to move	Easiness to move

4. **Operationalization**

4.1. *Mathematical definitions*

The typologies of agents are defined mathematically by different characteristics of dwellings and tenants, where $\{s_1, s_2, s_3 \dots\}$ are the set of the characteristics of the different socio-economic, lifestyle-based parameters associated to an agent, and $\{d_1, d_2 \dots\}$ are dwelling properties. A tenant typology $h(t)$ associated to agent a at given time step $= t$ can be represented as the function of these set of characteristics. Based on the previous typology of the agent, the current typology $h(t)$ is $f_a(\{s_1, s_2 \dots\}, h(t - 1))$. These typologies help in defining the intentions from the effects of the past typologies and the peer effects (see Figure 2). The dwelling typologies are the functions of the *non-substitutable characteristics* and the *dwelling function* as defined by the preferences of the tenant

typology $\{b_1, b_2 \dots\}$. Therefore, a dwelling typology $d(t)$ can be defined as $g_a(\{s_1, s_2 \dots\}, d(t-1)) * p_a(\{b_1, b_2 \dots\}, d(t-1))$, where g_a is the ‘dwelling-associated’ tenant typology function, and p_a is the preference function of that agent.

4.2. Operational structure

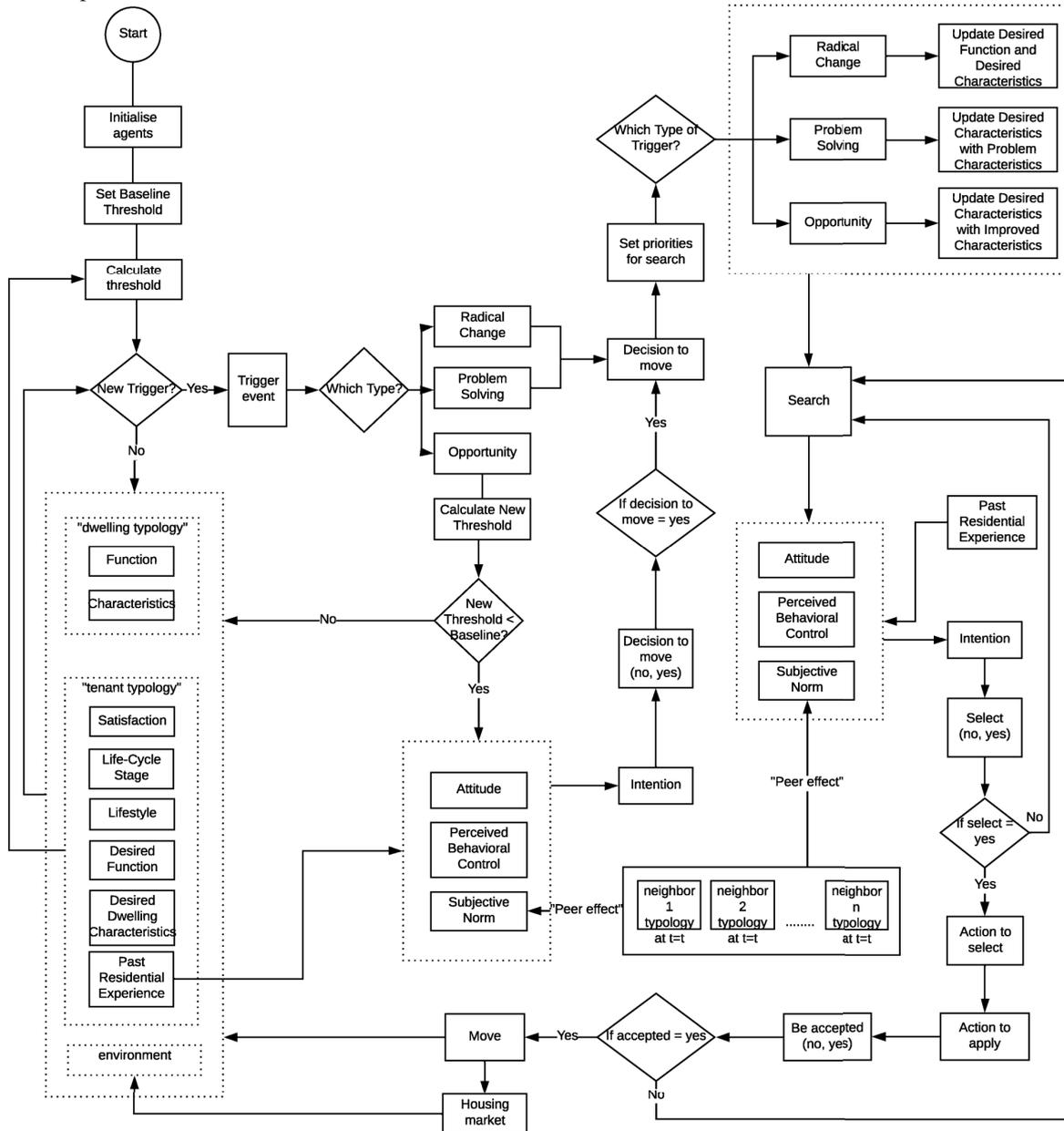


Figure 2. Operational framework for the implementation of the ABM on tenants’ residential choices.

The operational framework presented in Figure 2 displays the tenant-agents, their behaviours, and the environment. The environment is composed by the ‘opportunities’, such as changes in the housing market, job offers, owners’ decisions (e.g., building, renovating or demolishing a dwelling). Triggers are generated from any change in the tenant’s and dwelling’s typologies, or the environment. To understand the operational structure that will help design the experiments for the ABM, a simple example can be considered first. Let’s assume that the household’s head (agent, a) gets a professional promotion and raise in salary (trigger/event, $e(t)$) at a given moment (time step, t). The trigger, which

belongs to the ‘*opportunity*’ type (or any change in the ‘*environment*’), increases the propensity to move of the tenant typology (or decreases the stress *threshold*). Its threshold is now lower than the baseline threshold. The environment (e.g., housing market), with its triggering power, overcomes the new threshold: the tenant decides to move (action, c). There are multiple functions that play a role between this event-to-action process: e.g., each agent evaluates their own preferences (change in utility, $u(a)$ based on the characteristics, $u_a(\{s1, s2, \dots\}) - u_a(\{s1', s2', \dots\})$), and decides whether it is favorable (*attitude*) to act (0,1) or not. Agent’s peers (neighbor agents defined by a *spatial distance*) tell them that moving out is/is not a good idea. Furthermore, the tenant had a past residential experience (past tenant typology of agent, $h(t - 1)$) reminding them that moving required/didn’t require a lot of effort.

When the trigger corresponds to a radical change (i.e., any change in lifestyle or life-cycle stage e.g., divorce); or to a problem to solve (i.e., change in the institutional rules, e.g., rental contract, or in the quality of one non-substitutable characteristic, e.g., distance to job) the decision to move is immediate.

The final decision on *where* to move (action to choose from dwellings $\{x1, x2 \dots\}$) is also the result of a recursive process of the same steps as mentioned above. First, the tenant sets the priorities for the search (here, each type of trigger affects differently the non-substitutable characteristics and the desired function for the new dwelling). Then, s/he looks for a housing that is e.g., larger than the previous, better located, more expensive, etc. (the *attitude*, or relation between tenant new typology, $h(t)$ and dwelling desired typology, $d(t)$). Agent’s peers live/don’t live in the same type of dwelling that s/he found. Furthermore, the tenant had a past residential experience (past tenant typology of agent, $h(t - 1)$) informing them e.g. that the market will / will not provide another apartment as good as the one found. Finally, once the dwelling is selected, the tenant will apply for the desired apartment, and eventually get it (be *accepted*). The move will provide a feedback to the housing market.

4.3. Towards the next steps: the set-up of the test runs

To implement the model simulations, we set up test runs following different steps. We set up the model framework in Python with the Mesa library, allowing us to develop two main classes: *Model* and *Agent*. More specifically, the *Model* class contains all the model attributes which help to manage the agents (e.g. order of their activation i.e. how the agents take the next step in the model, providing them *unique IDs*, etc.). We then developed a skeleton code, which checks whether the information from one function of the agent transfers to the next correctly. Lastly, we created the *MeasurementGen* class, supporting the allocation of the distributions of the various tenant properties (e.g., between the three types of tenants of Table 1). This makes it possible to determine (i) if the model works close to the assumptions of the frameworks (Figure 1, Figure 2), and (ii) if the right values of properties are associated to the right typologies of agents (e.g. how the $h(t)$ is defined using the set of agents’ properties $\{s1, s2, \dots\}$).

5. Discussion

This paper proposes a conceptual and an operational framework for understanding tenant’s residential choices as a base of an agent-based model. We integrate theories from sociology and psychology by means of system and computer science approaches to conceptualize individual intentions with the goal to explore their effects on the system’s dynamics. This interdisciplinary understanding of the housing system makes this approach unique. It provides a contribution to the literature on households’ residential preferences as well as on the behavioral aspects of the interactions between users and buildings in ABMs. The limitations of this study also need to be acknowledged: the set-up of the test runs showed major challenges with regard to the quantification of the preferences associated to the agents. One of the possible improvements will be to understand the relation of each agent property as a separate function affecting the goal to move or not, thus to represent the agents as cumulative function of these properties. Further research will focus on the application of these frameworks to a real world case and the quantification of the different relationships. Firstly, we will administer a survey to the households of the 10,000 dwellings belonging to our partners, with the goal to quantify the determinants of the residential mobility and refine the typologies proposed. Secondly, we will incorporate (i) the dynamics of the buildings (considered this time as agents) and (ii) the learning of the tenant-agents to adapt their choices

through time. Additionally, for setting up the real experiments, we will use real values from the Swiss occupants' databases and adapt the *MeasurementGen* accordingly. Finally, in order to explore the environmental impacts induced by the household and its dwelling, we will link life-cycle impact databases for consumption categories (e.g., from EXIOBASE and ecoinvent) to the households' material and energy (resource) use.

Conclusion

In this paper, we propose two conceptual and operational agent-based model frameworks representing the residential mobility and location choices of tenants, with the goal to understand the agent-choice behaviors leading to different bottom-up effects on housing sustainability. The conceptualization of the tenant's decision-making process resulted in a display of the interrelationship between social structure, environment and agents, whose behavior is defined by the intention to perform it. The operationalization showed the relationship between the typologies of agents, the triggers generated from the environment, and the final decision. The set-up of the first test runs showed the need for additional research on the role played by the tenants' properties in affecting their mobility. This will allow us to implement the actual runs, link the ABM with the life-cycle inventory database of households, and explore the buildings' sustainability dynamics in relationship to the movement of tenants.

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