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METHODOLOGICAL FOUNDATIONS AND ALGORITHMIC CORE OF AN AGENT-BASED MODEL FOR A REAL ESTATE PLATFORM

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Traditional macroeconomic and agent-based models (ABMs) of the real estate market largely ignore the digital layer of modern PropTech platforms. By modeling matching processes through abstract macro-functions, these approaches fail to capture the cognitively constrained realities of online property searches. Digital interfaces, however, act as active "choice architects." Their underlying ranking, pagination, and filtering algorithms create new digital search frictions that exacerbate information asymmetry and severely limit users' visibility into available objects. To bridge this methodological gap, this study develops the conceptual foundations and algorithmic core of an agent-based model for a real estate platform, grounded in empirical clickstream data. To ensure architectural integrity and scientific reproducibility, the proposed approach integrates five leading global methodologies – FREIDA, MAIA, the Smajgl et al. approach, the ODD+D protocol, and the TRACE framework – into a unified five-step development and validation protocol. As a result, a novel algorithmic core is developed that completely replaces aggregated macro-formulas with a stochastic system of discrete decision trees. Agent behavior is dynamically formalized through rules of bounded attention, local micro-conversion, seller price adaptation, and the satisficing heuristic. Meanwhile, empirical initialization of agent attributes is achieved by clustering raw server logs, thereby providing a robust, data-driven micro-foundation. The integration of the digital platform as an independent institutional environment allows for the authentic "bottom-up" generation of complex emergent macro-phenomena, such as the filter bubble effect and the quantitative impact of algorithmic ranking on asset liquidity. Ultimately, applying this framework shifts the paradigm of real estate research from abstract macroeconomic determinism to applied digital behavioral economics, ensuring high predictive validity and providing a reliable tool for testing business hypotheses across various scenarios.

Keywords: agent-based modeling, PropTech, real estate market, clickstream, digital platform, emergence, bounded rationality.

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1. INTRODUCTION

Traditional approaches to modeling socio-economic systems, in particular econometric regression modeling and Dynamic Stochastic General Equilibrium (DSGE) models, mostly rely on the representative agent paradigm and aggregated macroeconomic equations, i.e., Equation-Based Modeling (EBM). In contrast, Agent-Based Modeling (ABM) is based on the philosophy of methodological individualism and the theory of Complex Adaptive Systems [1, 2]. The main principle of Agent-Based Modeling (ABM) is the "bottom-up" approach: macroeconomic phenomena, such as pricing or market liquidity, are not determined by predefined global macro-formulas. They arise exclusively as an emergent (derived) consequence of non-linear micro-interactions of a large number of heterogeneous agents. In accordance with this paradigm, autonomous agents act under conditions of information asymmetry and bounded rationality according to H. Simon [3] was guided by local behavioral heuristics rather than by mathematical global optimization of utility functions.

An analysis of the corpus of existing publications on agent-based modeling of the real estate market demonstrates the evolution of scholars' focus, allowing the available academic achievements to be structured into three main directions. First, spatial-economic models and urban dynamics (Spatial / Urban ABM) focus on the geographical dimension. The classic works of T. Filatova laid the foundations for modeling land markets in which prices are determined by bid-rent theory and bilateral spatial search [4]. N. Magliocca expanded this approach in the well-known CHALM model, integrating land-use change processes at the level of Geographic Information Systems (GIS) maps [5]. Urban segregation and sprawl have been extensively explored through entity-based and automata-based geosimulation [6, 7]. More recently, J. Ge explored the spatio-behavioral dynamics of buyers and investors in the generation of endogenous price bubbles [8]. Second, models of macro-financial shocks and systemic risks examine the relationships among real estate, macroeconomics, and financial crises. The models of J. Geanakoplos [9] and R. Baptista for the Bank of England [10] explore the impact of credit constraints (LTV) and macroprudential policy on the formation of price bubbles. R. Axtell applies a network approach to analyze the development of a price bubble in Washington, using 1.5 million real tax records [11]. E. Erlingsson considers the housing market as an integrated part of macroeconomic dynamics in stress tests of the Icelandic economy [12]; this also includes the large-scale European macroeconomic model EURACE [13]. Third, models of market microstructure and the matching process focus on behavioral distortions. R. Kouwenberg integrates psychological loss aversion into agent behavior [14]. N. Gilbert explores the market through the lens of complex housing chains [15]. G. Lisi investigates direct search frictions and the matching process within the housing market [16].

Despite the significant scientific contributions of the mentioned works, a common methodological feature, and at the same time a critical limitation, is that their information-search mechanism is overly abstract. The meeting of a buyer and a seller is most often modeled through matching functions, a random Brownian walk, or the direct mass mailing of offers. The real, cognitively and technologically bounded process of information scanning is ignored. With the rapid development of the property technology (PropTech) ecosystem, the real estate market has undergone a radical transformation: the key environment where demand is formed and agents meet is no longer the physical space of the city but digital interfaces—real estate platforms and aggregators [17–19]. A platform is a classic two-sided market that acts as an active "choice architect", shaping the information field through ranking and routing algorithms [20, 21].

Modern agent-based models (ABMs) completely ignore this digital layer, treating platforms as passive and neutral "bulletin boards". In reality, the buyer never sees the entire market — they interact only with a narrow sample of items presented by the ranking algorithm. Interface constraints (filters, pagination) create a new digital search friction that determines the visibility of objects and critically affects the transaction probability and the ultimate liquidity of assets. To overcome this methodological gap, a transition from purely theoretical assumptions to microfoundations grounded in big data is necessary — for example, by analyzing digital footprints or clickstream events (such as impressions in the feed, clicks on listings, session duration, and pagination depth). Clickstream is the only objective, empirical reflection of an agent's decision-making process under bounded-rationality conditions. The integration of clickstream analytics allows for the abandonment of contrived utility macro-functions in favor of calibrated behavioral patterns. This transforms the model from an abstract simulation into a valid data-driven business tool, aligning with modern standards for formalizing agent cognitive decisions [22–24].

The purpose of the article is to develop the conceptual foundations and algorithmic core of an agent-based model for a digital real estate platform, grounded in empirical behavioral microdata (clickstream). In accordance with the stated purpose, the following objectives are formulated:

- To synthesize leading agent-based modeling methodologies (FREIDA, MAIA, ODD+D, TRACE) into a unified integrated framework;
- To justify the abandonment of macroeconomic aggregation in favor of discrete decision trees and behavioral agent heuristics;
- To develop a step-by-step implementation protocol for the digital real estate platform model.

2. METHODS

To ensure scientific reproducibility, validity, and architectural integrity, the proposed model is developed through a complex synthesis of 5 leading global agent-based modeling methodologies.

2.1. Detailed Description of the Applied Methodologies

1. **FREIDA Methodology (eliciting expert knowledge).** Developed to overcome the problem of a lack of numerical data regarding the internal cognitive motivation of agent behavior [24]. Even in the presence of big data, platform logs show "what" the user did, but do not explain "why". FREIDA structures the process of transforming the implicit knowledge of domain experts (product managers, marketplace analysts) into concrete computational rules. It generates three artifacts: Expected System Behaviors (ESB) for a qualitative description of the expected macro-dynamics; Calibration Statements (CS) to establish the cognitive boundaries of agents (e.g., "a user rarely scrolls beyond the third page"); and Validation Statements (VS) for the expert evaluation of the results for realism.
2. **MAIA Framework (Institutional Analysis).** Developed based on institutional analysis (E. Ostrom's IAD framework) [25]. In the context of this study, MAIA allows conceptualizing the digital platform not just as a passive environment, but as a formal "Action Arena". The platform has strict institutional Rules: sorting algorithms, paywall systems, publication limits. MAIA requires modeling agent actions exclusively under these systemic constraints, taking into account their "Evaluative capabilities" to read interface signals (e.g., reacting to a "Top listing" badge).
3. **Parameterization Approach by Smajgl et al. (empirical initialization).** This methodology is a recognized standard for integrating empirical microdata into ABM, which prevents the arbitrary "guessing" of parameters [26]. Of the 5-phase approach, Phase 4 is key, applied for clustering arrays of raw clickstream logs using data mining methods. This allows the extraction of objective behavioral user profiles. Statistical patterns (e.g., conversion from view to click depending on the position in the search results) are transformed into probabilistic agent attributes.
4. **ODD+D Protocol (documenting cognitive behavior).** The ODD standard was created to unify the description of ecological models. The "+D" (Decision-making) extension is specifically designed to document complex human cognitive behavior [27]. The most important concept in it is the formalization of the Sensing block (how an agent perceives information). In the platform model, Sensing is strictly limited: the agent can process only objects within the visibility zone of its screen (Top-N), completely ignoring all other offers.
5. **TRACE End-to-End Validation Framework.** TRACE (TRansparent and Comprehensive Ecological Modeling Documentation) is a methodology of continuous validation and verification (V&V) [28]. It requires critical testing of the model at every stage: from the textual justification of the conceptual structure (Problem

formulation) and the assessment of input data bias (Data evaluation) to unit testing the code for errors (Implementation verification) and comparing simulated macro-patterns with empirical ones.

2.2. Synthesis of Methodologies into a Unified Framework

Each of the described methodologies covers a separate development stage, forming a single integrated algorithm for creating a data-driven simulation (Table 1).

Table 1

Integration of development methodologies into a unified framework

Development Stage	FREIDA	MAIA	Smajgl et al.	ODD+D	TRACE
1. Conceptualization	Expected System Behaviors (ESBs)	"Action Arena" structure, institutional rules	Phase 1: Identification of goals and typologies	Overview: Purpose, Entities, Scales	Formulating a problem, Conceptual model
2. Cognitive Core	Calibration Statements (CS), cognitive boundaries	Evaluative capabilities	Phases 2-3: Structuring logic (decision trees)	Design concepts, Decision-making (Sensing)	Sub-model formulation, logical justification
3. Parameterization	Synthesis of metrics and expert judgments	Information infrastructure (Data layer)	Phase 4: Clustering arrays of clickstream logs	Initialization, Input data (database snapshot t=0)	Data evaluation (assessment of quality and bias)
4. Implementation	—	Validation of architecture for compliance with rules	Timing of the user lifecycle	Details: Submodels (Schedule / Sequence of events)	Implementation verification (Unit tests of code)
5. Analysis (V&V)	Validation Statements (VS)	Assessing the impact of algorithms on outcomes	Phase 5: Macro-validation, Sensitivity analysis	Observation: Collection of emergent macro-metrics	Model output verification (POM validation)

3. RESULTS

3.1. Architecture of the Algorithmic Core: Abandoning Aggregation in Favor of Emergence

Abstract aggregated formulas (e.g., calculating the general market price through the intersection of global supply and demand curves, macroeconomic elasticity equations, or aggregated matching macro-functions) are fundamental antagonists to the philosophy of agent-based modeling. Their use at the micro level completely undermines the logic of emergence, since no participant in a digital market has complete information about macroeconomic aggregates when making local decisions.

The algorithmic core of the developed model is based exclusively on a system of discrete decision trees and state machines that reflect local behavioral heuristics during interaction with the marketplace interface. The complex macroscopic dynamics of the system (changes in average prices, overall platform conversion, time-on-market of objects) arise only as an emergent consequence of millions of local micro-actions. The behavioral logic relies on the following rules:

- **Search and Filtering Rule (Search Heuristic):** The agent initiates a query with strict constraints (budget, number of rooms), cutting off irrelevant options using interface filters. The global utility of the entire market is fundamentally not calculated.
- **Bounded Attention Rule:** The agent is physically capable of analyzing only the Top-N listings proposed by the algorithm. Objects on further pagination pages objectively "do not exist" for them.
- **Micro-conversion Rule (Click Rule):** The probability of a click (CTR) on a specific listing is based on visual triggers in a local comparison, considering only the nearest neighbors on the search engine results page (SERP).
- **Satisficing Rule:** Instead of maximizing global utility (unlike homo economicus), the buyer stops searching and makes a choice as soon as they find an object that exceeds their internal psychological threshold of acceptability [3].
- **Seller Adaptation Rule (Adaptation Rule):** The seller adjusts the price not based on the global economic situation, but exclusively based on the clickstream analytics of their own object. If, over period T, the listing received hundreds of impressions in the search results but zero clicks (low conversion), the seller lowers the price or buys paid promotion (Boost).

3.2. Step-by-Step Implementation of the Model

The integration of the five described methodologies allows the model development to be structured into 5 logical steps.

Step 1. Conceptualization of the Platform Environment and Ontology Definition

- **Step Description:** Definition of system boundaries and transition from the paradigm of geographical space to the architecture of digital choice. Key agents (seekers, owners/realtors) and the platform as an independent institutional actor managing the interaction architecture are identified.
- **FREIDA Elements:** Formulation of "Expected System Behaviors" (ESBs) based on expert interviews with PropTech market representatives to understand how the platform infrastructure affects market dynamics.
- **MAIA Elements:** Description of the platform as an "Action Arena". Formalization of institutional Rules, which cover: 1) Filtering mechanisms; 2) Pagination mechanisms; 3) Ranking algorithms; 4) Agent routing algorithms; 5) Infrastructure constraints.
- **Parameterization Approach by Smajgl et al.:** Phase 1 — identification of target audience typologies of the platform and conceptual structuring of its elements.
- **ODD+D Artifacts:** "Overview" block — defining the Purpose, Entities, State variables, and Scales.
- **TRACE Description:** Problem formulation & Conceptual model — detailed justification for the necessity of modeling a digital platform instead of traditional spatial ABMs.
- **Expected Result:** Documented conceptual model (ontology) with clearly defined agent roles, extended institutional rules of the platform (filtering, pagination, ranking, routing), and basic modeling hypotheses.

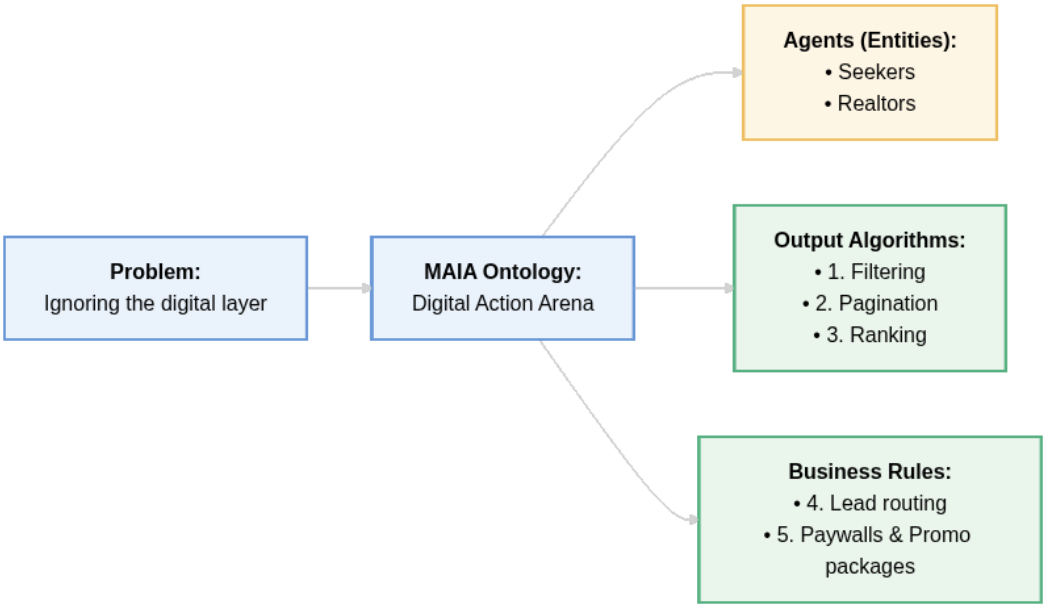


Fig. 1. Structural diagram of the MAIA methodology in the context of a real estate platform

Step 2. Designing the Cognitive Core and Decision-Making Rules

- **Step Description:** Transition from macro-intentions to micro-steps. Formalization of interaction logic with the interface and the transactional funnel based on heuristics, avoiding mathematical general equilibrium equations. An important feature is the probabilistic nature of each micro-step: the transition from view to click, from click to lead generation, lead routing to a specific agent, the agent's probabilistic decision to work with the lead, and the final deal closing are treated not as deterministic but as stochastic events.
- **FREIDA Elements:** Formulation of Calibration Statements (CS) regarding the cognitive and time boundaries of seekers, as well as the criteria and motivation by which real estate agents evaluate leads.
- **MAIA Elements:** Description of the "evaluative capabilities" of users — reactions to badges and interface signals, as well as the institutional rules of the platform regarding lead routing based on ratings and purchased services.
- **Parameterization Approach by Smajgl et al.:** Phases 2 and 3 — theoretical structuring of decision-making models in the form of logical graphs or decision trees covering the entire chain from search to deal.
- **ODD+D Artifacts:** "Design concepts" and "Decision-making" blocks. Description of the Sensing process as reading information from the device screen by the seeker and receiving data by the lead agent.
- **TRACE Description:** Sub-model formulation. Logical justification of the chosen behavioral heuristics and probability distributions at each stage of the funnel.
- **Expected Result:** Documented decision trees for each type of actor, step-by-step describing the full transactional chain of actions, taking into account their probabilistic nature.

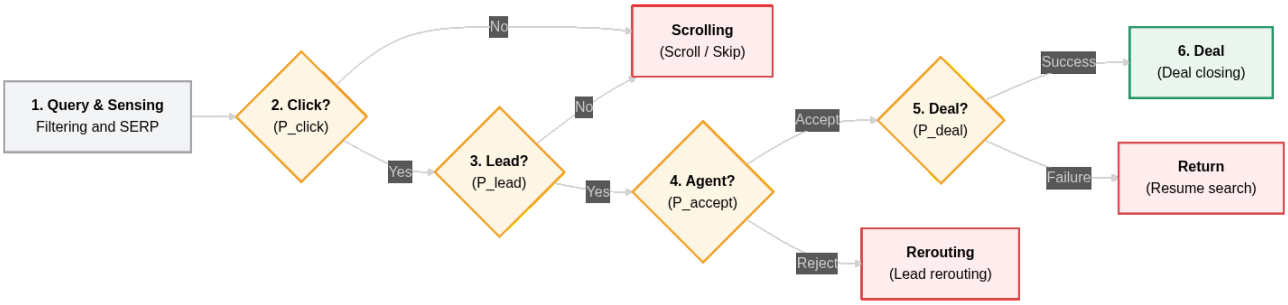


Fig. 2. Diagram of decision-making logic and agent behavior

Step 3. Empirical Parameterization and Initialization with Clickstream Data

- **Step Description:** Transformation of the theoretical abstract model into a data-driven simulation. Filling in empty agent parameters with real data from server logs.
- **FREIDA / MAIA Elements:** Synthesis of quantitative logs and qualitative expert judgments where logs do not provide an understanding of internal motivation (e.g., reasons for session abandonment).
- **Parameterization Approach by Smajgl et al.:** Phase 4 — application of Data Mining methods (in particular, clustering) to arrays of clickstream logs for extracting user profiles.
- **ODD+D Artifacts:** "Initialization" and "Input data" blocks. Initialization of variables based on historical snapshots of the platform database (moment t=0).
- **TRACE Description:** Data evaluation. Assessing representativeness and identifying algorithmic bias in raw logs.
- **Expected Result:** An agent population whose attributes and behavioral parameters are fully calibrated based on the statistical distributions of the behavior of real marketplace users.
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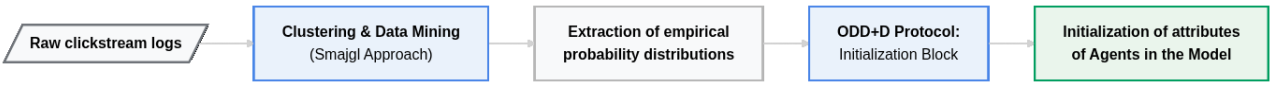


Fig. 3. Stages of empirical parameterization based on clickstream data

Step 4. Implementation of the Algorithmic Core into Code

- **Step Description:** Programmatic implementation of the developed heuristics in a computational simulation environment (via Object-Oriented Programming).
- **FREIDA / MAIA Elements:** Validation of the software code architecture for compliance with conceptual institutional constraints.
- **Parameterization Approach by Smajgl et al.:** Setting the frequency of action execution (ticks) in accordance with the real-life cycle of interaction with the platform.
- **ODD+D Artifacts:** "Details: Submodels" block. Formal schedule of event execution.
- **TRACE Description:** Implementation verification. Conducting unit testing of individual behavioral rules to guarantee the accurate reproduction of decision trees in code.
- **Expected Result:** Verified program code of the agent-based model (bug-free), in which the sequence of actions (ticks) imitates the real temporal progression of interactions on the digital platform.

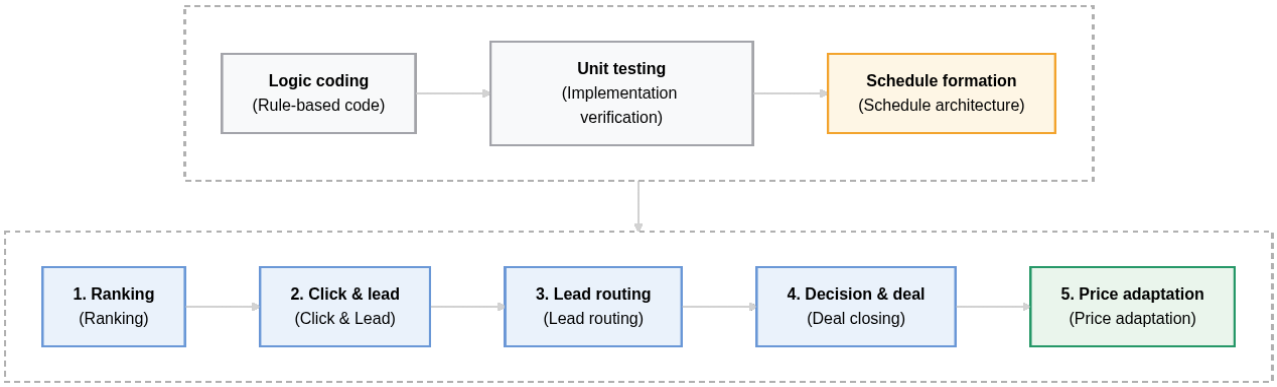


Fig. 4. Process of software implementation for the model's algorithmic core

Step 5. Emergence Analysis and Multi-level Validation and Verification (V&V)

- **Step Description:** Final proof that the developed micro-rules generate reliable macroscopic market dynamics.

- **FREIDA / MAIA Elements:** Application of Validation Statements (VS) and assessment of the impact of institutional changes in algorithms on the overall conversion rate of the platform.
- **Parameterization Approach by Smajgl et al.:** Phase 5 — macro-validation and sensitivity analysis.
- **ODD+D Artifacts:** "Observation" block. Collection of simulated emergent metrics.
- **TRACE Description:** Model output verification. Application of the Pattern-Oriented Modeling (POM) methodology — comparing simulated conversion funnels and time-on-market with real aggregated platform logs.
- **Expected Result:** A fully validated model whose emergent behavior reliably reproduces real market patterns (via POM validation), making it a ready-to-use tool for scenario testing of business hypotheses.

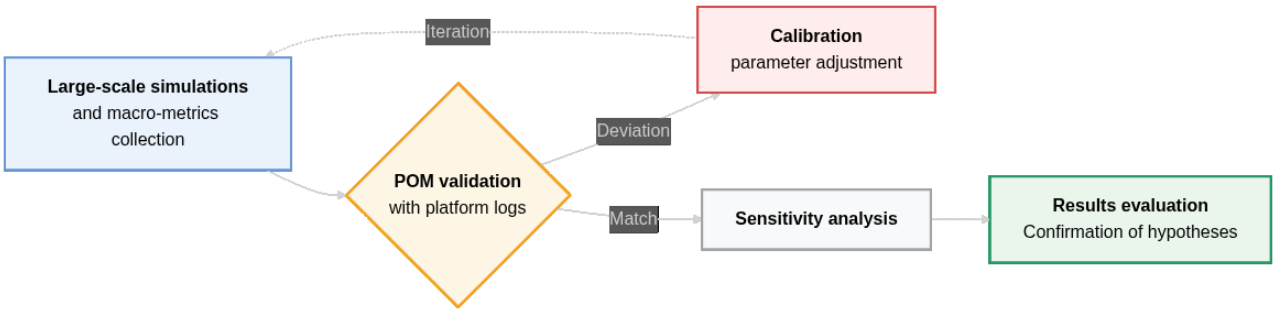


Fig. 5. Multi-level validation and emergence analysis framework

4. DISCUSSION AND CONCLUSION

4.1. Discussion

The methodological approach proposed in this article significantly shifts the paradigm of real estate market research from abstract macroeconomic determinism to the plane of applied digital behavioral economics. Abandoning global equilibria in favor of local decision trees and introducing the digital platform as an independent institutional choice architect enable exploration of fundamentally new market phenomena: the filter bubble effect, the impact of algorithmic ranking on pricing, and the quantitative impact of digital friction on overall asset liquidity.

The main challenge in applying this approach is its extremely high computational complexity, as simulating millions of micro-events for each individual click requires substantial hardware resources. In addition, the model's rigid dependence on empirical clickstream data places stringent demands on dataset quality, as it risks transferring the platform's algorithmic bias into the simulation's core. Nevertheless, it is exactly this micro-granularity and the transition to data-driven micro-foundations that provide the model with unprecedented predictive validity compared to traditional econometric (EBM) approaches.

4.2. Conclusions

1. The article critically analyzes the evolution of approaches to modeling real estate markets and expands the review of current scientific literature. The conceptual unacceptability of using aggregated macroeconomic formulas within the ABM paradigm is demonstrated, since the system's macroscopic behavior must be generated exclusively "bottom-up" through emergent mechanisms.
2. A critical methodological gap in the existing scientific literature is the lack of integration of the digital interface (Real Estate platform) as an independent institutional environment, which limits the visibility of objects to market participants and creates new friction in digital search.
3. A new algorithmic core is developed, based on discrete decision trees (bounded attention, local micro-conversion, satisficing heuristic) and on the empirical initialization of agents using clickstream analytics.
4. For the first time in this domain, a multi-step framework has been developed and structured to conceptually synthesize five leading global methodologies for development and validation (FREIDA, MAIA, the Smajgl et al. approach, ODD+D, and TRACE). This integrated protocol guarantees high transparency, reproducibility, and scientific reliability of the process of creating a data-driven simulation platform.

Prospects for future research in this direction involve the programmatic implementation of the developed algorithmic core within an agent-based modeling environment (in particular, using NetLogo), the parameterization of agent attributes based on real log datasets from a specific PropTech marketplace, and the execution of simulation experiments to evaluate the impact of the ranking algorithm, agent routing, and other adjustments on the market liquidity of real estate properties.

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МЕТОДОЛОГІЧНІ ЗАСАДИ ТА АЛГОРИТМІЧНЕ ЯДРО АГЕНТ-ОРІЄНТОВАНОЇ МОДЕЛІ ПЛАТФОРМИ НЕРУХОМОСТІ

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Традиційні макроекономічні та агентні моделі (ABM) ринку нерухомості здебільшого ігнорують цифровий шар сучасних PropTech-платформ. Моделюючи процеси метчингу через абстрактні макрофункції, ці підходи не здатні відобразити когнітивно обмежені реалії онлайн-пошуку нерухомості. Проте цифрові інтерфейси діють як активні «архітектори вибору». Закладені в них алгоритми ранжування, пагінації та фільтрації створюють нові цифрові тертя пошуку, що зумовлюють асиметрію інформації та

суттєво обмежують видимість доступних об'єктів для користувачів. Для подолання цієї методологічної прогалини у дослідженні розроблено концептуальні засади та алгоритмічне ядро агентної моделі платформи нерухомості, що ґрунтується на емпіричних даних клікстріму. З метою забезпечення архітектурної цілісності та наукової відтворюваності, запропонований підхід інтегрує п'ять провідних світових методологій – FREIDA, MAIA, підхід Smajgl et al., протокол ODD+D та фреймворк TRACE – в єдиний п'ятикроковий протокол розробки та валідації. У результаті створено нове алгоритмічне ядро, яке повністю замінює агреговані макроформули на стохастичну систему дискретних дерев рішень. Поведінка агентів динамічно формалізується через правила обмеженої уваги, локальної мікроконверсії, цінової адаптації продавця та евристики задоволення. Водночас емпірична ініціалізація атрибутів агентів здійснюється шляхом кластеризації сирих серверних логів, що забезпечує надійну data-driven мікроосновy. Інтеграція цифрової платформи як самостійного інституційного середовища дозволяє автентично генерувати «знизу вгору» складні емерджентні макрофеномени, такі як ефект інформаційної бульбашки та кількісний вплив алгоритмічного ранжування на ліквідність активів. Зрештою, застосування цього фреймворку зміщує парадигму дослідження нерухомості з абстрактного макроекономічного детермінізму до прикладної цифрової поведінкової економіки, гарантуючи високу прогностичну валідність і створюючи надійний інструмент для сценарного тестування бізнес-гіпотез.

Ключові слова: агент-орієнтоване моделювання, PropTech, ринок нерухомості, клікстрім, цифрова платформа, емерджентність, обмежена раціональність.