Autonomous Collective Housing Platform: Digitization, Fluidization and Materialization of Ownership

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Abstract. New social phenomena like digital nomads urge an upgrade in housing ownership. This research proposes an autonomous housing platform that shapes residential communities into adaptive and reconfigurable systems, framing a cycle of digitalization, fluidization and materialization of housing ownership. Specifically, the interactive interface carries the flexible ownership model that uses virtual space voxels as digital currency; the artificial intelligence algorithm drives the multilateral ownership negotiation and circulation, and modular robots complete the mapping from ownership status to real spaces. Taking project TESSERACT as a case study, we verified the feasibility of this method and presented expected co-living scenarios: the spaces and ownership are constantly adjusted according to demands and are always in the closest interaction with users. By exploring the ownership evolution, this research guides an integrated and inclusive housing system paradigm, triggering critical evaluation of traditional models and providing new ideas for solving housing problems in the post-digital era.

Keywords: Agent-Based Systems, Digital Platform, Housing Ownership, Space Planning Algorithm, Discrete Material System

1 Introduction

In the post-digital era, the fluctuating environment and complex demands are forcing a critical reshaping of traditional housing models. The deterioration of the natural and social environment, such as climate chaos, economic collapse, and pandemic threat, leads to rapid iterations in living behaviors and spaces. At the same time, the advancement of digital technology makes the living needs of individuals and groups present a trend of diversification and personalization. As a result, digital nomadism with frequent mobility has emerged: supporting a globalized nomadic life through online mobile work, corresponding to the temporary nature of the accommodation and the *intermittence of citizenship*. (Bravo, 2010) With the outbreak and spread of COVID-19, the number of digital nomads who make up today's workforce has increased significantly and continues to grow. The internal reasons include the employers' acceptance of remote work and the employees' desire for low living costs. The operation and transaction methods of traditional rigid housing ownership are facing unprecedented impact.

With the mobile requirement of population and ownership, the disruptive digital housing platform emerges as an online flexible and interactive information medium. The rapid expansion of rental-focused platforms such as Airbnb, which allows users to freely trade residential spaces of any size, form, and duration, is *increasingly blurring the boundary between short-term temporary uses and long-term residential uses*. (Ferreri & Sanyal, 2021) The rise of online platforms and the digitization of space property have intensified the mobility of social housing and profoundly affected the volatility of capitalist ownership, leasing practices, and space transactions.

The housing needs of digital nomads provide a particular research context to further explore the possibilities of ownership digitization and test new ideas for integration with the flexible housing platform. Therefore, from the perspectives of society, economy and architecture, this research proposes an autonomous housing model with digital ownership as a breakthrough to solve the current rigid ownership problem. As a unique platform medium, it shapes residential communities into adaptive and reconfigurable systems, framing a cycle of digitalization, fluidization and materialization of housing ownership. Taking the project TESSERACT as a case study, we build interactive interfaces to carry the flexible ownership model that uses virtual space voxels as digital currency, write artificial intelligence algorithms to drive the multilateral negotiation and circulation of ownership, and assemble modular robots to complete the mapping from ownership status to real spaces.

Finally, we verified the feasibility of this method within a certain scope and presented expected co-living scenarios: the spaces and ownership are constantly adjusted and circulated according to the demands and are always in the closest interaction with users. By exploring ownership evolution, this research establishes an integrated and inclusive global housing system paradigm, triggering critical evaluation of traditional models and providing new ideas for solving housing problems in the post-digital era.

2 Literature Review

Ownership refers to the owner's right or state to possess, use, benefit and dispose of property, and its evolution has activated different models of private property rights that shaped the principal economic models of society.

(Athiana, 2019) As real estate, the ownership of housing establishes a deep connection and bond between people and land (living spaces), making residence an accumulation of property and a manifestation of power, and nurturing the formation of personal belongingness and the preservation of social stability. Historically, different forms of housing ownership have significantly shaped the evolution of the residential environment (cities and architecture), and vice versa, the development of both can also lead to new modes of ownership. Today, the direct, stable, and limited relationship between people and the land will be disrupted and transformed into an indirect, online, and broader interconnection.

As a supporter of this interconnection, interactive platforms originate from the new raw material of capitalism in the digital era: data as a way to maintain economic growth. *Platform capitalism* (Srnicek, 2017) enables interaction between different roles, allowing users to create their own products, services and marketplaces, enhancing the concentration and circulation of ownership. In this context, such digital technologies for housing are referred to as *"platform real estate", which better encapsulates the connective capacities and paths of action related to ownership, use, and exchange of land and buildings*. (Shaw, 2020) The prosperity of digital platforms changes the relationship between capitalism and housing problems, facilitating the informal expansion of the real estate industry, exacerbating the dynamics and indeterminacy of social housing, and advancing the digital transformation of the present ownership model and space transaction mechanism.

In the practice or research of digital housing platforms, new ownership and transaction models are constantly emerging. In practice, representative platforms such as Airbnb and WeLive, mainly based on rental services, can trade limited ownership like use rights. Among them, *Airbnb allows common homeowners to rent out vacant rooms of any size, form, and duration as accommodation for tourists*. (Guttentag, 2015) The system reservation mode is similar to that of a hotel: the owner uploads free space information, and the tenant searches the space according to specific needs, so that both parties can rent or book different types of spaces freely and conveniently, realizing the segmentation and refinement of the ownership and subverting the traditional leasing method. *WeLive, on the other hand, is committed to creating a mutual community.* (Hansen-bundy, 2018) The operator centralizes static ownership and distributes mobile use rights to tenants, encouraging them to share and exchange spaces, organize group activities, form social networks, and regain the healing properties of communities.

Research on housing platforms based on advanced algorithms and artificial intelligence technologies provides new ideas of ownership evolution. The project *Nomas* (Hosmer et al., 2020) has set up an ownership exchange system: users have a stable spatial state within the platform and can switch between various locations in the world to adapt to a globalized nomadic life. Unlike the platform in Welive, which tends to be a social network, Nomas has artificial intelligence algorithms as the backbone, which is not only the brain responsible for plan generation and evaluation, but also the bridge linking different roles. However, since the opposing position between investors and users still exists, the fairness and neutrality of the algorithm need to be discussed and supervised. *Public Parts proposes an autonomous communal life platform managed by artificial intelligence* (Rodrigues et al., 2021), which adopts a collective ownership model where occupants jointly possess the housing community and participate in space assembly and system maintenance. This project completely removes capital from the platform, relies on artificial intelligence algorithms for space allocation and organization, and creates a user-driven resocialized community with a communist nature.

In Airbnb, WeLive, and Nomas, the use rights are finely distributed to each user, while in Public Parts, the ownership belongs to the entire collective. These two types of attempts represent different approaches to realizing ownership innovation, facilitating transactions of rights and exchanges of spaces. However, due to the simplification of the traditional capital operation relationship, the latter is more inclined to an idealistic harmonious vision based on the user's moral level and technical literacy, which may hide practical problems that are difficult to solve. This research still hopes to retain the variable relationships between investors and users in digital platforms to promote the further digitization and quantification of ownership rather than just blurring the concept in a utopian commune.

3 Methodology

The project TESSERACT is a futuristic housing platform for digital nomads and other mobile lifestyles. Through the overall quantification of the ownership model, a user-centered global housing system with a continuous lifecycle is constructed to realize the free interaction and rapid circulation of ownership. Its research process revolves around the three steps of digitalization, fluidization, and materialization of ownership:

1) Digitization: the integrated digital platform undertakes comprehensive management, defining a flexible ownership model with voxelized space nodes as vectors of digital ownership.
2) Fluidization: the multi-agent algorithm based on reinforcement learning drives the multilateral negotiation and circulation of ownership to provide solutions and balance interests.
3) Materialization: the discrete robotic material system completes the construction and reconfiguration of physical spaces, enabling the material mapping of ownership.

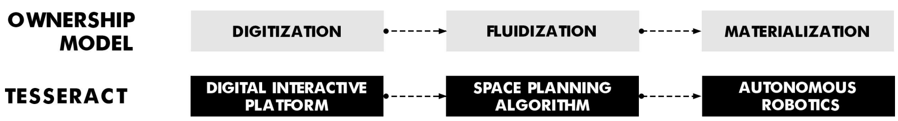

Figure 1. The Correspondence between digital ownership research process and TESSERACT system composition. Source: Authors**.**

3.1 Ownership Digitization Rooted in Interactive Platform

The platform-based digitalization of ownership in TESSERACT separates ownership from geographical locations or territorial belongings and quantifies it as an abstract digital code in the platform database. Digital ownership can retain value across relocations and expand, contract, transfer and circulate anytime and anywhere.

Specifically, the ownership model relies on a 3D grid consisting of discrete space voxels with side lengths of 0.3m. Each voxel in the grid contains basic information such as ID, position, typology, color, and multi-level feature information related to living, including lighting conditions, landscape views, etc. According to their information status, the nodes have different ownership codes and values. For example, the value of nodes with sufficient sunshine in the site is generally higher than those without sunshine. In the operation process, the characteristic information will be imported in the form of a formula or a bitmap and converted into a three-dimensional matrix with a value between 0 and 1. The superimposed ownership value is the sum of the products of these different data information D and the value coefficient K.

$$O_N=K_1*D_1+K_1*D_1+....+K_1*D_1 \quad (1)$$

At this time, the traditional possession of the whole building is quantified as the occupation of the space voxels. Therefore, the partial ownership set of all nodes occupied by the spaces forms the overall ownership in the platform.

$$O(User)=O_{N1}+O_{N2}+....+O_{NI}=O_{space} \quad (2)$$

In addition, the concept of Space Currency (SC) is introduced as transaction chips in the digital platform, which measure the specific value amount of ownership in different space voxels.

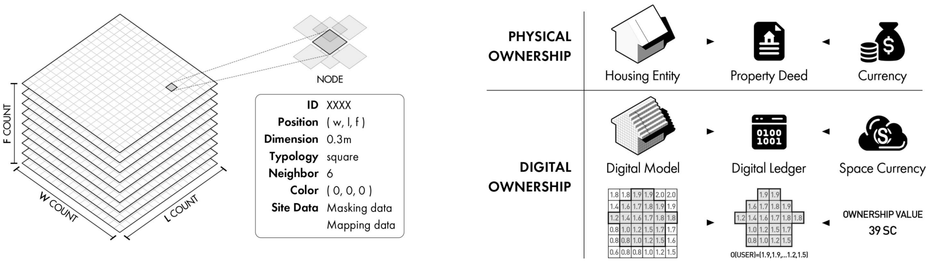

Figure 2. Left: the 3D grid and a node. Right: the comparison between traditional physical ownership and digital ownership. Source: Authors**.**

Based on the above principles, when users enter the platform, they can buy and hold a certain amount of space currency according to the local exchange rate and purchase the ownership of the space voxels required for the corresponding residence in the base station. If users would like to change the living range, they only need to resell the unnecessary space voxels to other users or the system and buy new parts. In order to incentivize customer to customer (C2C) space tradings, the ownership transaction fee among users is lower than that between users and the system.

3.2 Ownership Fluidization Driven by Space Planning Algorithm

The flow of digital ownership in TESSERACT coincides with the exchange of users' living space, forming the essential part of the housing platform. Therefore, a user-oriented distributed spatial planning algorithm, which takes a multi-agent system as a framework and integrates bottom-up local agents and top-down global constraints, is developed to coordinate user needs, site conditions, investment programs, and other multilateral elements and relationships. Additionally, the implantation of reinforcement learning realizes the behavior control of the agent to adapt to the changes in users' living and social needs, completing the real-time generation and reconfiguration of the spaces and continuously promoting ownership circulation.

The space planning algorithm operates on the above-mentioned three-dimensional grid, which contains a set of programmable colored agents representing spaces owned by users. Based on specific behavior patterns, these agents occupy space voxels to expand the territorial ranges and form internally closed geometries. Through the release of pheromones, they conduct constant communications with neighbors and the environment, shaping spatial boundaries in the negotiation among multiple agents.

3.2.1 Ownership Configuration

For each user, the configuration of ownership corresponds to the generation of spaces, related to the individual living demand. Therefore, this algorithm introduces Space Code to correlate the user's specific needs for the room as the local target of the planning behavior. It consists of three parameters describing volume, proportion, and form, representing the space size, the aspect ratio, and the basic shape of the required space. A Space Code links a separate living space, and a user can set multiple codes. In this case, the digital ownership of the user is:

$$O(User)=O_{Space1}(V_1,P_1,F_1)+O_{Space2}(V_2,P_2,F_2)+...+O_{SpaceN}(V_N,P_N,F_N) \quad (3)$$

Reinforcement learning is applied as a decision-making mechanism to control the operation strategy of the agent in real-time, mapping the parameters in Space Code to the planning behavior to form a voxelized model. The training dataset is 600 groups of parameters generated by random combinations of {V, P, F} within a defined range. The agent's behavior is controlled by policy (x, y, z), in which the three variables represent the growth intensity in each direction. The training purpose is to help the agent respond to Space Code, continuously adjusting the parameter combinations in the policy to make the occupied region match the design goal. The training rewards include immediate rewards (the captured node is within the target range), staged rewards (the proportion of qualified nodes reaches 30%, 60%), and final reward (the proportion of qualified nodes exceeds 95%). After $6*10^6$ episodes, the training curve is basically stable. At this time, the agent can adapt to the changes in Space Code in real-time and accomplish the corresponding space planning tasks.

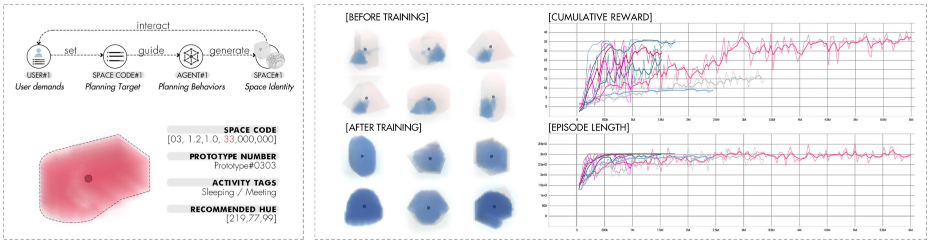

Figure 3. Left: the principle and example of Space Code. Right: The behaviors of the agents after training, and the graphs (pink one success) with the cumulative reward and the episode. Source: Authors**.**

3.2.2 Ownership Circulation

For multiple users, the circulation of ownership corresponds to the reconfiguration of spaces, related to the collective organizational inclination. The algorithm uses Negotiation Code to meet the adjacency requirements of users or the system, guiding the attraction and repulsion behaviors between multiple agents and realizing the negotiation and transaction of node occupancy through deformation or displacement. Similarly, the Negotiation Code is also composed of three parameters. The ownership contains the part based on Space Code and the other part affected by Negotiation Code:

$$O(User)=O_{Space1}(V_1,P_1,F_1)+O_{Space2}(V_2,P_2,F_2)+...+O_{SpaceN}(V_N,P_N,F_N)$$
$$+O_{Negotiation1}(I_1,C_1,E_1)+O_{Negotiation2}(I_2,C_2,E_2)+...+O_{NegotiationN}(I_N,C_N,E_N) \quad (4)$$

Specifically, in Negotiation Code, Interaction Tendency represents the adjacency willingness between the agent and its neighbors. For each surrounding agent, there is a weight factor $K_{I\text{-}A}$ between [-2,2], which guides the generation of attractors and determines the repulsive or attractive strength. Cluster Tendency is expressed as K_C between [-1, 1], describing the agent's relationship to space clusters of similar or opposite colors.

Environment Tendency demonstrates the agent's thirst for environmental resources. The factor K_E aggregates their reaction to preset site information, leading to specific behaviors such as phototaxis or light avoidance.

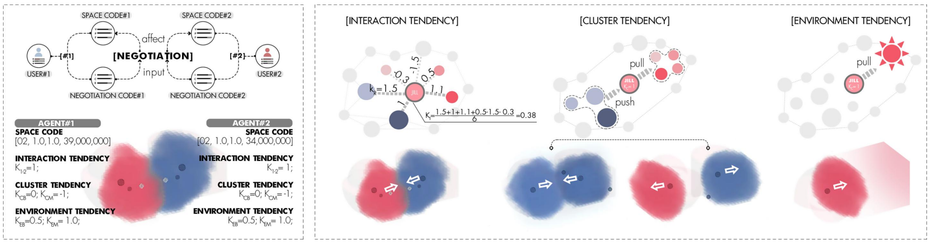

Figure 4. Left: the principle and example of Negotiation Code. Right: Three parameters of Negotiation Code. Source: Authors**.**

3.2.3 Ownership Restriction

For the entire space system, the global constraints are embedded in the discrete planning environment in the form of data matrices, not only including information such as lighting conditions that determine the value of space ownership, but also includes the global regulation behind the platform: imposing necessary restrictions on changes in digital ownership through influencing the planning behaviors of the agents. Among them, masking data is used to mark areas that cannot be occupied by living spaces, such as core tubes, historical relics, public squares, etc., while mapping data can record the natural and social background and zoning information in the planning environment.

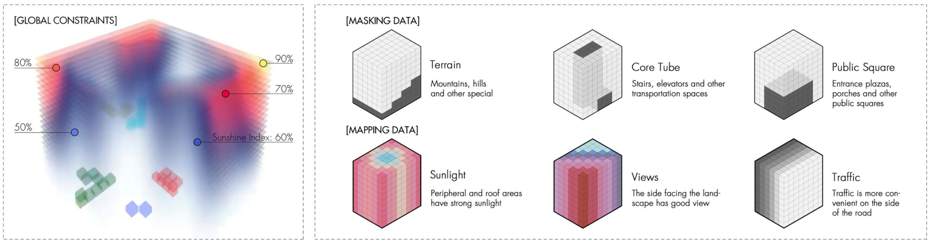

Figure 5. Left: the example of a global constraint in the planning environment. Right: the examples of mapping data and masking data. Source: Authors**.**

3.3 Ownership Materialization Supported by Robotic Material System

Materializing digital ownership is the last step in the TESSERACT platform operational process. The autonomous material system composed of voxelized static components and modular robots maps the changes of virtual projects to the reconfiguration of physical reality in real-time. In the prototype design, the static component and the robot are cubes with a side length of 0.3m, corresponding to voxels in the ownership model. The static components are bricks that make up the building, shaping spaces by stacking and combining, while the robots are equipped with power units, reconfiguring spaces by actively changing the positions of the static components.

In terms of fabrication, the static components can be divided into actuation, structural, and panel parts. The actuating parts facilitate relative sliding and locking, equipped with cross slots in the positive directions of each axis and flat knobs in the opposite. The structural parts form a frame with tracks for gears in the knobs. The panel parts determine the decorative coating, which can be replaced according to the user's preference or selected from the traditional materials to blend into the local built environment. Modular robots are the same size as static components with similar fabrication details, but structural parts are filleted to prevent collisions during movement. Two servomotors are installed behind each knob for driving and steering. The body of one robot consists of three linked cubic parts forming an L-shaped combination with an action mode for sliding its cubic parts along tracks in its body or in static parts. Robots can slide, change direction, push and pull, and lock and unlock through the mutual collaboration for reconfiguration tasks.

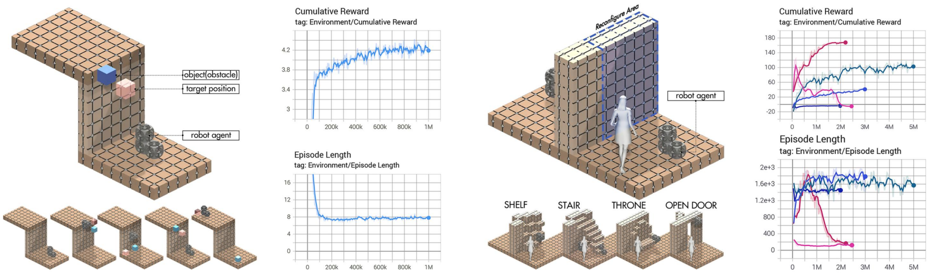

Figure 6. The training models and the training results of robots. Source: Authors**.**

Reinforcement learning is used to formulate adaptive strategies for the robots to coordinate the biased and constrained behaviors in dynamically changing structured environments. The simulator was set up with L-shaped robots composed of three independent agents taking observations of the current and target state of each agent and component to carry on a curriculum learning with increasing difficulty. The reward is set to be inversely proportional to the distance from the target. If situations like falling off the bounds or touching the obstacles occur, the agent will be punished by -1 point, and rewarded with 10 points when reaching the target position. Additional rewards are also related to metrics such as robot energy consumption. In the final training results, the robotic agents can autonomously select moving targets, arrange action steps, complete the construction and reconfiguration tasks of various spatial states such as opening doors and windows, laying stairs, and shaping furniture with strong execution and cooperation capabilities.

4 Results

This digital ownership model is of great significance for maximizing space utilization. It makes space transactions as convenient as mobile payment and substantially stimulates users' willingness to update the current space. By assigning extra spaces or deploying activity venues, the system meets and adapts users' various requirements for living, realizing the rational allocation of space resources. Besides, this model allows users to camp in different base stations around the world, establishing a global housing pattern. When the user has travel, business trip, immigration and other needs, the digital ownership can be automatically transferred to the target site to generate a remote residence that conforms to the accustomed lifestyle, maintaining a warm sense of belonging.

In the circulation of digital ownership, the space planning algorithm establishes a multilateral convention to maintain the AI-assisted algorithm's position as an intermediary between users and investors, balancing the reasonable interests of each party. In a range of 12m*12m*6m, we conducted experiments on the space group generation with five agents to simulate the ownership activities of two users in the system. In the experiment, the Cluster Tendency is set to 1 to ensure that agents of the same user form a group. By adjusting the Interaction Tendency, we simulated the gradual process of the organizational relationship between two users from no tendency to mutual resistance and mutual acceptance. The real-time planning results are shown in Figure7. The space occupancy relationship is negotiated, and different spatial forms emerge, verifying the algorithm's ability to drive ownership flow and promote mobility.

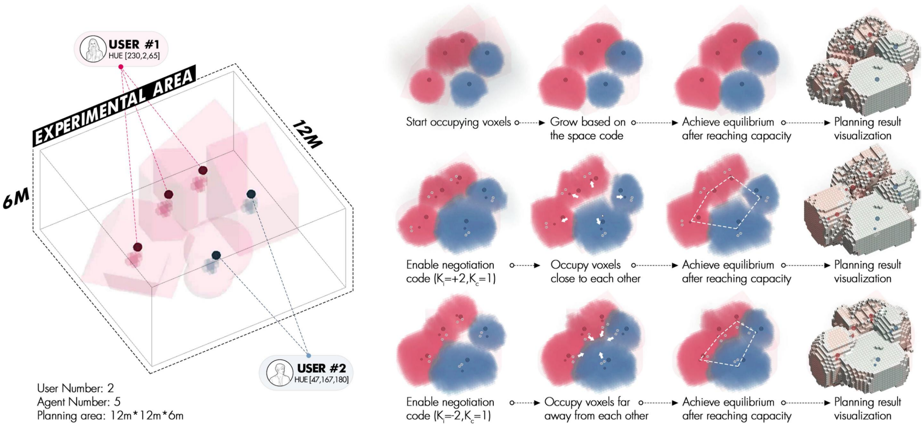

Figure 7. The planning process of three stages in the experiment. Source: Authors**.**

Finally, the material system is the basis for the materialization of ownership, giving the housing system unique flexibility. The physical prototypes are manufactured by 3D printing at a scale of 1:1. The two servomotors installed on the robotic knobs are Dynamixel AX-12A, driven by Raspberry Pi to link their speed, rotation angle, and other information with the digital model in Unity3D. In the experiment, the robots can achieve basic tasks such as handling, pushing and pulling, which preliminarily proves the feasibility and stability of the system.

The above results effectively demonstrate the viability and integrity of TESSERACT as a housing model with digital ownership, which can support nomadic life in the context of requirement complexity and extreme mobility.

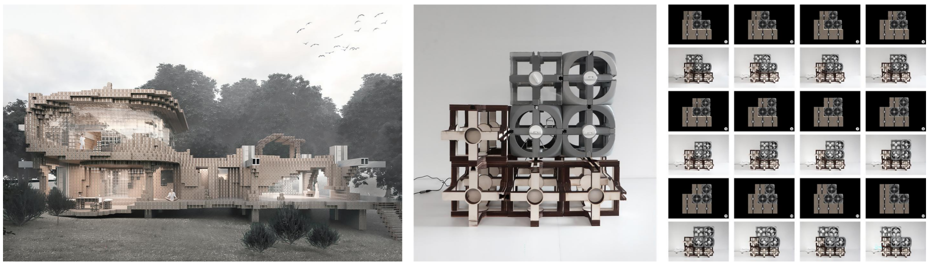

Figure 8. Left: project TESSERACT rendering. Right: the experiment of pushing and pulling a static component. Source: Authors**.**

5 Conclusion

In the post-digital era, the dwelling needs of digital nomads provide a special research context, and digital housing platforms' model updates traditional socioeconomic issues. By reflecting on the concept of solidified physical ownership, this study comprehensively explores a new model of housing ownership and the co-living vision in autonomous housing systems through the cycle of ownership digitization, fluidization, and materialization.

TESSERACT enables different groups to obtain equal and direct access to decision-making and interaction to fully coordinate various housing requirements. At the same time, the flexible and mobile digital ownership model transforms the concept of property from a territorial attribution to a digital symbol, while encouraging residents to sell idle space resources at any time to realize the system's transformation and maximize spatial utilization. TESSERACT is a promising model to test new capital ideas and digital intelligent design, leading to the circulation and reallocation of ownership. It forces a revolution in the housing industry, activating new ways of working and inhabiting and driving the grow of an autonomous architecture system.

In future work, more simulations based on real big data and participated by actual users are crucial, including the construction and optimization of interaction interfaces, the introduction of technologies such as blockchain to ensure fairness and transparency of AI, and the experiments on stronger mechatronics to shape large-scale spaces, etc. In addition, more evaluation mechanisms and visualization methods need to be introduced to better control the rationality of the generated spaces. TESSERACT proposes a well-thought-out vision for a housing system, showing the unwavering courage and unprejudiced attitude to face the conflict of post-digital housing issues.

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