

Article

Evaluation of Universal Accessible Housing (UAH) Design Using Virtual Reality: A Focus on Circulation Areas

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Abstract: Independent living is a central goal for people with disabilities, and the accessibility of the home environment plays a key role in achieving it. In particular, circulation areas within the household are essential to ensure autonomous and safe mobility. Although regulations guide the design of accessible housing, they do not always account for the specific needs of users. This study proposes a method for evaluating the design of universally accessible housing (UAH) through virtual reality simulations, with an emphasis on circulation areas. The Design Science Research Methodology (DSRM) was used to structure the study, guiding the development of an immersive virtual environment that integrates a housing model designed according to physical accessibility standards established by Chilean regulations. The simulation recreated everyday situations related to independent living, assessing indicators such as collisions with environmental elements, the time required to perform specific tasks, and the difficulty of maneuvering a wheelchair. The results show that the use of virtual reality enables the early identification of accessibility barriers from the end-user perspective, allowing design adjustments before construction and contributing to more inclusive and user-centered planning.

Keywords: virtual reality; accessibility; BIM; disability; housing design; accessible housing



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1. Introduction

1.1. Disability and Accessible Housing

In recent decades, an approach has been consolidated that recognizes the central role played by physical and social barriers in limiting the full participation of people with disabilities in everyday life [1]. This perspective has driven a paradigm shift from a deficit-based model to one that promotes inclusion, equal opportunities, and autonomy [2]. Disability can affect anyone at different stages of life—due to age, illness, accidents, or the natural aging process—highlighting the need for built environments that accommodate this diversity [3]. This aligns with the social model of disability, which posits that disability arises from the interaction between individuals with impairments and attitudinal and environmental barriers that hinder their full and effective participation in society on an equal basis with others [4]. Consequently, the pursuit of “inclusive immersion”, maximizing accessibility and enjoyment for users with diverse capabilities in emerging digital and

physical environments, has become a significant objective [5]. The overarching goal of inclusive design is to understand diversity to inform design decisions that maximize usability for as broad a population as possible [6]. In this context, universal accessibility is established as an essential principle for ensuring environments that are safe, autonomous, and usable by all people, regardless of their abilities [7]. Universal design, as a design strategy, seeks to integrate this diversity from the outset of the design process, promoting inclusion through housing solutions that consider the physical, cognitive, and sensory capacities of inhabitants [8]. This approach is closely linked to ergonomics, as it considers the characteristics, needs, and abilities of individuals in the configuration of habitable spaces that are functional, safe, and comfortable [9].

Housing is one of the most important spaces for exercising the right to independent living [5,6]. Therefore, accessible design must go beyond mere compliance with regulatory parameters and ensure that people can move and function autonomously within their homes. In this regard, circulation and access areas are fundamental components, as they provide spatial and functional continuity within the home [7]. These areas must guarantee obstacle-free paths, adequate turning spaces for assistive devices such as wheelchairs, and fluid connections between different rooms [8]. Their proper design directly impacts a person's ability to perform daily activities—from moving freely to accessing basic household services. Advancing the design of accessible housing thus requires a person-centered approach that prioritizes the quality, continuity, and safety of circulation areas, understood as key elements in enabling functional autonomy within domestic spaces [10,11].

1.2. Virtual Reality to Support the Design of Accessible Housing

In recent years, virtual reality (VR) has emerged as a powerful tool across various fields of knowledge, enabling users to interact with three-dimensional computer-generated environments through immersive devices such as VR headsets, sensors, and haptic controllers [11,12]. This technology allows the recreation of realistic and controlled scenarios, where it is possible to simulate events, experience environmental conditions, and make informed decisions based on the visualization and immersion in these spaces [13,14].

In the field of Architecture, Engineering, and Construction (AEC), VR has proven effective in reducing the time and cost associated with design iteration phases, facilitating early project visualization and promoting collaboration among diverse stakeholders [15,16]. Virtual housing prototypes can be evaluated by professionals, users, and experts, allowing early feedback and significant improvements in quality and functionality [17]. Traditional design review processes often rely on 2D orthographic projections and renderings, which can be abstract and fragmented, requiring expert interpretation and potentially leading to miscommunication and rework [18]. Extended Reality (XR) technologies, such as VR and Mixed Reality (MR), offer a more intuitive means of design comprehension. For instance, studies using MR have shown effective communication of 85% of design information compared to 70% with 2D media, alongside enhanced understanding of material aesthetics [19]. Specifically, in the design of accessible housing, VR offers a valuable opportunity to experience spaces from the perspective of a person with a disability prior to construction [20,21]. By integrating three-dimensional architectural models into immersive environments—many of them developed using Building Information Modeling (BIM) tools—it is possible to validate both regulatory and functional aspects of accessibility, going beyond mere dimensional verification [22]. This capability is crucial as research in VR accessibility actively explores novel interaction techniques tailored to users with specific needs, considering trade-offs between accessibility, realism, and spatial awareness [23,24]. The inherent advantages of VR, including a wide field of view, high customizability, and an immersive sense of presence, make it a suitable platform for simulating how individuals,

such as wheelchair users, experience and navigate designed spaces [25]. Moreover, the integration of XR with BIM is a significant and growing trend in the AEC sector. VR, in particular, is frequently paired with BIM in design and engineering case studies to enhance stakeholder collaboration and design understanding, thereby supporting more informed decision-making [26–28]. This allows for the simulation of assistive device maneuvers, identification of mobility barriers, and early detection of specific adaptation needs before project execution [29].

Additionally, virtual reality can facilitate co-design processes, enabling the active participation of people with disabilities in the evaluation and refinement of housing designs. Such early inclusion not only captures specific accessibility requirements but also promotes the development of personalized solutions that effectively address diverse individual needs and contexts [16,30]. From this perspective, VR becomes not only a technical validation tool but also a means of empowering individuals who have historically been excluded from design processes, strengthening their sense of ownership and influence in decisions that affect their quality of life [19,31]. Several initiatives aim to incorporate virtual reality as a method for evaluating accessible design. Immersive virtual environments stand out as an effective visual communication tool among designers, users, and AEC professionals [32]. However, technical, methodological, and implementation challenges persist, limiting the widespread adoption of VR in accessible design practices [33,34]. Indeed, while the potential of immersive environments like the Metaverse to enhance digital accessibility is considerable, realizing this potential requires that accessibility principles are embedded within their core design and development, addressing current gaps in assistive technology integration and interoperability [35].

1.3. Gaps and Research Objectives

The right to independent living has been widely recognized as a fundamental principle for people with disabilities, as established by the Convention on the Rights of Persons with Disabilities [9,24,36]. This right entails not only the freedom to choose where and with whom to live, but also the need for environments that support autonomy and full participation in everyday life [25,37]. In this context, housing plays a central role as a space for personal and social development [26,27,38]. Despite these advancements, explicit gaps remain evident in the current literature and practices, highlighting significant limitations that require further research attention. Specifically, three primary gaps have been identified, which are outlined below:

- **Lack of standardized and user-centric methodologies:** Existing approaches predominantly address minimum regulatory requirements without sufficiently integrating user experience and real-life functional needs, resulting in solutions that frequently fall short in practical contexts.
- **Limited customization in accessibility assessments:** Current regulatory frameworks typically adopt generalized criteria, inadequately accounting for the diversity of individual capabilities, preferences, and daily challenges faced by people with disabilities. This approach often compromises the actual usability and effectiveness of designed spaces.
- **Insufficient validation of emerging technologies (VR and BIM) for pre-construction evaluation:** While virtual reality and its integration with Building Information Modeling (BIM) have recognized potential, there remains a notable shortage of rigorous, validated methodologies explicitly focused on evaluating housing accessibility during the design stage, particularly concerning diverse disability types and realistic daily-life scenarios.

Considering these explicitly identified gaps, this study emphasizes the critical limitation of standardized regulatory approaches, which frequently fail to capture the diverse needs, experiences, and spatial habits of individuals with disabilities [28,35]. This limitation is particularly critical in circulation areas, where small design errors can become significant barriers to safe and autonomous mobility within the home. In this scenario, virtual reality (VR) emerges as a promising technology to address these gaps by enabling pre-construction functional evaluation of spatial designs [34,35,39,40], and its integrations with BIM is enhancing design review processes in the AEC sector [5,7]. However, its application still faces challenges, including the lack of specific methodologies for accessibility analysis and the need to adapt virtual environments to different types of disabilities, such as sensory or cognitive impairments [29].

To address this issue, the general objective of this research is to evaluate the design of universally accessible housing (UAH) in virtual reality environments, with a focus on circulation areas. To achieve this, key parameters related to the design and assessment of these areas are identified and analyzed using virtual reality as the primary tool. Based on this analysis, conceptual elements and indicators are developed and programmed within the virtual environment to assess circulation and functional accessibility. These components are implemented in VR scenarios simulating daily life situations, allowing users to interact and move through the space in first-person view. Finally, these scenarios are validated and tested by experts to assess their effectiveness in identifying accessibility barriers and to support design adjustments that contribute to more inclusive, user-centered housing solutions.

2. Research Methodology

For the development of this research, the Design Science Research Methodology (DSRM) was used. This methodology allows for a practical representation of the research process, structured into five stages: (1) identification of observed problems, (2) definition of objectives for a potential solution, (3) design and development, (4) implementation, and (5) evaluation. Figure 1 outlines the research scenarios and activities, along with the tools and methodologies used throughout the process.

In Stage 1, the key parameters for the design and evaluation of universally accessible housing (UAH) using virtual reality (VR) were defined. A literature review was conducted using scientific databases such as Web of Science and Scopus, complemented by the analysis of technical standards, regulations, and reports at both national (Chile) and international levels. Based on this information, a collaborative analysis was carried out to assign representative values to the identified parameters. A subsequent comparative analysis between national and international standards was conducted to establish a robust foundation for validating these parameters.

Stage 2 aimed to define the scope of a technological solution in response to the identified challenges. In this context, virtual reality was proposed as a powerful tool to evaluate the design of accessible housing. The requirements derived from the parameters defined in the previous stage were addressed by leveraging the potential of VR to create realistic and immersive evaluative environments. In Stage 3, the evaluation method for accessible housing in VR environments was conceptually designed. This stage included four main activities: (1) the creation of the methodological procedure, outlining the workflows for conducting evaluations; (2) the definition of how accessibility parameters would be implemented in the virtual environment; (3) the development of data collection systems based on these parameters; and (4) the creation of an evaluation rubric for the immersive experience.

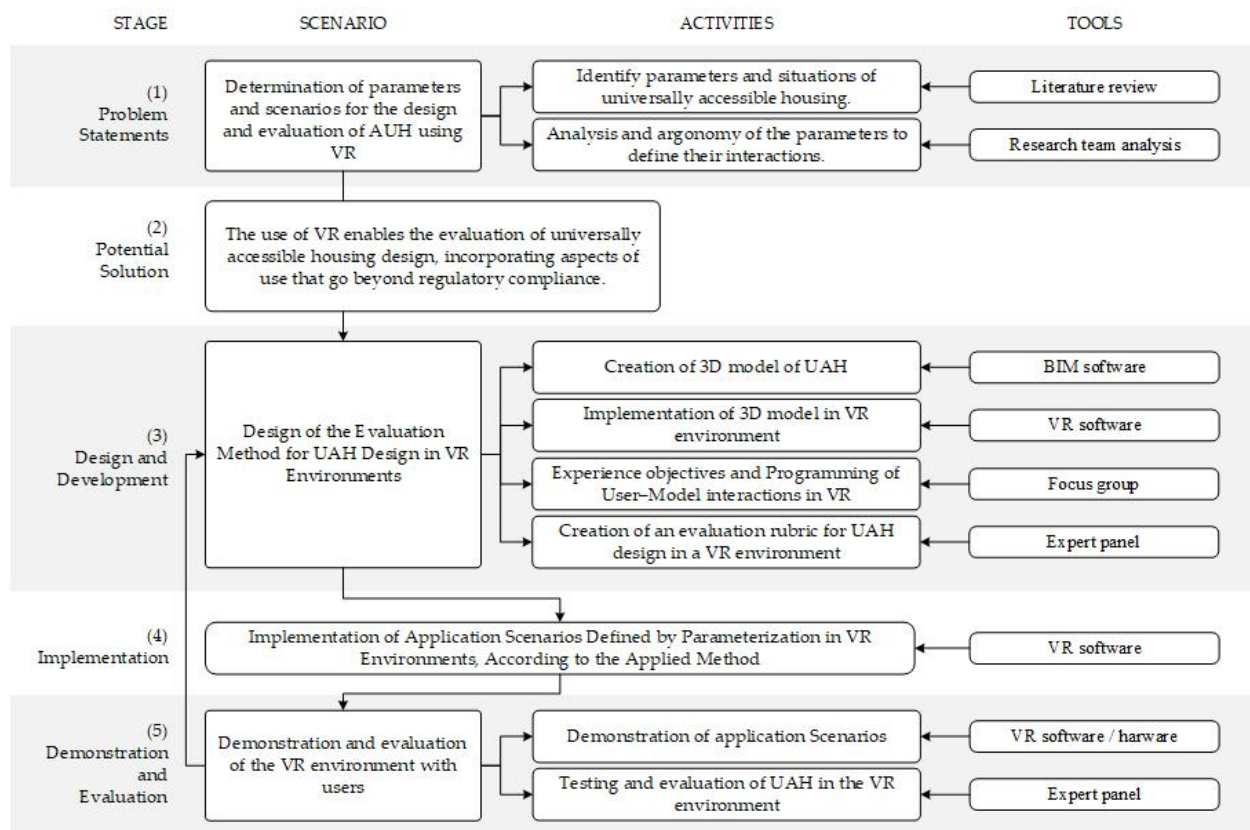


Figure 1. Research methodology.

In Stage 4, the VR tool was implemented based on the previously designed method. To demonstrate its application, a housing unit was selected as a case study. A 3D architectural environment was modeled using BIM software (Autodesk Revit, 2023 version), considering the critical aspects to be evaluated. The model was then imported into the VR development platform (Unreal Engine), where immersive and interactive dynamics were programmed—first-person navigation, collisions, environmental physics, interactive objects, information menus, and visual feedback, among others. Finally, in Stage 5, corresponding to the demonstration and evaluation phase, the method was tested alongside the defined scenarios. A group of experts was selected to validate the tool based on their experience in accessibility and immersive technology development. The evaluation used three instruments: the Simulator Sickness Questionnaire (to assess cybersickness), the User Experience Questionnaire (to evaluate usability), and the Presence Questionnaire (to measure immersion levels). Both qualitative and quantitative analyses were conducted to validate the tool and its functional components.

3. Proposed Workflow for the Tool Design

With the aim of evaluating the functional accessibility of circulation areas in universally accessible housing (UAH), an immersive virtual reality experience was developed, structured into five methodological stages. Figure 2 illustrates the proposed workflow for the development of an evaluation tool for universally accessible housing design in virtual reality environments. The process comprises five stages, ranging from the definition of the type of housing and the relevant regulatory and ergonomic parameters, to the implementation of an interactive virtual environment that simulates everyday situations from the perspective of a wheelchair user. The proposed approach combines the use of BIM models, realistic environmental rendering, movement and interaction programming through Blueprints in Unreal Engine, and the integration of automated measurement systems to

record collisions, time spent in specific areas, and user interactions during the experience. While the tool is based on Chilean regulations [21] its analysis and applications are extensible to other international standards. It enables the creation of a controlled, realistic, and functional environment aimed at assessing accessible design under virtual conditions prior to construction, incorporating key elements for spatial performance analysis and facilitating the identification of accessibility barriers.

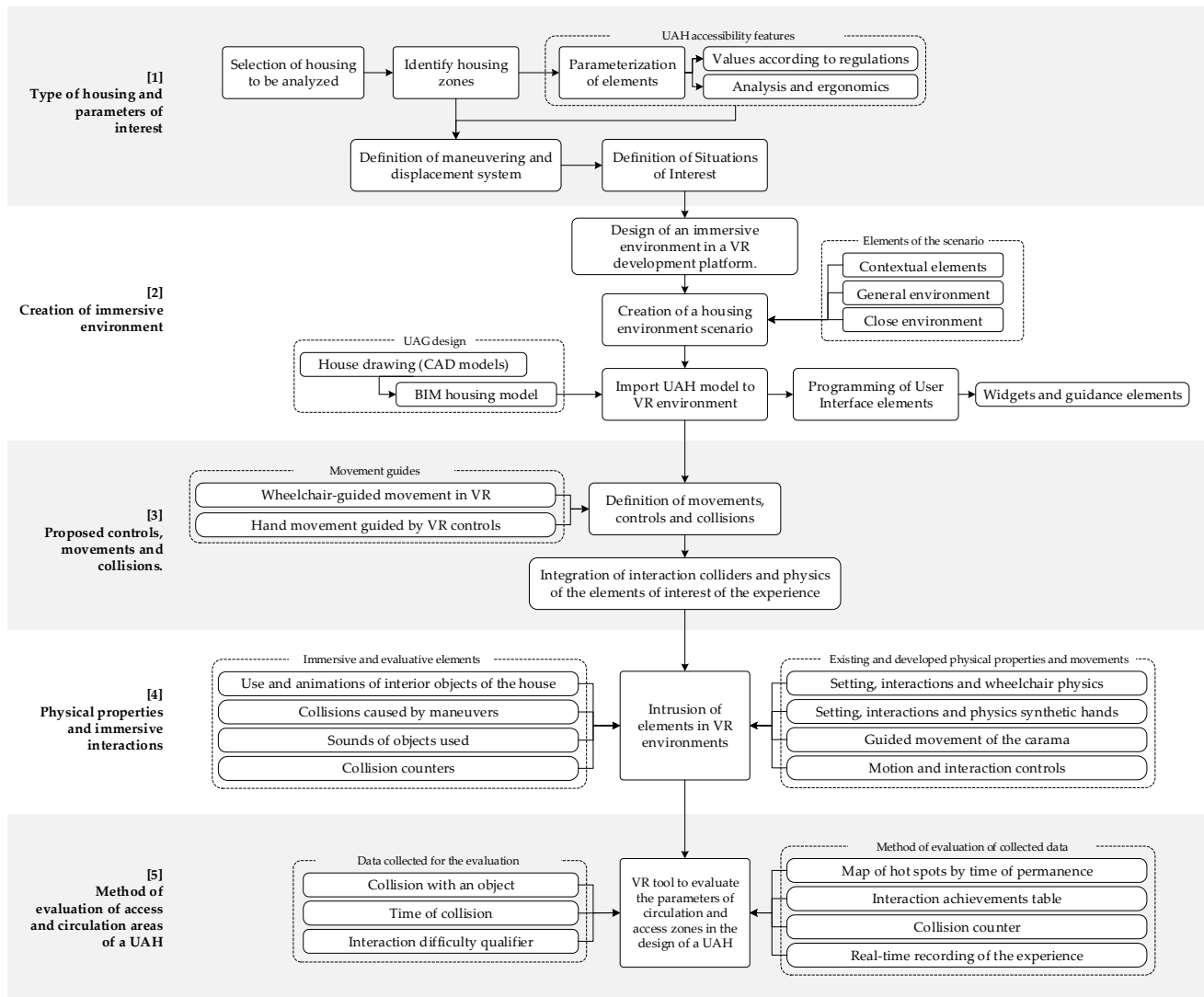


Figure 2. Proposed workflow for the tool design.

The following section describes each stage of the proposed workflow.

- **Stage 1—Type of Housing and Parameters of Interest.** This stage serves as the starting point of the process. The type of housing to be used is defined, along with the specific areas to be evaluated, focusing on interior access and circulation spaces. A set of parameters aimed at ensuring accessibility in these areas is identified, which must be analyzed based on current regulations and ergonomic criteria. This analysis considers the maneuvers a wheelchair user can perform within the home, as well as the everyday situations they may encounter in their daily life.
- **Stage 2—Creation of the Immersive Environment.** In this phase, the process begins with a BIM model (multi-parameter 3D model) of a previously designed accessible home. This model is exported in .FBX format for integration into the virtual reality development engine, Unreal Engine. Once integrated, the environment is enriched

with complementary elements to enhance realism, such as neighboring houses, sky, vegetation, lighting, and everyday objects like switches and doors. This environmental design aims to increase user immersion by adapting the virtual setting to an urban or rural context, depending on the housing location.

- Stage 3—Design of Controls, Movements, and Collisions. This stage involves the design of the user's movement and interaction logic within the virtual environment. The experience begins with the user seated in a virtual wheelchair, with leg movements disabled to maintain consistency with the represented avatar. No visible virtual character is included to avoid the perception of "another"; instead, only synthetic hands are used, positioned where the VR headset controllers are gripped. A conceptual interaction model (hands, wheelchair, and camera) is defined, establishing possible movements guided by the wheelchair, which acts as the pivot for first-person navigation. The virtual wheelchair's dimensions were modeled to approximate standard adult manual wheelchair sizes, referencing common anthropometric data and the maneuvering space requirements (e.g., an approximate width of 70 cm and a length ensuring a 1.5 m turning diameter). While a formal kinematic calibration against a specific real wheelchair model was outside the scope of this study's initial development phase, the movement dynamics (forward, backward, and rotation speed via joystick control) were iteratively adjusted during pilot testing to ensure intuitive control and representative maneuverability for basic navigation tasks. The fact that participants were seated in a physical wheelchair during the VR experience also aimed to enhance the perceived authenticity of the interaction.
- Stage 4—Physical Properties and Immersive Interactions. At this stage, the physical properties of the virtual environment and the key interactions for evaluation are defined. Collider Collision detection was managed using Unreal Engine's built-in physics engine and standard collider components attached to the virtual wheelchair and relevant environmental elements. The engine's capability to detect geometric intersections between these colliders is a core and generally reliable function for identifying contact events. Our implementation focused on registering these detected collision events for data collection. The specific response to a collision (e.g., stopping movement, audio feedback) was then programmed based on these detected events. The user's movement is controlled via the VR headset joysticks: the left joystick moves the user forward and backward, while the right joystick controls wheelchair rotation. The main camera is adjusted to eye level to maximize immersion. Additionally, prefabricated camera movement and synthetic hand motion are incorporated, both responding to the real position of the controllers. Users can interact with elements such as doors (which open 90° using animations triggered by the synthetic hands) and light switches, all programmed through Blueprints. These virtual actions enhance realism and enable functional evaluation of access and circulation areas under controlled conditions.
- Stage 5—Evaluation Method for Access and Circulation Areas in UAH. Finally, with all elements integrated (movements, collisions, and interactions), an evaluation system is established to guide users through the environment naturally and intuitively. During the experience, key data are collected, including the number of collisions between the wheelchair and environmental elements, time spent in specific areas (measured in three-second intervals), and interactions with virtual objects. These data are automatically recorded by Unreal Engine at the end of the experience, generating a report used to construct heat maps from the floor plan view. These maps reveal areas with the highest levels of interaction and permanence, as well as critical collision points. The information obtained forms the basis for evaluating the accessibility parameters

defined in this study and for proposing design adjustments that better respond to users' real needs.

4. Design, Development, and Implementation

4.1. Parameterization, Analysis, and Ergonomics for the Rirtual Reality Experience

To develop a conceptual design of the elements that constitute a universally accessible housing (UAH) unit, along with the indicators to be programmed in the virtual reality environment, the process begins with the first stage of the methodology. This stage focuses on the design and evaluation of maneuvers and interactions within circulation areas, specifically aimed at individuals with physical disabilities, with the goal of ensuring functional accessibility within the domestic space.

In this regard, a specific parameterization is proposed for the evaluation, analysis, and application of ergonomic criteria within the virtual environment. This research adopts a comprehensive approach to assess accessibility in a UAH, utilizing Building Information Modeling (BIM) methodology to create detailed 3D models, complemented by 2D floor plans. This approach enables precise visualization and analysis of how circulation dimensions and spaces comply with current accessibility regulations for people with physical disabilities.

The use of BIM models facilitates the early detection of architectural barriers and allows for the assessment of regulatory compliance from the initial design stages. Additionally, a clear strategy will be established for evaluating these parameters within the virtual reality environment. This strategy may include interactive simulations that enable experts to virtually experience and assess the home's circulation areas, aiming to ensure optimal accessibility design and to identify potential improvements prior to physical implementation.

4.2. BIM Model Export and Scenario Definition for VR Experience

To carry out the simulation, Autodesk® Revit software (2023 version) was used to export the reference model of the housing unit. This model was meticulously designed in accordance with current accessibility regulations and serves as the basis for implementing various scenarios within the virtual reality experience aimed at supporting the evaluation process. The model was imported into the Unreal Engine game engine using the FBX format, which is commonly used for 3D model integration.

Figure 3 shows the BIM model of the accessible housing unit. The scenarios developed for parameter evaluation include master bedroom, circulation hallway, kitchen, bathroom, secondary bedroom, small bedroom, and living–dining area. Each scenario was designed to collect data that contributes to the evaluation of the dwelling in terms of circulation areas, based on current accessibility standards, with the goal of identifying both compliant zones and areas with potential for improvement.

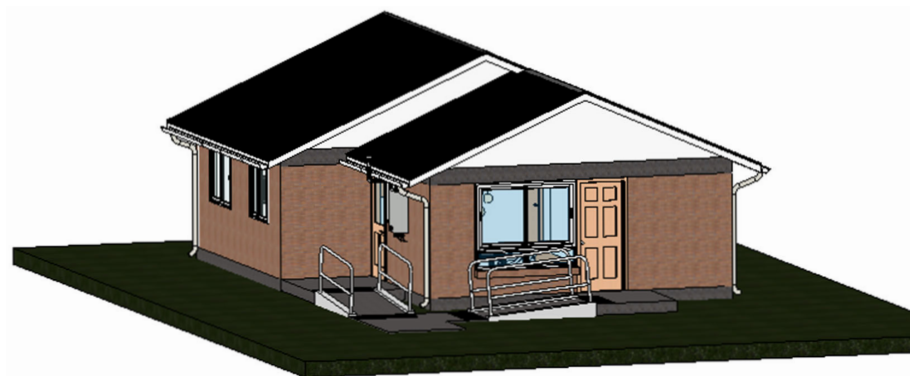


Figure 3. BIM model of the accessible housing.

The development of this housing model in virtual reality enables the creation of a tool for the early identification of accessibility issues in circulation areas, supporting the optimization of the design before the physical construction of the house.

4.3. Identification of Circulation Area Parameters in Universally Accessible Housing (UAH)

To understand the parameters and various variables that influence the housing design in relation to circulation areas, a set of data was collected from Chile's current accessibility regulations, specifically Supreme Decree (DS No. 49) [21]. It is important to emphasize that the evaluation focuses on specific parameters related to the circulation areas of a universally accessible housing (UAH) unit. These parameters were critically identified by a focus group to ensure accessibility and are therefore subject to assessment during the conceptual design phase of the virtual experience. Advanced technologies such as virtual reality and BIM will be leveraged to conduct a detailed analysis.

The identified parameters are presented in Table 1, which contains detailed information for each one as defined in [21], specifically for the design of universally accessible housing. The selection of these parameters allows the research to focus on the essential elements that ensure the dwelling meets the basic needs of individuals with physical disabilities.

Table 1. Parameterization, analysis, and ergonomics of UAH: Chilean Regulation DS No. 49.

Area and Zone No.	Parametrization	Minimum Value	Analysis and Ergonomics
1. Master Bedroom	Bed aisle width	0.6	Independent
	Free maneuvering space	1.5	Independent, Fixed
	Clear width	1.5	Independent
	Aisle width	0.9	Independent
	Clear height	0.7	Independent, Fixed
2. Bathroom	Transfer area	0.8×1.2	Independent
	Free maneuvering space	1.5	Independent, Fixed
	Clear height	0.7	Independent, Fixed
3. Living–Dining Room	Circulation width	0.8	Independent
	Free maneuvering space	1.5	Independent, Fixed
4. Kitchen	Free maneuvering space	1.5	Independent, Fixed
	Clear width	0.9	Independent
5. Circulation Hallway	Free maneuvering space	1.5	Independent, Fixed
	Circulation width	0.95	Independent
6. Small Bedroom	Free maneuvering space	1.5	Independent, Fixed
	Aisle width	0.9	Independent
7. Secondary Bedroom	Bed aisle width	0.9	Independent
	Free maneuvering space	1.5	Independent, Fixed

It is important to note that these specific parameters establish the scope of the research, clearly defining the focus and boundaries of the evaluation to enhance understanding and efficiency. To clarify the nature of the parameters presented in Table 1, the “Analysis and Ergonomics” column categorizes them based on their dimensional characteristics as stipulated by Chilean regulation DS No. 49:

- **Independent:** These parameters are typically defined by a minimum regulatory value. While their specific dimensions are not primarily dictated by interaction with other particular architectural elements for their definition, they permit design flexibility (e.g., a ‘Bed aisle width’ is regulated with a minimum of 0.6 m but can be designed wider depending on the available space and design intent).
- **Independent, Fixed:** These parameters are characterized by precise, unalterable dimensions or a specific set of dimensions mandated by the regulation for that named parameter. These values must be met as stated and are not typically subject to design

variation. For instance, the ‘Free maneuvering space’ consistently requires a 1.5 m diameter clear of obstacles, and the ‘Clear height’ beneath designated elements is fixed at 0.7 m by the regulation.

This distinction is important for understanding how regulatory requirements translate into spatial design and how they are evaluated within the VR experience.

Although the spatial parameters applied in this study were defined according to Chilean regulation DS No. 49, they also reflect foundational ergonomic principles related to human mobility, reach, and spatial comfort. For example, the minimum 1.5 m turning radius corresponds to established maneuverability standards for wheelchair users based on anthropometric and biomechanical data. These values are used here as a referential baseline for the case study. However, the core of the evaluation lies in correlating these dimensions with the actual performance of users during simulated daily living tasks in the virtual environment. This ensures that the assessment moves beyond static regulatory compliance to a dynamic, user-centered analysis of accessibility in practice.

4.4. Maneuvering and Mobility System

The environment within a universally accessible home must enable individuals with physical disabilities to actively participate in their daily occupations. This is particularly relevant in relation to the interaction between the environment and the person, as it involves both physical barriers and the ways in which the environment can facilitate participation in everyday activities. This perspective is supported by the field of ergonomics, understood as a model that promotes diverse operations acknowledging human variability and aims to adapt environmental demands to individual needs.

Ergonomics plays a crucial role in housing design by considering people’s abilities and needs across different areas of the home. Special emphasis is placed on accessibility, ensuring that wheelchair users can move freely and use the space safely and independently. The term maneuver refers to any degree of turning that allows a person with physical disabilities to perform actions within a furnished environment. Figure 4 illustrates standard measurements and maneuvering areas required for wheelchair use.

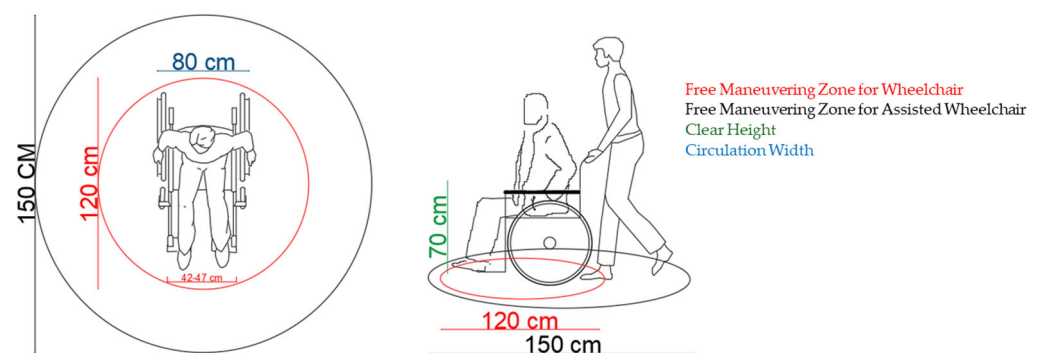


Figure 4. Standard measurements and wheelchair maneuvering areas.

4.5. Proposed Zones and Scenarios for the VR Experience

Seven evaluation scenarios were considered, from which parameters were collected, as shown in Figure 5. These simulation zones focus on enabling users to perform a series of actions within the space, including the execution of various maneuvers and interaction with circulation areas and elements such as light switches and power outlets.

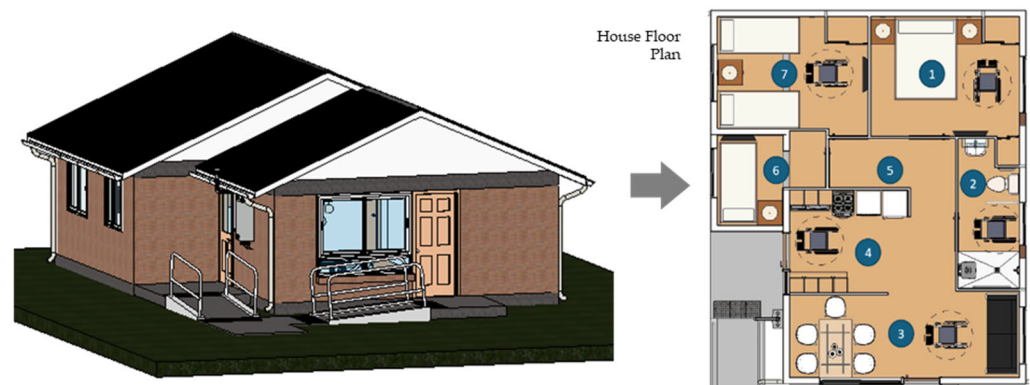


Figure 5. General floor plan of UAH with indicated scenarios.

Figure 6 details three of the seven scenarios described in Figure 5. These are representative due to the similarity of the parameters being assessed in the zones, which include the master bedroom, bathroom, and living–dining room. Each scenario is approached with a specific focus to reflect the distinct characteristics of the corresponding space.

To carry out the scenarios presented, design considerations aligned with current accessibility regulations were applied. These considerations are essential to ensure that the virtual experience accurately and realistically addresses accessibility requirements while complying with the necessary standards:

- Turning and counter-turning maneuvers performed with the wheelchair must meet minimum rotation radius requirements, specifically a clear diameter of 1.5 m and a free area of 1.5×1.5 m.
- Each interior area of the home must have a clear circulation width.
- Specific furniture must have a minimum clear height of 0.7 m.
- Lever-type or recessed locks must be used for doors.
- According to regulations, doors must open inward, except for the bathroom door, which opens outward.
- Maneuvering zones must allow for a full 360° turn for a person in a wheelchair.

These considerations and parameters, as defined by the accessibility standards for universally accessible housing, are fundamental during the simulation scenarios. They ensure that the evaluated environments meet the established requirements, resulting in a more immersive and realistic experience. Emphasizing these regulatory aspects supports the development of inclusive and functional housing design, providing a suitable living environment for people with disabilities and aiming to deliver a home that offers both comfort and independence.

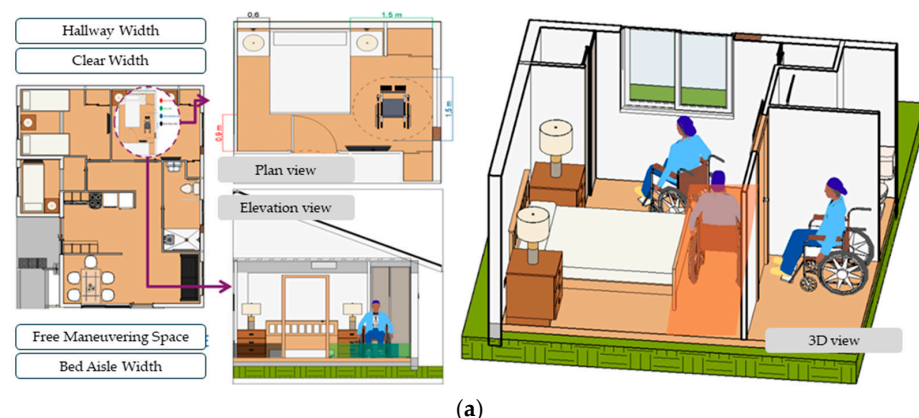


Figure 6. Cont.

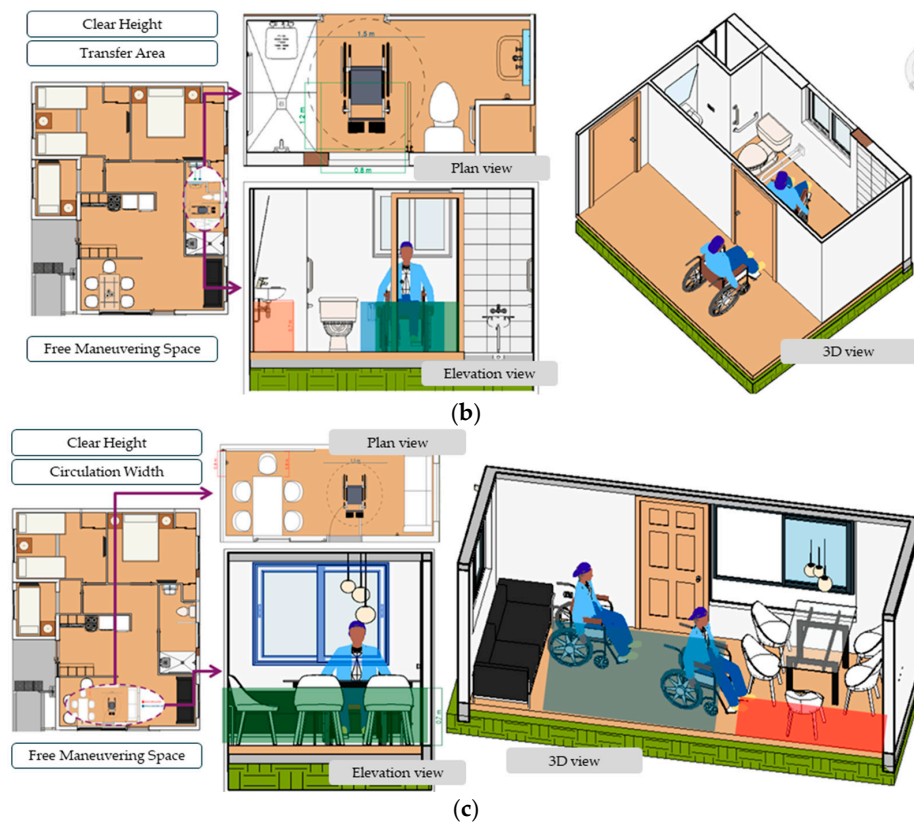


Figure 6. Scenario modeling. (a) UAH master bedroom plan view and 3D perspective view, (b) UAH bathroom plan view and 3D perspective view, (c) UAH living–dining room plan view and 3D perspective view.

4.6. Setup Levels

To conduct the simulation, the experience was designed across two levels: Level 1—Tutorial; Level 2—UAH Model. Figure 7 shows the components of each level, the outputs generated, and the parameter evaluation methods.

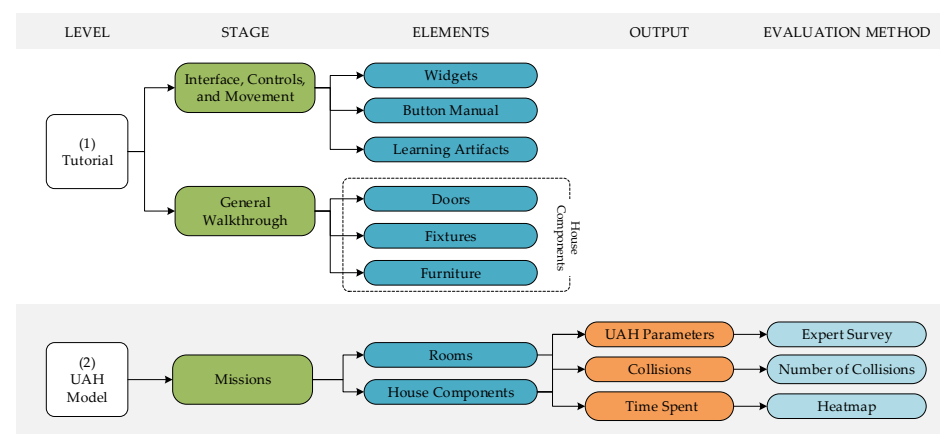


Figure 7. Virtual reality VR experience design diagram.

In Level 1—Tutorial, the user has an initial interaction with the virtual reality components (controllers, headset, and synthetic hands), as well as with key elements representative of a universally accessible housing (UAH) unit in the simulated environment. This level is intended to help the user become familiar with the functionality and use of the VR tool. The tutorial is divided into two stages: a welcome lobby and a general walkthrough. In the first stage, the user is seated in a real wheelchair and wears the VR

headset. The experience begins in a virtual welcome lobby that includes visual guides (illustrative panels) explaining how the controls work, an interactive light switch, and a start button that transports the user to the main simulation map where the evaluation will take place. At this point, users also receive general guidance about what they will encounter and what is expected during the experience. The main objective of this stage is to assess whether the user understands the basic functioning of the VR system and how to navigate and interact within the environment. The second stage consists of a guided walkthrough of the virtual home, starting from the exterior and moving through each room. During this tour, users can observe the furniture and fixtures with which they might collide or interact, helping them become familiar with the space and understand the controls and interaction mechanics. It is important to note that, during this phase, interactions with elements related to the UAH parameters are not yet enabled, as the goal is purely spatial recognition. At the end of this stage, a text file is generated to build a heatmap that records the user's position every 3 s. These data highlight key areas of interest and help interpret user behavior within the environment.

In the Level 2—UAH Model, the user must move through the space, interact with objects, and perform specific maneuvers related to the previously defined accessibility parameters. To guide this process, the user receives instructions or “missions” such as turning on light switches, opening doors, or moving to certain rooms. In addition, the user is free to explore and interact with all available elements, further enhancing immersion and natural engagement with the environment. Evaluation in this level is based on the use of heatmaps, collision counters, and detailed tables recording which elements were collided with. These tools help determine the complexity of maneuvers and the functional accessibility of the environment.

The experience was designed so that the user follows the path “without realizing they are evaluating the design.” Tasks are structured with hidden objectives —namely, evaluating the design's accessibility parameters— but are presented as natural in-context actions, avoiding overt instruction. This approach strengthens the sense of immersion and supports a more spontaneous and realistic evaluation. Figure 8 summarizes the stages of the VR experience.

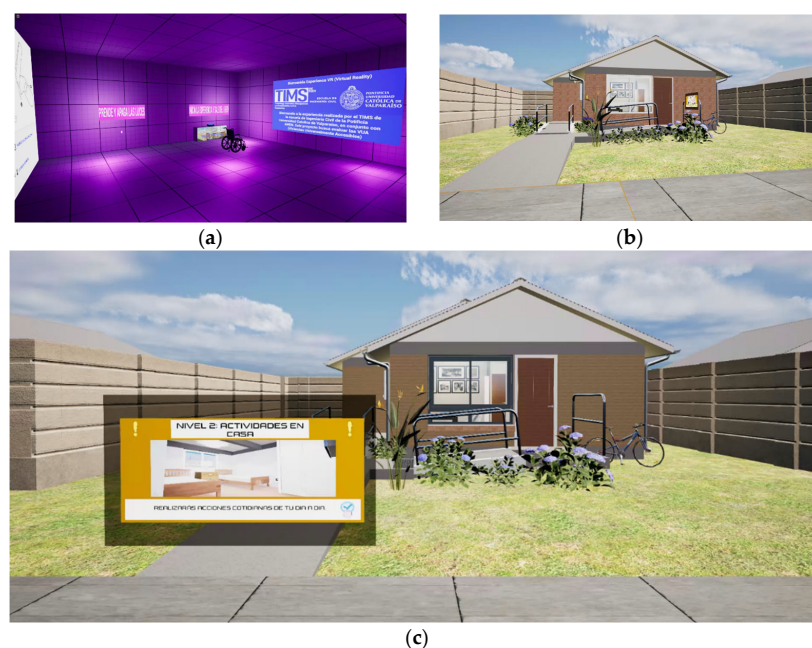


Figure 8. (a) Level 1 tutorial level scenario, (b) Level 2 UAH model scenario with environments; (c) instruction label in Level 2.

4.7. Setup and Technical Specifications of the Equipment

The implementation of the proposed workflow for the development of the virtual reality tool considered the hardware and software setup detailed in Table 2. From a graphical perspective, special attention must be paid to the computer's graphics card to ensure proper and smooth texture processing. In this case, the application was run from the computer and was visualized and interacted with through virtual reality headsets.

Table 2. Hardware and software used.

Components	Minimum	Minimum Recommended	Used
GPU	NVIDIA GTX 1070	NVIDIA GeForce RTX 3080	NVIDIA GeForce GTX 1650 Ti
CPU	Intel i7-6700	Intel i7-11800	Intel i5-10300H
RAM	16 GB	32 GB	16 GB
Video Output	HDMI 1.3	HDMI 1.3	HDMI 1.3
USB	USB 3.0	USB 3.0	USB 3.0
Operating System	Windows 8 64 bits	Windows 11 64 bits	Windows 10 64 bits
VR Headset	Meta Quest 2	Meta Quest 2/3	Meta Quest 2

It is noted that while the Intel i5-10300H CPU used (10th generation) is more recent than the listed minimum recommended i7-6700 (6th generation), the latter belongs to a higher performance tier. However, for the specific demands of our VR simulation, which prioritized GPU performance for rendering the Unreal Engine environment, the i5-10300H coupled with the NVIDIA GeForce GTX 1650 Ti provided a smooth and consistent user experience without noticeable performance degradation or frame rate issues that would impede the evaluation tasks. Any potential minor performance differences were deemed not to have impacted the study's outcomes regarding accessibility evaluation.

For the testing sessions and overall use of the experience, it is recommended to have an adequate physical space that allows for the safe use of the VR headset, free from movement restrictions or risk of collisions with surrounding objects. A stable Wi-Fi connection and a clear, unobstructed working area are particularly important. Figure 9 shows the configuration of the testing space (virtual reality lab), which includes a Meta Quest 2 headset, Oculus Link cable, 50" TV, wheelchair, support computer, development and evaluation computer, and a smartphone tripod used for recording the testing sessions.

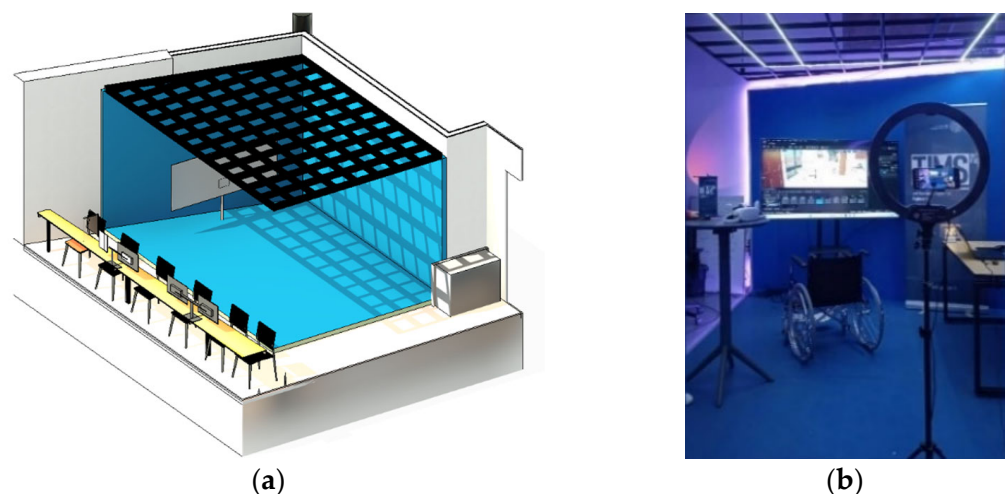


Figure 9. Laboratory setup for testing: (a) 3D model—general view of the laboratory; (b) testing setup.

4.8. Pairing Virtual Reality Headsets and Controllers

To ensure the proper use of the virtual reality headset, it is first necessary to configure the physical space where the experience will take place. This involves selecting a safe area for VR use and defining the floor level, which serves as the lower boundary for the avatar's movement within the virtual environment. This setup is achieved through the headset's internal interface and must be adjusted by the testing team to guarantee correct functionality.

Once the initial setup is complete, the headset must be connected to the Meta Quest Link interface, which should be pre-installed on the testing computer. This tool allows the VR headset to be linked with the system running the immersive experience.

In addition, the SteamVR interface is used to connect the Meta Quest 2 headset with the Unreal Engine platform, which is employed to develop and operate the virtual reality simulation.

Figure 10 shows the workflow required to properly link the VR headset with the testing workstation. Once the headset is connected and ready for use, a series of input controls must be configured. These controls are pre-defined in the application setup but require adjustments to the array elements, as the default configuration only includes third-person control settings.

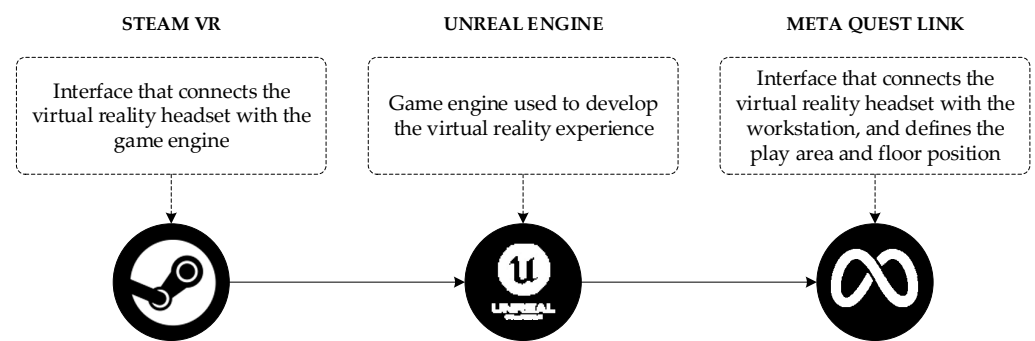


Figure 10. Flowchart made to link VR virtual reality glasses with computer.

4.9. Functioning of Code Boxes (Blueprints)

To illustrate the practical functioning of the programming system used in the development of the virtual reality (VR) experience, several examples are presented to demonstrate how interactions and animations are generated for user engagement during immersion. Figure 11 displays six implemented functionalities, contrasting the programming environment with user interaction and visualization in VR.

Figure 11a shows the interactive dropdown menu, which includes three main buttons: Restart Level, Exit Experience, and Return to Last Saved Point. This menu is designed to support quick decision-making during the simulation and is programmed using Blueprints, with each button linked to a specific in-game action, ensuring a fluid and user-friendly interface. Figure 11b illustrates the wheelchair movement logic within the virtual environment. The user can move forward, backward, and rotate, simulating realistic wheelchair dynamics. The programming integrates colliders and physics that replicate real-life maneuverability, allowing the evaluation of accessibility parameters such as turning space and path clearance in different areas of the house.

Interactions with common objects are highlighted in Figure 11c and Figure 11d, which depict doors and light switches, respectively. In the case of Figure 11c, doors open in response to proximity and interaction via the virtual hands, activating animations that simulate a 90° opening, aligned with accessibility regulations. Figure 11d shows how light switches can be toggled on and off, enhancing immersion and mimicking routine daily

actions. Figure 11e presents widgets—visual elements placed throughout the experience that deliver instructions, tasks, or reminders to the user. These are designed to improve understanding of the navigation and actions to be performed, supporting autonomy within the virtual environment. Finally, Figure 11f displays the implementation of save points, which allows the user to return to a safe location in the environment in case of errors, collisions, or technical issues. This feature, also developed using Blueprints, ensures uninterrupted evaluation sessions and improves the overall user experience.

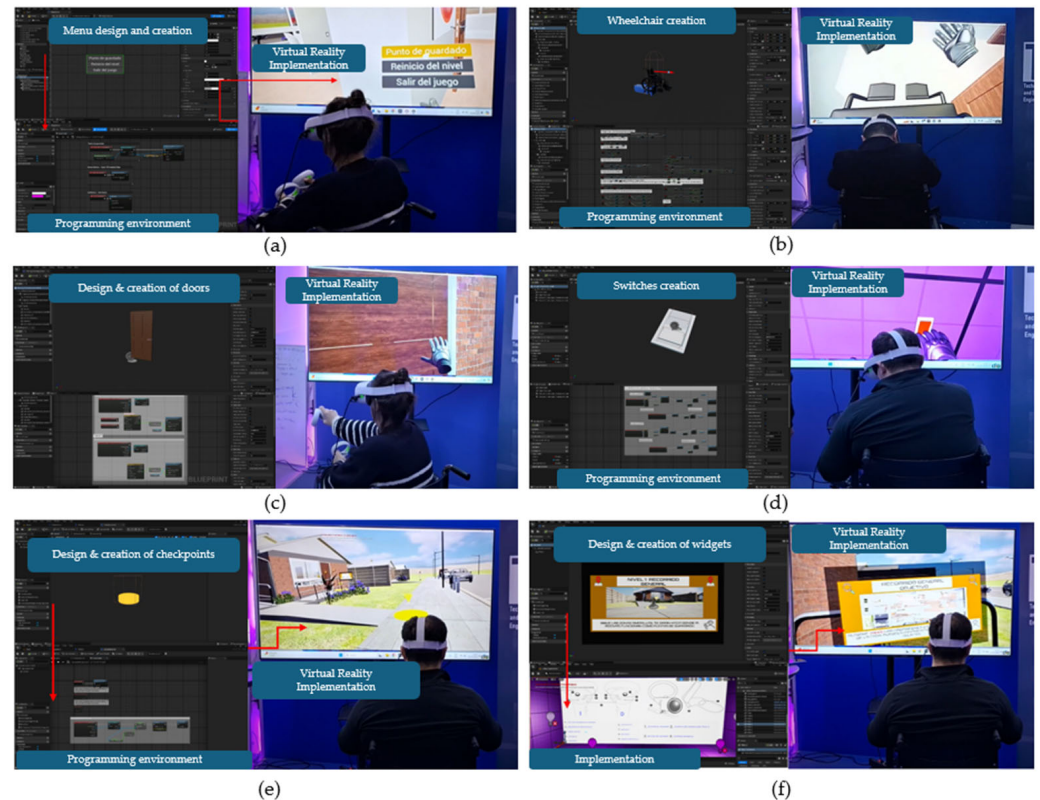


Figure 11. Key functionalities of the VR experience. (a) Interactive menu with restart, exit, and save options, (b) wheelchair movement system with realistic physics, (c) door interaction with programmed opening animations, (d) light switch interaction for turning lights on/off, (e) instructional widgets for user guidance; (f) save point system for resetting to safe locations.

Together, these functionalities are seamlessly integrated into the simulation, offering an immersive, functional, and user-centered experience. At the same time, they allow for objective measurement of accessibility performance—such as the number of collisions or time spent in key areas—supporting design validation and decision-making prior to physical implementation.

5. Testing, Results, and Analysis

5.1. Expert Panel

To carry out the evaluation of the universally accessible housing (UAH) case study, a group of five experts participated in testing sessions. The objective was to assess both the simulation, and the tool used to implement it, as well as the parameters related to the core focus of this research. To ensure a representative sample of the key topics involved, the expert group included professionals from university education, care and disability, UX/UI development, and virtual reality (see Table 3).

Table 3. Expert panel.

Profession (Degree)	Occupation	Field of Work	Years of Experience
Special Education Teacher, PhD	Professor and Researcher	University Education, Care, and Disability	>20
Special Education Teacher, PhD	Professor and Researcher	University Education, Care, and Disability	>20
Architect, MSc	Professor and Researcher	UX/UI Developer, Virtual Reality, and Disability	>20
Civil Engineer, PhD	Professor and Researcher	University Education, Virtual Reality	>5
Civil Engineer, PhD(c)	Professor and Researcher	University Education, Virtual Reality	>5

The expert evaluation was conducted through individual testing sessions with each participant, ensuring that each experience remained unique and free from external influence. Experts interacted independently with the simulation, allowing for unbiased assessment of performance and usability. During these sessions, they explored the virtual environment while the system recorded key evaluation parameters, such as time spent in specific zones and the number of collisions per area. This individualized approach provided consistent and objective data for analyzing the effectiveness of the VR-based assessment tool.

5.2. Evaluation Approach and Instruments for the Case Study

To evaluate the virtual reality (VR) experience and the accessibility of the universally accessible housing (UAH) model, a structured assessment approach was designed and applied. This approach included a set of specifically designed questionnaires aimed at measuring key aspects of the simulation, user experience, and accessibility-related interactions. The evaluation process involved classifying each item according to its focus on the environment, movement, and interactions (Table 4), and applying targeted instruments that addressed the core dimensions of the study. Tables 5–8 present the detailed questionnaires used during the evaluation phase. These include items related to the assessment of accessibility parameters in the UAH (Table 5), the simulation’s realism and fidelity (Table 6), the usability and functionality of the VR tool (Table 7), and the potential symptoms associated with the use of VR systems (Table 8). Each instrument was designed to be applied by expert participants and aimed to capture both qualitative and quantitative feedback essential to the analysis of performance and user-centered design.

Table 4. Question classification for measuring the perception of VR experience.

Questionnaire	What It Evaluates	Environment	with Respect to Movement	Interactions
Evaluation of UAH Parameters	Accessibility	Visual guides	Wheelchair Collisions Turns	Outlets Light switches Bathroom/Kitchen faucets
Simulation Evaluation	Realism	Visual aspects Sound aspects	Wheelchair Collisions Controls	Household items Furniture
VR Tool Evaluation	User experience	Visual guides	Camera	-

Table 5. Evaluation questionnaire for UAH parameters.

	Questions	Answers
1	How much were you able to control the maneuverability of the wheelchair when interacting with objects?	(1) None; (2) Little; (3) Moderate; (4) Quite a lot; (5) A lot
2	How much were you able to control the maneuverability of the wheelchair when moving?	
3	Regarding maneuverability, does it allow the person to position themselves correctly when interacting with the different devices? Example: Entering the restroom and making turns to position themselves in the transfer area.	(1) Strongly Disagree; (2) Disagree; (3) Neither Agree nor Disagree; (4) Agree; (5) Strongly Agree
4	Do you consider that the person can perform actions and interact with objects without the need to perform full maneuvers (understood as full maneuvers such as 180°, 360° and reverse turns)?	
5	Interactions with switches and sockets: Do you consider them to be adequate for the evaluation of the accessibility of the housing?	
6	Interactions with bathroom and kitchen faucets: Do you consider them to be adequate for the evaluation of the accessibility of the housing?	
7	Do you consider that the visual guides are clear and help to understand what to do within the simulation (where to go, how to interact), thinking about a person with a disability?	
8	Do you consider the housing in the simulation to be affordable?	

Table 6. Simulation Evaluation Questionnaire.

	Questions	Answers
1	In general, do you consider that the simulation would represent a real situation in which a person with a physical disability could perform an activity of daily living?	(1) Strongly Disagree; (2) Disagree; (3) Neither Agree nor Disagree; (4) Agree; (5) Strongly Agree
2	Do you consider that the simulation succeeds in representing the conditions of a physically disabled person in a wheelchair?	
3	The movements correspond to the character and the chair: do you consider that they achieve real movements and in real time, thinking of a person with a physical disability?	
4	Do you consider that crashes or collisions manage to recreate real crashes with a person with physical disabilities in mind?	
5	Are the interactions with switches and sockets realistic with a person with a physical disability in mind?	
6	Are the interactions with bathroom and kitchen keys realistic with a person with a physical disability in mind?	
7	Are interactions with artifacts and furniture realistic with a person with a physical disability in mind?	
8	Regarding the visual aspects, how immersive were they within the simulation?	(1) None; (2) A little; (3) Moderate; (4) Quite a lot; (5) A lot
9	How much do you think visual aspects affect immersion for a person with a physical disability?	
10	Regarding the sound aspects, how immersive were they within the simulation?	
11	How much do you think the sound aspects affect immersion for a person with a physical disability?	

Table 7. Virtual reality (VR) tool evaluation questionnaire.

Questions		Answers
1	Do you consider that the visual guides are clear and help you understand what to do within the simulation (where to go, how to interact)?	(1) Strongly Disagree; (2) Disagree; (3) Neither Agree nor Disagree; (4) Agree; (5) Strongly Agree
2	Do you consider that the camera movements were in accordance with the movement when you turned your head in reality?	
3	Do you consider that camera movements could have an impact on a person with a physical disability?	
4	How difficult do you think it would be for a person with a physical disability to use the control devices (VR controllers) to move within the virtual reality environment?	(1) None; (2) A little; (3) Moderate; (4) Quite a lot; (5) A lot
5	How difficult do you think it is to learn movement within the simulation?	

Table 8. Questionnaire for symptoms associated with the use of virtual reality (VR).

Symptoms		Answers
1	Nausea	(1) No malaise; (2) Mild; (3) Moderate; (4) Severe; (5) Heavy
2	Sweating	
3	Dizziness	
4	Headache	
5	Eye fatigue	
6	Blurred vision	
7	Difficulty concentrating	
8	Loss of balance	
9	Disorientation	
10	General malaise	

5.3. Analysis and Results

To carry out the analysis and present the results, the data collected from the expert evaluations were divided into two types: quantitative and qualitative. The quantitative results are shown in Table 9, which presents the record of collisions throughout Level 2 of the VR experience, involving the specified elements. In addition, Figures 12 and 13 display the heatmaps generated based on the time spent—recorded every three seconds—by each user within the house during Level 1 and Level 2 of the simulation, respectively.

Table 9. Record of collision time with different elements by zone within the UAH.

Experience Zone	Interaction Object	Expert #1	Expert #2	Expert #3	Expert #4	Expert #5
Living–Dining room	Door frame	Yes	No	Yes	Yes	Yes
	Walls	Yes	No	Yes	No	No
	Furniture	Yes	No	No	No	No
	Doors	Yes	No	No	Yes	Yes
Kitchen	Door frame	Yes	Yes	No	No	Yes
	Walls	Yes	Yes	Yes	Yes	Yes
	Furniture	Yes	Yes	Yes	Yes	Yes
	Doors	Yes	Yes	No	No	Yes
Bathroom	Door frame	Yes	Yes	Yes	Yes	Yes
	Walls	Yes	Yes	Yes	Yes	Yes
	Furniture	Yes	Yes	Yes	Yes	Yes
	Doors	Yes	Yes	Yes	Yes	Yes
Main bedroom	Door frame	Yes	Yes	Yes	Yes	No
	Walls	Yes	Yes	Yes	Yes	No
	Furniture	Yes	Yes	Yes	Yes	No
	Doors	Yes	Yes	Yes	Yes	No

Table 9. Cont.

Experience Zone	Interaction Object	Expert #1	Expert #2	Expert #3	Expert #4	Expert #5
Secondary bedroom	Door frame	No	No	No	No	No
	Walls	Yes	Yes	Yes	Yes	No
	Furniture	Yes	Yes	Yes	Yes	No
	Doors	Yes	Yes	Yes	Yes	No
Small bedroom	Door frame	No	No	No	No	No
	Walls	Yes	Yes	Yes	Yes	No
	Furniture	Yes	Yes	Yes	No	No
Circulation hallway	Doors	No	No	No	No	No
	Walls	Yes	Yes	Yes	Yes	Yes

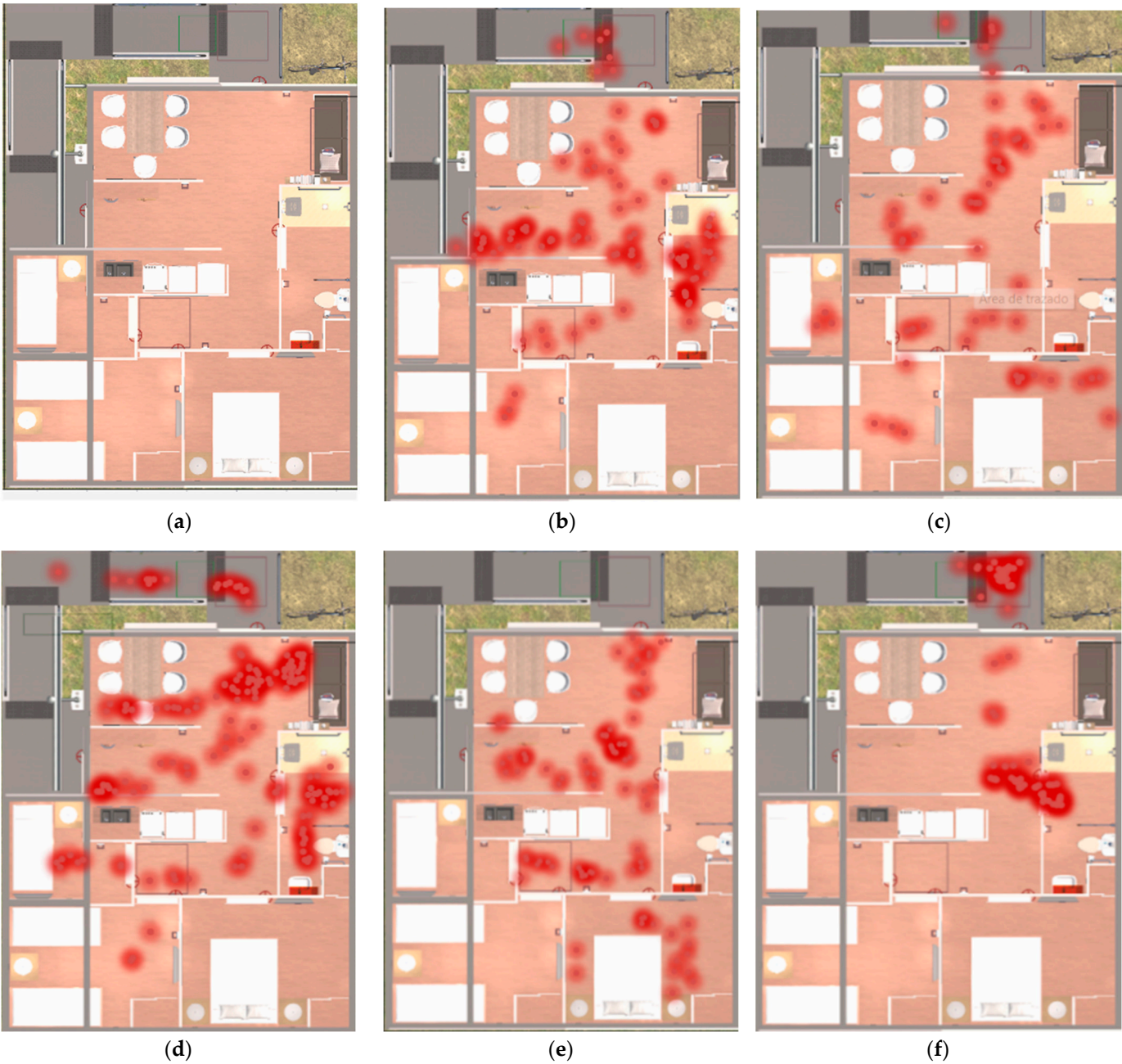


Figure 12. Heatmaps of movement during testing—Stage 1. (a) Floor plan of the house—Stage 1, (b) heatmap of Expert #1 in House 1, (c) heatmap of Expert #2 in House 1, (d) heatmap of Expert #3 in House 1, (e) heatmap of Expert #4 in House 1; (f) heatmap of Expert #5 in House 1.

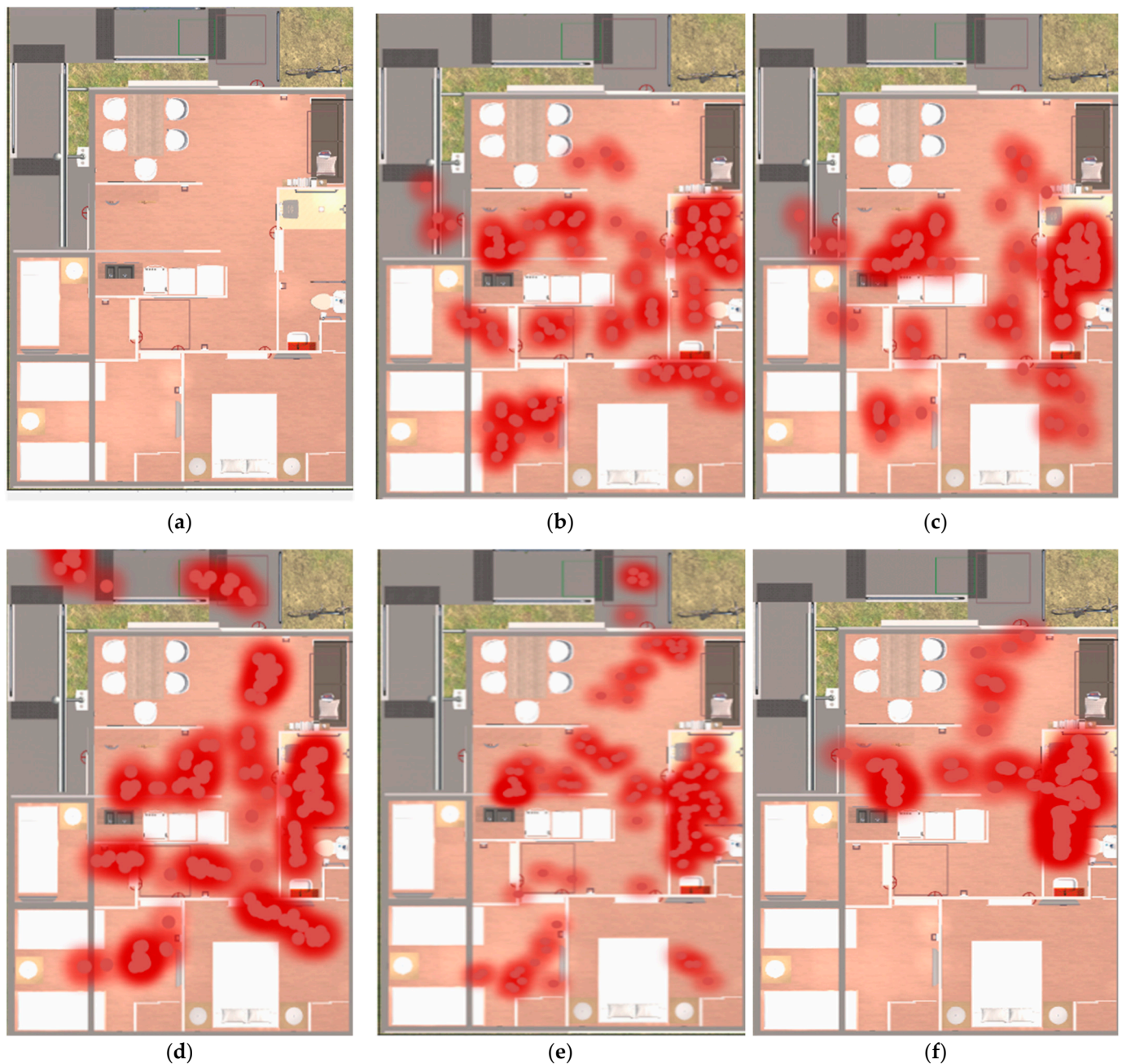


Figure 13. Heatmaps of movement during testing—Stage 2. (a) Floor plan of the house—Stage 2, (b) heatmap of Expert #1 in House 2, (c) heatmap of Expert #2 in House 2, (d) heatmap of Expert #3 in House 2, (e) heatmap of Expert #4 in House 2; (f) heatmap of Expert #5 in House 2.

For example, the frequent collisions observed at the bathroom door frame—reported across all expert participants—suggest that the minimum width of 0.9 m defined by regulations may not be sufficient in practice. A potential design adjustment, such as increasing the width to 1.0 m or reconsidering door swing direction, could be evaluated using this tool. While this study does not aim to prescribe specific architectural changes, these insights demonstrate the tool’s capacity to identify accessibility issues and guide future design decisions. The emphasis remains on validating the methodology and immersive framework as a replicable approach for evaluating functional accessibility in circulation areas.

The analysis of the results from the heatmaps and collision tables revealed that areas with a higher number of dwell points frequently coincided with zones where collisions were most prevalent. Rather than applying statistical tests—which are not appropriate given

the limited number of expert participants—this study adopted a triangulated analytical approach to evaluate potential design limitations. This approach integrated three key elements: (1) spatial data derived from the heatmaps (recorded every three seconds), (2) the quantitative record of collisions across each room and element, and (3) qualitative insights provided by the experts during and after the VR experience.

Through this integrated analysis, a consistent pattern emerged: areas with extended dwell time, such as the bathroom and small bedrooms, were also the locations with the most frequent collision events. These same zones were independently highlighted by multiple experts as spaces where circulation and maneuverability posed significant challenges. For instance, in the bathroom, narrow transfer zones and constrained turning areas resulted in extended task duration and repeated contact with environmental elements. These findings suggest that increased time spent in specific areas may be indicative of underlying design limitations that hinder autonomous mobility and task execution.

Additionally, the non-linear nature of the simulation allowed users to navigate the space freely, resulting in variation in user paths and time spent across scenarios. This design choice, while promoting immersion and natural behavior, also contributed to differences in collision frequency among participants. It is also worth noting that one expert (Expert #5) was unable to complete the full experience due to low familiarity with VR technology, slightly reducing the comparative depth of the data set.

The qualitative results are presented in Figures 14–16. These reflect the perceptions of the five experts in the areas of experience realism, the accessibility of the universally accessible housing (UAH), user experience, and symptoms experienced by the experts due to the use of the virtual reality tool.

In addition to the graphs, qualitative feedback was collected from the five experts regarding the simulation, the accessibility of the housing unit, and the use of the virtual reality (VR) tool. Together, their insights help identify both the strengths and the areas for improvement of the developed virtual environment. In terms of simulation, the experts agreed that visual aspects such as flat colors, uniform lighting, and low-quality textures negatively affected the sense of realism. Although some interactions were described as immersive, they were also noted to lack technical refinement and physical consistency. For example, the automated repositioning of the wheelchair after collisions was perceived as unnatural, and the turning speed and movement dynamics were suggested to be improved. The addition of contextual sounds—especially during collisions or when activating switches—was recommended to enhance immersion.

Regarding accessibility, there was consensus that certain areas, such as the kitchen, bathroom, and small bedroom, were difficult to navigate using a wheelchair. While the design was acknowledged to follow regulatory guidelines, several experts pointed out that furniture layout and narrow space widths often hinder effective maneuverability. This highlights a gap between regulatory compliance and real functional use. As for the VR tool itself, experts recognized its potential as a resource for evaluating accessibility and supporting inclusive housing design. However, they also identified technical limitations that should be addressed: challenges in spatial perception, physical discomfort (e.g., fatigue or dizziness) during use, and a learning curve that may affect the user experience—especially for individuals unfamiliar with this type of technology. Clear instructions before beginning the experience and more flexible control schemes were also recommended.

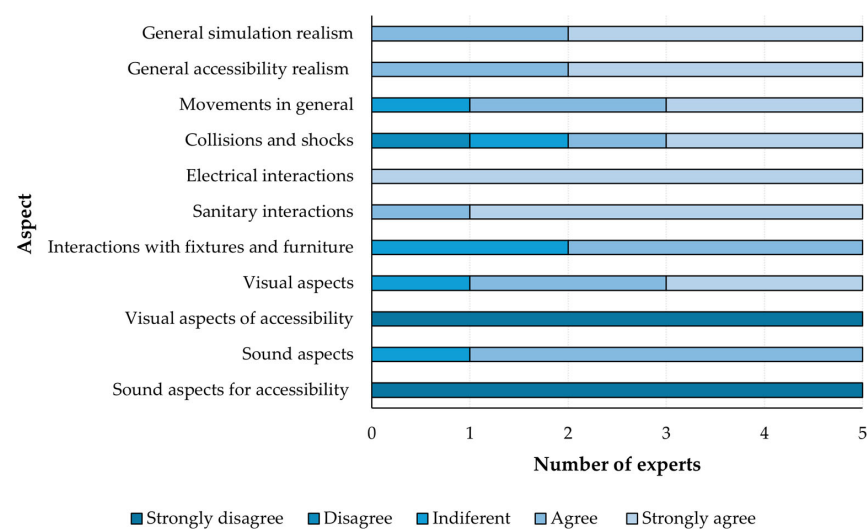


Figure 14. Chart showing responses based on the questionnaire used to evaluate the realism of the experience.

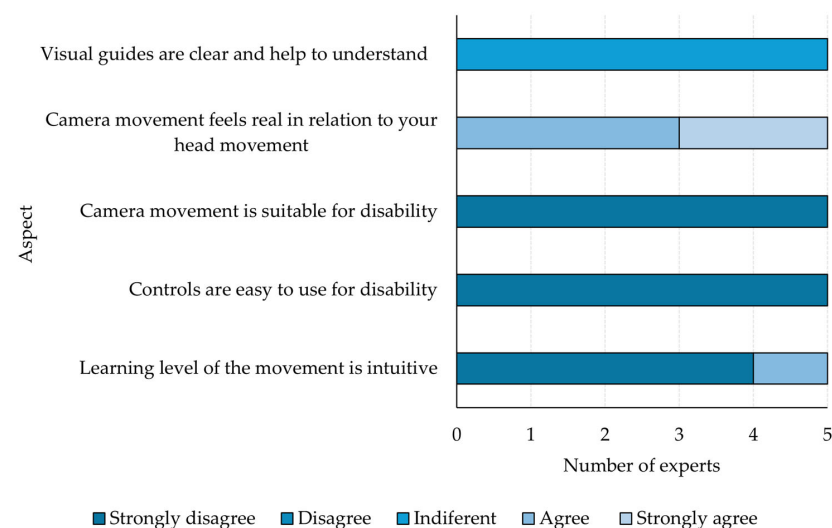


Figure 15. Chart showing responses based on the questionnaire used to evaluate the user experience of the simulation.

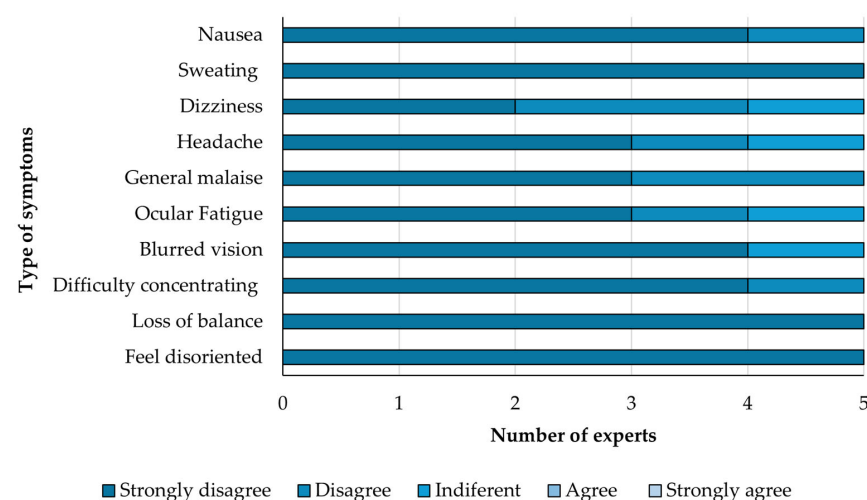


Figure 16. Chart showing responses based on the questionnaire used to evaluate symptoms caused using virtual reality.

In summary, the qualitative evaluation suggests that the tool holds strong potential to support accessible design, but it requires technical improvements and enhanced usability to reach its full effectiveness. The expert feedback provides valuable direction for a more user-centered development process, grounded in real-life accessibility conditions within the domestic environment.

6. Discussion

6.1. Reflections on the Use of the VR Tool

Based on the design and expert evaluation of the universally accessible housing (UAH) prototype, several contributions emerged from the chosen research approach. One key insight relates to the use of virtual reality headsets, which, while powerful, show wide variability in user adaptability. Some participants quickly became familiar with the device—especially those with prior experience—while others found it challenging, requiring extended learning time. Furthermore, stable internet connectivity is essential for effective use, which can become a limitation if not guaranteed.

Experts expressed overall positive perceptions of VR for this study's objectives. Nonetheless, their reactions to the tool varied: some experienced physical discomfort, potentially influenced by pre-use conditions such as food intake, sleep quality, or familiarity with technology. The way each expert envisioned the tool's potential also depended on their exposure to immersive technologies; those with more experience anticipated a higher level of realism and development.

6.2. VR as a Tool to Evaluate Universally Accessible Housing

Based on the results obtained in this research, it is possible to project a series of practical applications that can significantly contribute to the development of more inclusive housing solutions. These applications not only optimize design time and resources but also allow homes to be tailored to the specific needs of people with disabilities, anticipating accessibility issues before physical construction. Some of the potential uses emerging from the proposed approach are outlined below:

- **Realism of Experience:** The VR environment achieved a generally effective visual representation of the housing model. However, developing precise interactions and animations requires considerable time and effort. Lighting and material choices were also found to be critical—both factors directly impact the sense of immersion. Poor material choices can flatten the perceived realism of the environment.
- **Wheelchair Maneuverability:** The VR-based wheelchair simulation provided realistic movement and interaction, in part thanks to using a physical wheelchair during testing. Nevertheless, the lack of deformable objects in the virtual world limits collision realism. Enhancing this with motion sensors to synchronize virtual and real wheelchair movement could significantly boost immersion and fidelity.
- **Collision Detection and Parameter Evaluation:** Although Unreal Engine easily registers collisions, the current system allows the virtual wheelchair to keep moving after impact instead of stopping—reducing realism. Also, objects do not deform upon collision, which would improve feedback and realism. Introducing controller vibration during contact and improving physical feedback would further enhance the experience. Despite these issues, the tool remains functional for data collection.
- **Data Collection Performance:** The VR tool successfully captured the intended parameters, such as collision counts and user dwell time in different spaces. However, collecting these data is labor-intensive, requiring each interactive object to be tagged individually. Improving automation would streamline future evaluations.

Overall, the issues raised by experts can be addressed through extended development time and iteration. Importantly, all experts agreed that the tool effectively evaluates circulation and access zones within accessible homes. They also consistently noted that certain spaces, particularly bathrooms and smaller rooms, did not meet accessibility standards—aligning with the heatmaps and collision data gathered during the study.

6.3. Practical Applications

Virtual reality presents promising applications for accessible housing design. It enables early-stage iteration and visualization, which can reduce design time and support better decision-making about furniture layout, switches, outlets, and door orientations. VR also facilitates testing of spatial dimensions, ensuring houses meet accessibility standards. In public housing programs, the tool could help match housing layouts to the specific needs of applicants with disabilities, potentially improving satisfaction and functional independence.

6.4. Adaptability of the Proposed VR-Based Evaluation Tool to International Standards

Although this study specifically utilizes the Chilean regulation DS No. 49, the developed methodology can easily be adapted to other international regulations. The flexible and customizable nature of virtual environments allows specific parameters such as dimensions, distances, heights, and turning radii to be readily adjusted according to the requirements established by different global standards and regulations (e.g., Americans with Disabilities Act (ADA) in the United States, UNE standards in Europe). The real value of the proposed tool lies in its capability to evaluate not only the dimensional conformity of spaces but also the practical execution of daily tasks by users, thus providing a functional assessment of accessible design. This characteristic enables international professionals and experts to adapt the approach to their specific regulatory contexts, always maintaining user experience and the practical functionality of designed spaces as central objectives.

6.5. Limitations

The expert panel for this validation phase comprised five professionals. While a larger sample might provide broader insights, a panel of five experts is often considered acceptable for qualitative feedback and identifying major usability or conceptual issues in formative evaluations of new tools or methodologies, particularly when in-depth interaction and detailed feedback are sought [8,9]. The aim of this expert evaluation was not to achieve statistical generalization but to gather rich, qualitative data to validate the VR tool's core functionalities and its potential for accessibility assessment. The findings from this panel were intended to inform further iterative development and larger-scale user studies. In addition to previously mentioned limitations, the composition of the expert panel—consisting primarily of academics and technical professionals—represents a gap. While expert validation is crucial for assessing technical feasibility and ensuring that the tool meets fundamental usability and functionality requirements, it lacks direct input from end-users with disabilities. Such direct engagement is essential for capturing the nuanced experiences and specific accessibility needs that only actual users can provide. The current study, therefore, represents a necessary initial phase of validation, establishing foundational effectiveness before more extensive and inclusive user-centered evaluations.

The study faced both software and hardware limitations. Unreal Engine is optimized for general first-person applications, but documentation on using VR for accessibility evaluations is sparse. Most practical knowledge comes from independent developers. On the hardware side, while basic setups suffice for simple experiences, increasing visual and interactive complexity demands high-end components, making cost a potential barrier. Another limitation was the exclusive focus on physical disability. Although UAH models are designed for all types of disability or reduced mobility, this study did not address

cognitive, sensory, or psychosocial disabilities. More comprehensive frameworks are needed to accommodate diverse user needs.

Finally, the simulation did not address tactile feedback or object-level product design, both of which would enhance immersion. Haptic sensations were limited, reducing physical realism. However, with additional development and time investment, these aspects could be improved, leading to a significantly more realistic and immersive VR experience.

7. Conclusions

The design of universally accessible housing represents significant progress in guaranteeing the fundamental rights of people with disabilities. However, this research reveals that, in practice, this type of housing does not fully ensure the autonomy and functional mobility it aims to provide. This study successfully developed and validated a virtual reality (VR) tool focused on the functional evaluation of universally accessible housing (UAH), specifically targeting access and circulation areas. The development was based on a structured methodology and the implementation of technologies such as BIM and Unreal Engine, allowing the creation of an immersive environment that realistically simulates the experience of using a home from the perspective of a wheelchair user. The main advantage of this tool lies in its ability to anticipate accessibility issues before physical construction takes place. It enables the simulation of maneuvers, identification of barriers, and evaluation of designs in controlled virtual conditions. This provides a valuable contribution to the housing design process, as it allows critical accessibility parameters to be validated through empirical evidence, such as collisions, heatmaps of time spent in specific areas, and qualitative observations from experts.

Applied to a real case study, the tool proved effective in identifying areas with maneuverability and access challenges. Although the dwelling met the dimensional requirements established by Chilean regulations (DS N°49), the results showed that certain areas—such as the bathroom, kitchen, and small bedroom—had limitations that could affect the autonomy of a person with physical disabilities. This outcome underscores the need to differentiate between limitations inherent to regulatory frameworks and those resulting from specific design decisions. While the dwelling adhered to the minimum dimensional standards mandated by DS No. 49, functional challenges persisted—suggesting that current regulations may not fully capture the complexity of real-world use. In addition, certain layout choices and spatial configurations within the model exacerbated maneuverability constraints, despite meeting prescribed dimensions. These findings reinforce the importance of tools that can bridge the gap between regulatory compliance and actual usability through immersive, user-centered evaluation.

This demonstrates that regulatory compliance does not necessarily translate into functional accessibility and highlights the need to incorporate practical evaluations that include the user experience. Experts agreed that the tool provides a more precise and detailed understanding of accessibility conditions, facilitating early design decision-making. Moreover, there is potential to scale its use to different types of disabilities by adjusting the simulation models, paving the way for the personalization of housing design according to users' specific needs. The virtual reality tool presents an effective, replicable, and high-potential solution to support the design and evaluation of accessible housing. Its use allows for the optimization of resources, reduction in redesign costs, and significant improvement in the quality of life for people with disabilities. With additional development time and technical refinement, this technology could become a standard for validating accessibility in inclusive housing projects.

Building upon the results obtained, future research must prioritize the direct participation of end-users with disabilities in validation processes. Engaging actual users in the next phase will allow for the collection of richer, subjective feedback, ensuring the tool's real-world applicability and enhancing its practical effectiveness. Furthermore, future studies should aim to adapt the VR tool comprehensively across various types of disabilities—including sensory, cognitive, and psychosocial—through participatory co-design methodologies. Additional future lines of investigation include automating redesign report generation, performing comparative analyses across international accessibility standards, and improving the technical performance of the tool in resource-constrained environments. These efforts will help consolidate its utility as a practical, inclusive, and scalable tool for the design and evaluation of accessible housing.

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