Crafting Smart Homes

Crafting Smart Homes:

Innovative Design Strategies to Enhance Housing Quality for Ageing Well

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven,
op gezag van de rector magnificus prof.dr. S.K. Lenaerts,

voor een commissie aangewezen door het College voor Promoties, in het openbaar
te verdedigen op dinsdag 24 september 2024 om 11:00 uur

door

Chuan Ma

geboren te Henan, China

Dit proefschrift is goedgekeurd door de promotoren en de samenstelling van de promotiecommissie is als volgt:

voorzitter:	prof.dr.ir. A.S.J. Suiker
promotor:	prof.dr.ir. M. Mohammadi
copromotor:	dr. O. Guerra-Santin
leden:	dr. Y. Lu
	prof.dr. S. Ben Allouch (University of Amsterdam)
	dr.ir. L. Vaandrager (Wageningen University & Research)
	prof.dr. D.A.J.A. Derks (Erasmus University Rotterdam)

Het onderzoek of ontwerp dat in dit proefschrift wordt beschreven is uitgevoerd in overeenstemming met de TU/e Gedragscode Wetenschapsbeoefening.

Crafting Smart Homes

Innovative Design Strategies to Enhance Housing Quality for Ageing Well

Chuan Ma

Smart Architectural Technologies

Department of the Built Environment

Eindhoven University of Technology

September 2024

EINDHOVEN UNIVERSITY OF TECHNOLOGY

Crafting Smart Homes: Innovative Design Strategies to Enhance Housing Quality for Ageing Well
| by Chuan Ma

A catalogue record is available from the Eindhoven University of Technology Library.

ISBN: 978-90-386-6129-2

NUR code: 955

Bouwstenen: No. 394

Cover design: Chuan Ma

Printed by: ADC Dereumaux

Ph.D. thesis, Eindhoven University of Technology, the Netherlands

Acknowledgements

Looking back on my PhD journey, I am filled with immense gratitude for the support, guidance, and encouragement I have received along the way. My supervisors, colleagues, friends, and family have played significant roles in my academic and personal development.

I am profoundly grateful to my supervisors, Prof. Masi Mohammadi and Dr. Olivia Guerra-Santin. Without your unwavering guidance, encouragement, and support, this dissertation would have remained a distant dream. Dear Masi, the opportunity you gave me to begin my PhD at TU/e was a new chapter in my life. Thanks to your guidance, I embarked on my academic journey, and you instilled in me the confidence to pursue the research direction that truly captivated me. You taught me to see the world through the eyes of a researcher other than a designer. Your unparalleled expertise and mentorship were not just influential—they were the very foundation upon which my research was built. Your passion for work and rigorous research attitude have deeply encouraged and inspired me. It has been an honour to learn from you and to complete this dissertation under your insightful guidance. Dear Olivia, your patience, encouragement, and advice have been my compass throughout this challenging journey. I have consistently received your patient guidance and professional advice in research design, paper writing, and academic presentations. This has enabled me to master various research methods and advance my progress rapidly. I am deeply grateful for your help in dispelling my doubts and for your generous support for my academic growth. Your impact has been immeasurable, and my gratitude knows no bounds.

I sincerely thank the esteemed members of my doctoral committee: Prof. Daantje Derks, Prof. Somaya Ben Allouch, Dr. Lenneke Vaandrager, and Dr. Yuan Lu. I profoundly appreciate your willingness to join the committee and the time, expertise, and insightful feedback you have provided throughout the development of my dissertation. I would also like to express my appreciation to Prof. Akke Suiker for graciously presiding over the defense ceremony. Additionally, I thank Dr. Pauline van den Berg for her constructive feedback and invaluable suggestions during the nine-month evaluation of my research proposal.

I would like to acknowledge the colleagues from TU/e and HAN, who have created an inspiring and supportive research environment. The collaborative spirit and the willingness to help one another have made working here a truly enriching experience. Thank you, Dr. Morteza Hosseini, Dr. Berrak Kırbaş Akyürek, Linh Nguyen, Peyman Najafi, Nitant Upasani, Moniek van Loon, Coosje Hammink, Kim Hamers, Anne Grave, Leonie van Buuren, Sophie Peters, Ruth Bles, Wim van den Bouwhuijsen, Dr. Nienke Moor, Dr. Anneke Terneusen, Dr. Gerald Gosselink-Ramos, Dr. Shore Shahnoori, Laurèn Pennings, and Toine van Lieshout, for the chats, discussions, presentations, coffee, snacks, meals, greetings and hugs. It has been an invaluable advantage to my PhD journey to have had the opportunity to work with you. I also extend my gratitude to colleagues in the HR department, especially Silvie van Dam, Tanja van der Werff, Carola Tak, and Tonatiuh Cruz Rico, who helped to ensure that the procedures of my PhD journey went smoothly.

Special thanks to Sante Partner, Wooninc, Simaxx, VTEC, and many of the participants in my studies. Special thanks to Ilja Rodermans, Rosina Schouten, Maaike Steenbeek, and all care professionals and staff working in the nursing home. Your help and support for my research will always be kept in my heart. I also miss some of the older people who participated in my studies who have passed away. Thank you, and the time I spent with you will remain a precious memory to me.

Big thanks to my lovely friends, Aiyu, Bin, Qingfeng, Yongchen, Nuo, Sheng, Maryam, Alireza, Chaobo, Haopeng, Yingxin, Shengchen, Luyi, Shuwei, Bowen, Dongdong, Yinuo, Senkai, Hua, Bei, Pei-Hsuan, Xinyi, Leo, Nadia, Avin, Muxi, and Hui, for your care, encouragement, assistance, and the delicious food that supported me throughout my studies here. I am incredibly fortunate to have such wonderful friends, and I will always cherish the memories we have made together during these years.

I would like to express my deepest gratitude to my family. To my parents, thank you for your unconditional support, understanding, and concern. Despite the distance and the limited time we could spend together while I was abroad these years, your love has always been with me. To my beloved wife, Weijie, whose care, companionship, encouragement, and steadfast support have been the cornerstone of my journey throughout this PhD. We faced countless challenges, shared moments of joy, and experienced tears and laughter. Your presence has always been my constant source of motivation, my hope, and my angel. The pressures of pursuing a PhD were immense but having you by my side gave me the strength to persevere. Marrying you has been the greatest fortune of my life, and I will do my best to make our future better.

This journey would not have been possible without you. I am profoundly grateful for your guidance, support, inspiration, friendship, and love.

Chuan Ma
August, 2024

Summary

Population ageing has emerged as a significant demographic trend. The global number and proportion of older adults are projected to increase from 524 million (8%) in 2010 to nearly 1.5 billion (16%) by 2050. This demographic shift calls for innovative policies and solutions to address multifaceted social issues, particularly in relation to housing and caregiving. In this regard, the 'ageing-in-place' policy has been developed to enable older adults to reside in their homes and communities while receiving necessary care and support. This approach helps to circumvent strain on institutional caregiving resources and promotes autonomy and well-being. However, the absence of housing specifically designed for this target group may pose potential hazards in their daily lives or lead them to move to care facilities. Acknowledging that the concept of ageing-in-place may not be applicable to those in care facilities (e.g. nursing homes), this study underscores the significance of innovative design solutions for enhancing the living quality of older adults, whether in their homes or nursing homes. The primary objective remains a commitment to fostering optimal ageing experiences within the (nursing) home settings. Therefore, the concept of 'ageing well' is employed for the holistic well-being of these groups.

The emergence of smart technology offers potential solutions to ensure the well-being of older adults and alleviate caregiving workloads on family members or healthcare systems. It includes interconnected devices and systems that support daily activities, monitor health indicators, and regulate living environments. However, challenges still exist in integrating smart technologies into (nursing) home settings. Thus, this research strives to transcend housing typologies, offering an approach to design that promotes healthy ageing across diverse living environments. To fulfil the research aim, the following specific objectives have been addressed:

- Establish a framework for smart technology applications in home settings based on state-of-the-art smart home research and practices on the ageing population. This focuses on technology definitions and design strategies that support older adults living independently.
- Understand and translate older adults' comfort through indoor environmental data. The study focuses on people with dementia and sensor application in nursing homes, aiming to understand how indoor environmental quality, assessed with sensor data, influences their comfort and daily activities.
- Investigate how indoor environmental and spatial design variations affect the activities and behaviours of older people with dementia. The aim is to find

methods to optimise the nursing home environment and management to improve the quality of life for the residents.

- Validate an empathic design approach and the use of virtual reality technologies for the design of a social housing renovation project. By collaborating with stakeholders in the design process, the renovation strategies are tested to create healthy ageing environments.

This research develops a framework for smart home renovation, focusing on home assessment, technology selection, design strategy, and user evaluation. It verifies how indoor environmental changes affect older adults' comfort and dementia-related behaviours based on building monitoring and observation data and underscores the value of smart technologies in enhancing living quality. To support the goal of 'Ageing Well', recommendations include optimising spatial layouts, building management, and sensor deployment. Utilising empathic design and virtual reality to showcase home renovation and smart technology application scenarios, the user-centred design approach deepens stakeholders' understanding of the home renovation benefits, thus fostering the development of smart homes.

Table of content

List of Figures

List of Tables

Nomenclature

Acronyms

AAL	Ambient Assisted Living
ADL	Activities of Daily Living
AI	Artificial Intelligence
AmI	Ambient Intelligence
ANOVA	Analysis of Variance
APMV	Adaptive Predicted Mean Vote
APRAM	Architectural and Psycho-environmental Retrofitting Assessment Method
AR	Augmented Reality
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
AT	Assistive Technology
BPSD	Behaviour and Psychological Symptoms of Dementia
CBS	Central Bureau of Statistics of the Netherlands
CDR	Clinical Dementia Rating
CO_2	Carbon Dioxide
COVID-19	Coronavirus Disease of 2019
GDS	Global Deterioration Scale
HCHO	Formaldehyde
HCI	Human-computer Interaction
HE	Housing Enabler
HSSAT	Home Safety Self-assessment Tool
IBE	Indoor Building Environment
ICT	Information and Communication Technology
IEQ	Indoor Environmental Quality
IoT	Internet of Things
IRT	Long-wave Infrared Thermography
KNMI	Koninklijk Nederlands Meteorologisch Instituut
PhD	Doctor of Philosophy
PM	Particulate Matter

PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
P-value	Probability Value
RmRs	Robotic Micro-rooms
SAPM	Sandia Array Performance Model
SD	Standard Deviation
SBS	Sick Building Syndrome
SPSS	Statistical Package for the Social Sciences
TAM	Technology Acceptance Model
TSV	Thermal Sensation Vote
TVOC	Total Volatile Organic Compounds
VOCs	Volatile Organic Compounds
VR	Virtual Reality
WHO	World Health Organization
XR	Extended Reality

Chapter 1
Introduction

1.1 Research Background

According to the World Health Organization (WHO) report, more than 1 billion people were over 60 in 2019, and the ageing population will increase to 2.1 billion by 2050. Meanwhile, the number of older adults aged 80 years or above is expected to triple during the same time frame to reach 426 million [1]. As societies age, the number of people living with dementia worldwide is expected to rise from 55 million in 2019 to 139 million in 2050 [2]. The Dutch Central Bureau of Statistics (CBS) reported 3,601,167 inhabitants aged 65 years and over on 1st January 2023, which was 20.2% of the population. Approximately 280,000 of them are presently living with dementia [3]. These growing numbers put pressure on limited health resources and place a substantial demand on care services [4,5]. Thus, the 'ageing-in-place' policy encourages older adults to remain in their home environment as long as possible, emphasising their need to live comfortably in familiar environments [6]. In this context, the number of residents of Dutch care institutions is about 115,000. This number is shrinking because of the shortage of caregivers and preferring to live at home [7]. More than 90% of Dutch older adults live independently, while over 40,000 live in an 'unsuitable' home environment, which increases the demand for suitable housing [8–10]. Ensuring these people live in healthy and supportive environments is essential.

Smart technology has been regarded as a potential solution for providing healthy and supportive living environments for older adults ageing-in-place [11–14]. The word 'smart' has recently become an umbrella term for innovative technologies, often used in research and design fields [15]. According to the existing studies, the 'smart home' concept integrates innovative technologies into residential spaces, aiming to enhance safety, reduce energy consumption, and provide healthcare and entertainment [16,17]. Smart homes designed for older adults are equipped with Assistive Technologies, Ambient Intelligence, Ambient Assisted Living, Internet of Things, Information and Communication Technology, Smart Home, or Artificial Intelligence to support their daily activities or monitor their behavioural patterns and health status. There has been a shift in the Netherlands towards more home-based care, with technical innovations evident in telehealth or telecare, and the implementation is accelerating in the home environment [18]. However, most existing housing conditions are inappropriate for deploying new devices or technologies that make home renovation indispensable [19]. Home renovation means alterations of permanent physical features in the home and its surrounding area, now also contains the installation of smart technology devices [20,21]. Currently, the smart home projects designed for older adults are limited and knowledge of combining smart technologies or systems with architectural design is lacking [12,22].

A qualitative shift is needed in design approaches to integrate the translation of older adults' needs as design factors and consider their health, behavioural, and living conditions [23].

Older adults prefer to live at home rather than in care institutions. No matter where they live, they usually spend most of their day (80% to 90%) indoors, and this percentage is likely even higher among people living in care facilities [24]. Thus, indoor environmental quality significantly influences older adults' health and well-being, especially those with cognitive or mobility decline [25]. Indoor environmental quality refers to the general quality conditions of indoor environments, which comprise four subdomains: indoor air quality, lighting quality, noise levels and thermal comfort [26]. In the later ageing stages (e.g. with dementia), older adults may be very sensitive to indoor condition changes [25]. Controlling indoor environmental quality could positively impact health, delay dementia progression, and reduce changed behaviours (e.g. agitation, hallucination, and wandering) [27]. Therefore, exploring the influence of environmental, spatial, and technological factors on older adults living in care institutions is essential, as it could provide scientific guidance for creating healthy ageing environments.

Smart technology applications contribute to care services with health and indoor environmental quality monitoring, maintenance of functioning, and caregiving management [28]. Furthermore, smart environments could assist the daily activities and independence of older adults with mobility or cognitive decline [29]. As a part of smart systems and non-intrusive technology, sensors are widely used in care facilities. Since the care facility environments are relatively simple and residents' daily routines are similar, many studies have applied sensors to explore the impact of environmental factors on older adults' comfort, health, and behavioural changes [30–35]. These technology implementations also aim to assist caregivers in tracking location, behaviour detection, and preventing social isolation of vulnerable groups (e.g. people with dementia).

Although the usability of smart technologies has been explored in previous studies and practices, the barriers to integrating smart technologies into (nursing) home settings still exist. Smart technologies are often inserted inside existing structures without considering environmental and user aspects. Although the extent to which the environment is tailored and accessible relates to universal design, a mismatch between technology and space usage can happen [36,37]. The user-centred approaches could specifically address individual and housing circumstances of senior households. Among them is the empathic design approach through exploration, translation, elaboration, and validation steps to design a suitable building for ageing groups. It enhances empathy during the design process for diving deep into older adults' needs [38]. Furthermore, the emergence of simulation-based tools in architectural design, such as augmented reality and virtual reality, can provide technological experiences that change how virtual models interact with the physical world. These technologies generate digital information or models overlaid on the real-world environment or create a totally artificial environment that allows designers and older adults to design, build, and experience virtual versions of smart homes before physical construction begins [39]. The advantages include visualising architectural concepts, optimising plans and models, enabling collaborative design, providing immersive scenarios, assessing the compatibility of spaces and devices, and simulating occupants' interactions [40–43]. Integrating these simulation-based technologies of real-world settings and digital models presents a novel method in the domain of architectural design, which could contribute to home renovation practices for achieving 'ageing well' purposes.

1.2 Problem Statement

Renovating smart homes based on existing housing conditions faces many challenges. Designers have little agreement on the design specifications for combining smart technologies with architectural design [12,22]. Additionally, home renovation to support older adults' independence and maintain their living qualities is a complex project. The methods to optimally integrate smart devices with the existing home settings, how these technologies can assist older adults or their caregivers with home care, and the effect of renovated home environments still need to be explored [44]. Firstly, guidelines for smart technology applications in home settings need to be addressed, and the changes in people's lifestyles and the diversity of housing structures should be holistically considered. Secondly, the means of using technologies appropriately for specific groups or purposes is essential. Normally, intrusive technologies with surveillance cameras and audio recording devices are not welcomed [45]. Although many senior homes and care facilities have deployed non-intrusive technologies, the barriers and thresholds still exist. For instance, caregivers do not always fully understand the indoor conditions and comfort of older adults through environmental data, and they still need to spend vast time observing by themselves. Lastly, traditional top-down design methods often lead to mismatches or deviations between design and use scenarios [37]. These problems should be addressed in studies.

Universal design is widely used as an adaptive strategy to cope with unknown needs and living situations of older adults [46], while it cannot be entirely applied to smart home design and renovation due to the diversity of individuals and the heterogeneity of housing types. User-centred design approaches have been proven to better understand and collaborate with older adults on their requirements [47]. However, the current concentration is mainly focused on product design and is rarely applied in architectural projects [48]. The increasing number of innovative technology applications used as research tools, such as virtual reality, to create immersive environments for older adults to experience, but require evidence-based design approaches to understand the effects of virtual environments [49]. This drives the development of the goal of this thesis, which is to explore and validate the user-centred approach to integrating innovative technologies into home renovation design.

1.3 Research Aim & Objectives

This PhD research aims to explore the approach to integrating smart technologies into home renovation for ageing well within the context of the increasing ageing population and age-friendly housing shortage in the Netherlands. The findings of this research can provide guidelines for innovative technologies as practical tools in the design process or for use as supportive devices in (nursing) home settings. Furthermore, this research has societal contributions, such as using sensor technology to support dementia care and improve care facility management. The research objectives are as follows:

1. Establish a framework of technology classifications and design strategies for integrating smart technologies into home environments that support older adults ageing-in-place.
2. Explore the application of sensor technologies in older adults' living environments. This includes monitoring indoor environmental parameters to find their correlations with human activity and determining whether sensor data accurately reflects the occupants' actual feelings, living conditions, and indoor environmental quality.
3. Investigate how indoor environmental and contextual factors affect older adults' activities and behaviours, focusing on when, where, and how these factors influence behaviour changes to guide the technology application, design, and management of (nursing) home environments.
4. Validate using innovative technologies and design approaches in a housing renovation project to optimise the design process with stakeholders and increase renovation design acceptance.

1.4 Research Questions

- How can smart technologies be integrated into home settings to enhance older adults' living qualities?

Sub-Questions:

- How are state-of-the-art design strategies and technologies used in smart home studies and projects to support ageing-in-place?
- How can sensor technologies be applied to collect indoor environmental data and information on older adults' comfort, activities, and living conditions?
- How do indoor environmental and contextual factors influence the behavioural changes of older adults?
- How can innovative technologies and design approaches be used in the housing renovation design process to meet the requirements of older adults for ageing well?

1.5 Research Design

To answer the research questions, the PhD research strives to transcend housing typologies, offering evidence and strategies for home renovation that promote older adults' well-being and living qualities. Acknowledging that the concept of 'ageing-in-place' may not apply to those in nursing homes, this study underscores the significance of integrating innovative technology and design solutions for enhancing living environment quality for older adults, irrespective of their living arrangements—whether in their own homes or nursing facilities. To further create smart environments for ageing well, this PhD research has studied from the architectural design perspective and technology application through quantitative and qualitative data analysis, including academic literature, case studies, and experimental studies. Following the empathic design framework, the research scope is defined through the literature review. The research objectives are explored and translated through case studies, then elaborated and validated through the experimental study [38]. The research flow diagram is presented in Fig. 1.1.

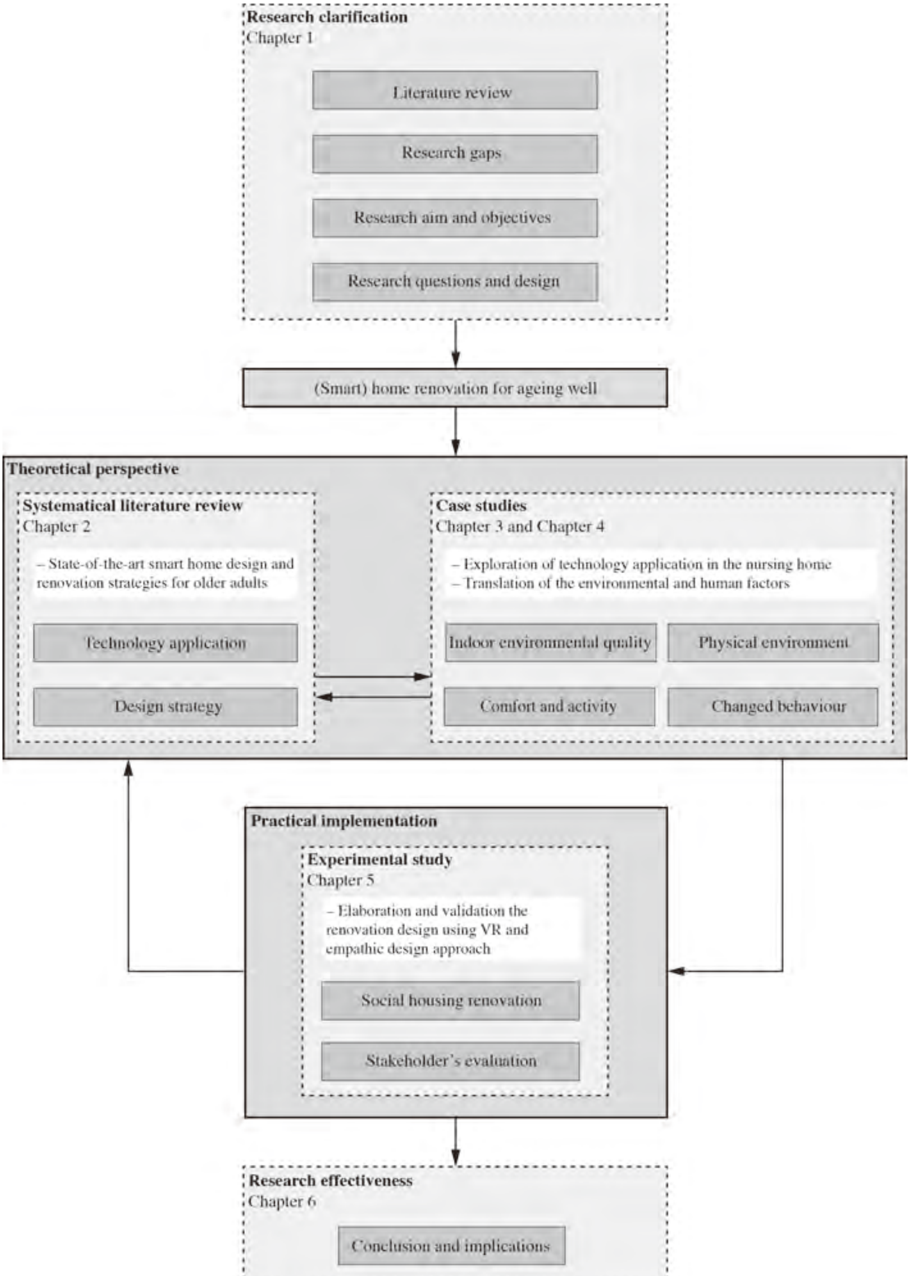


Fig. 1.1 Research design of the thesis.

1.6 Outline of the Thesis

This thesis is structured as follows:

Chapter 1 introduces the research before providing the background, problem statements, aim and objectives, and research questions that underpin this enquiry.

Chapter 2 provides an overview of current studies and practices on smart home design and renovation for ageing-in-place in interdisciplinary fields. The systematic approach is appropriate for revealing an overview of relevant studies and identifying knowledge gaps. These studies include different phases and implementation strategies (design concept, prototype, living lab, pilot project, and widespread application). This chapter sets the scope of the PhD research.

Chapter 3 focuses on the influences of the indoor environment on older adults' comfort and the actual indoor environmental quality presented by sensor data. Due to the heterogeneity of older adults and the complexity of housing typologies, the case study is narrowed to people with dementia and the nursing home environment. The target group living in the nursing home has basically the same daily routine and living environment, which minimises the variables from environmental aspects. The qualitative data (questionnaire and interviews) of professional caregivers and nursing home staff and quantitative data collected by sensors (temperature, humidity, carbon dioxide, total volatile organic compound, particulate matter, and illuminance) and associated with local weather, building facility operations, and nursing reports are analysed to find the correlations of comfort, indoor environmental parameters, human activities, and facility management. Additionally, this chapter contributes to the nursing home design and management and provides insight into applying sensor technology for dementia care.

Chapter 4 considers the influences between people with dementia, behaviour, and indoor environment based on Bandura's triadic reciprocal causation model of social cognitive theory [50]. This exploration is based on the fly-on-the-wall observation method and environmental sensor data collection to record participants' living conditions and behaviours in the nursing home [51]. To achieve comprehensive results, indoor environmental parameters (temperature, humidity, carbon dioxide, total volatile organic compound, formaldehyde, and particulate matter), building ventilation control, participants' locations, activities, clothing levels, activities, and changed behaviours are recorded and analysed. Fisher's exact tests are used to examine the indoor environmental and contextual factors with participants' changed behaviours. The heatmap charts illustrate the participants' locations and behaviours at some specific moments according to the data analysis results.

Chapter 5 explores the approach of integrating empathic design and virtual reality within a social housing renovation project, which focuses on four primary aspects: a) the investigation of current housing conditions by housing assessment tools and interviews, b) the translation of user requirements and problems of current housing conditions into design strategies, c) the development of empathic designed digital models and immersive scenarios of pre- and post- renovated buildings, and d) the validation by stakeholders through the virtual reality experience. Based on the perceptions of stakeholders, the approach is developed to increase the empathy and acceptance of older adults for housing renovation and improve design effectiveness using innovative technologies.

Chapter 6 concludes the thesis by answering the sub-questions and the main question of this research. Subsequently, the limitations of the entire research are discussed. Finally, the chapter describes the implications and recommendations for further research and practice.

Chapter 2
Smart Home Modification Design Strategies for Ageing-in-Place: A Systematic Review [1]

Abstract

This chapter explores current strategies and approaches to integrating innovative technologies in home modification to support independent living and ageing-in-place. The systematic review considered studies conducted from architecture, smart technology, and gerontology perspectives. Scientific databases of related disciplines (e.g. Scopus, Web of Science, Engineer Village, Google Scholar, and Crossref) were searched and supplemented by hand search method. Thirty-three out of 2594 articles were analysed from three perspectives: the framework of the smart home environment for ageing-in-place, the smart home modification process, and problems and countermeasures of independent living. The result shows that both home modification and smart technologies can support older adults' independent living, especially with fall prevention and indoor accessibility. Technologies deployed in older adults' homes are transiting from manual assistive technology to more intelligent devices, and the notion of the robotic home has emerged. According to existing practices, universal design is an extensively adopted smart home design and modification strategy. However, in most cases, universal design is used as a retrofitting guideline for general home settings rather than specifically for smart homes. The fundamental requirements in smart home modification phases are customisation, minimum life interference, and extensible technologies to cope with the ageing process.

---

[1] A previous version of this chapter was published as:
Ma, C., Guerra-Santin, O., and Mohammadi, M. (2022). Smart home modification design strategies for ageing in place: a systematic review. *Journal of Housing and the Built Environment*, 37(2), 625-651.

2.1 Challenges of Ageing-in-Place and Potential Solutions

The ageing population is growing rapidly in the Netherlands. By 2050, 26.9% of the population is projected to be over 65, and 11.3% of the population to be over 80 [52]. Simultaneously, compared with working-age groups, the number of retired people is growing faster, which puts pressure on limited health resources and increases the demand for care, services, and medical devices [5]. Therefore, the Dutch government encourages older adults to 'ageing-in-place', which is defined as living in their home environment for as long as possible [6]. The latest data reveal that more than 40,000 Dutch households aged 65 and above live in an 'unsuitable' home environment [5,8,53]. Because of the physical decline of older adults, the housing designed for the general population could gradually become uncomfortable or even dangerous. Including the Netherlands, all housing stock in Europe faces this serious problem, especially for the very old group (over 80 years old) [54].

Smart technology has been regarded as a potential solution for providing a supportive living environment for ageing-in-place [11–13]. The word 'smart' has recently become an umbrella term for innovative technologies, including partial assistive technologies (AT), ambient intelligence (AmI), ambient assisted living (AAL), Internet of Things (IoT), information and communication technology (ICT), smart home, and artificial intelligence [15]. This thesis will use 'smart technologies' to refer collectively to these technologies. Generally, smart technologies have four essential functions: entertainment, safety, healthcare, and energy-saving [16,17]. For older adults living independently, these technologies aim to enhance personal safety, health monitoring, living environment control, and improving social interaction [55].

The development of smart technologies brings a more detailed classification and selection. Technically, a complete smart home system consists of four components: external devices, a control system, a communication system, and a database [56,57]. Smart home systems are usually classified according to the combination of components. Chief among them are the external devices responsible for receiving information and monitoring. Sensors, as one type of external device, have hundreds of classifications by functions and use patterns. Thus, selecting sensors is vital for creating a smart home environment. From the viewpoint of the relation between sensors and housing infrastructure, Ding and her colleagues determined three main categories: wearable sensors (worn by people), direct environment sensors (distributed in the environment), and infrastructure mediate sensors (installed on the housing infrastructure) [22]. Not all external devices of smart systems are required to be embedded in the housing structure [57,58], but home modification is still indispensable in eliminating the effects of the surrounding environment and ensuring the device operates effectively. Furthermore, the conditions of most existing home environments are not appropriate to deploy new smart devices [19].

Deploying smart technologies into the existing housing stock is a challenge, but only relying on the new technology-compatible housing market is unrealistic [16]. There is a growing interest in renovating existing housing stock to cope with the future ageing population. Generally, home modification for older adults means alterations of permanent physical features in the home and its surrounding area to facilitate daily tasks, increase comfort, reduce the number of accidents, and support independent living [20,21]. It has been proven to be an effective way to prolong older adults' lives in their own homes. Measures include reconstruction of the building structure (building functional improvement), rearrangement of the housing layout (increasing usability and safety of indoor features), and now also contains the installation of smart technology devices (supporting activities and compensating declining functions). The mainstream of existing research focuses on how smart technologies affect older adults' quality of life regarding domestic features, accessibility, home satisfaction, user-friendliness and technological acceptance [10,59]. In most of them, home modification and smart technology were considered as two unrelated interventions but with some overlapping functions. A scoping review by Carnemolla and Bridge pointed out that home modification does not equal smart technology since it focuses on the house structure itself [60]. Some blank areas remain in the effects of home modification, such as the influence of housing typology. A review by Agree explained the difference between universal design and assistive devices/environmental modifications and suggested taking into account individual capacity to the physical environment [61]. Lee and Kim highlighted that smart technology should be customised according to changes in people's lifestyles and housing structures [62]. These knowledge gaps related to smart technology integration and home modification need to be explored in future research.

So far, the real-life smart home projects designed and constructed for older adults are limited. In a systematic review, Pal and colleagues reported that most application scenarios were conducted in ideal environments, such as laboratories or academic institutions [63]. Some researchers avoided mentioning the relationship between home modification and smart technologies because this integration requires higher financial costs and more maintenance, complicating the situation [64]. Thus, the knowledge of combining smart technologies with architectural design is lacking, especially when it comes to retrofitting [12,22]. There is little agreement among designers on smart home design specifications. Dewsbury suggested achieving a qualitative shift in understanding the translation of needs into architectural design specifications before integrating appropriate technology in the home environment [23].

Along with the increasing number of smart technologies introduced in older adults' homes, the guidelines and standards on technology selection, installation, and application need to be explored. It is important to summarise state-of-the-art theoretical research, laboratory studies, and pilot projects that used advanced technologies to support ageing-in-place or integrated technologies into the existing housing. Creating smart home environments is an interdisciplinary area, and many different branches of disciplines have put forward research outputs from their expertise. Therefore, a systematic literature review method is used in this chapter to search related publications, classify involved technologies, and find the relevant experience and results associated with architecture. This chapter presents elementary design strategies and a framework of smart home modification to help better understand the application of architectural and technological interventions in the coming ageing society.

2.2 Systematic Literature Review Process

2.2.1 Search Strategy

The scope of smart home design and modification includes architecture, smart technology, and gerontology. To fully obtain knowledge from these different fields, a systematic literature search was conducted using interdisciplinary research databases, including Scopus, Web of Science, Engineer Village, Google Scholar, and Crossref and supplemented with the hand search (snowball method). A variety of several synonymous terms for 'smart technology', 'ageing-in-place', 'home', and 'modification' were searched. For example, Table 2.1 shows the search strategy in the Scopus database using Boolean logic. The combinations of these terms were adjusted in different databases according to the various search principles. The research period was limited to searching the state-of-the-art literature from January 1st, 2010, to December 31st, 2019.

Table 2.1 Search strategy for Scopus.

Keywords	Synonyms
Smart technology	'Assistive technology' or 'ambient intelligence' or 'ambient assisted living' or 'Internet of Things' or 'information and communication technology' or 'smart home'
Ageing-in-place	'Age in place' or 'live in place' or 'independent living' or 'independence'
Home	'Housing' or 'dwelling' or 'residence'
Modification	'Refurbishment' or 'retrofitting' or 'renovation'

2.2.2 Inclusion and Exclusion Criteria

After removing duplicates, the citations (including grey literature) were screened using the titles and abstracts. The review was restricted to the English language. The included studies focused on applying smart technology in home environments. Hence, the essential exclusion criteria were as follows:

- Studies were conducted in institutional facilities (nursing homes are outside the scope of this review).
- Studies focused on the neighbourhood, community, or larger scale.
- Studies were presented as abstracts only.
- Articles on the same topic from the same author (only include the latest one).

2.2.3 Study Selection

Records that met the exclusion criteria were removed after titles and abstracts were scanned. There was no specific age group limitation for study selection because different countries have different 'older adult' definitions. Moreover, studies focused on frail groups with similar characteristics, such as physical limitations, were also included.

On account of the polysemy of some definitions and keywords (e.g. 'architecture' has different meanings in architectural design and computer science), some uncertain studies on technology development and testing were included for the full-text screening.

This review focuses on smart home modification strategies for ageing-in-place. For selecting the relevant studies, full-text screening was required with the exclusion criteria:

- Studies only focused on medical science or computer science.
- Studies only focused on wearable technologies.
- Studies conducted by medical research methods.
- Studies were not specific for older adults or frail groups.
- No design process, guideline or strategy was provided.

Within the initial 2594 identified records, 126 titles and abstracts were deemed relevant. Of those relevant articles, 77 full-text studies were selected after the exclusion steps, and 28 were identified as eligible. The updated search identified an additional 29 studies using the snowball method; 5 were selected by the exclusion criteria, resulting in a total of 33 articles and book chapters (Fig. 2.1).

2.2.4 Data Extraction and Quality Assessment

Data extraction was undertaken by one researcher by using a designed and piloted extraction sheet (see Appendix A). Data extraction items included country, contribution category, technologies involved, research tools, research methods, technology application stages, and focuses. A second independent researcher with expertise in relative research fields checked the extracted data.

Since the topic reviewed in this chapter was a relatively new research field, a limited number of studies were fully matched. Therefore, all relevant studies, where even only a part of the contents mentioned 'smart home modifications' and 'older adults', were included. A quality assessment was conducted using the Cochrane Risk and Bias tool. Two researchers assessed the risk of bias independently and then discussed the disagreements, and the third researcher evaluated the result.

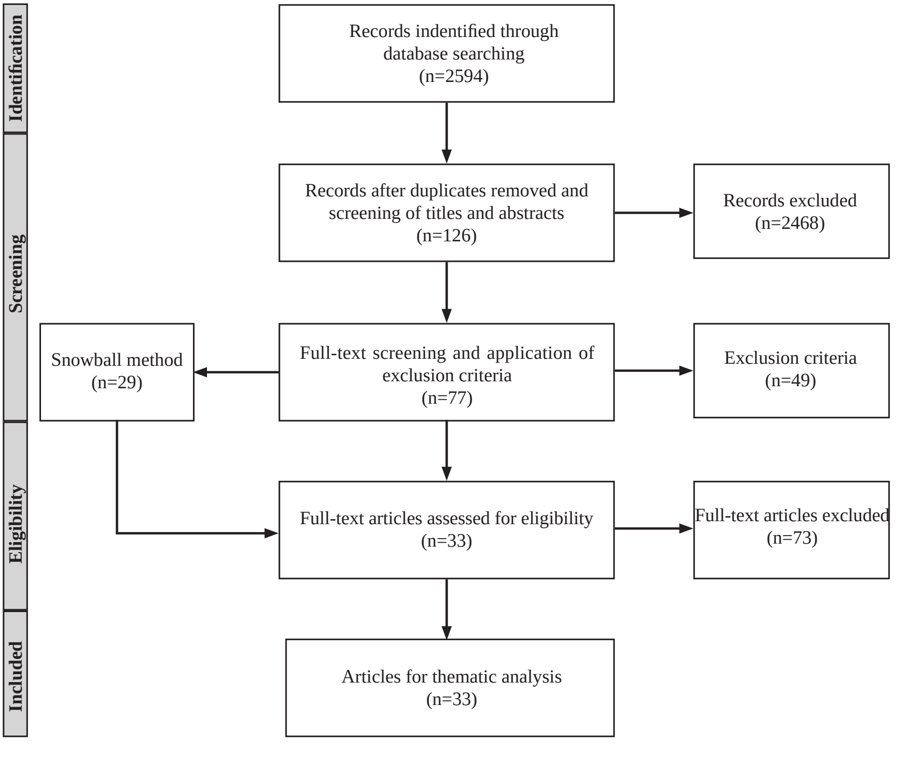


Fig. 2.1 The literature review process (PRISMA flow chart).

2.2.5 Data Synthesis

A thematic analysis was carried out on the selected studies, which were classified and summarised in three different perspectives of smart home modification: 1) the framework of the smart home environment, 2) the smart home modification process for ageing-in-place, 3) problems and countermeasures of independent living. The results related to each theme are shown in the following sections.

2.3 The Framework of Smart Homes: the Classification of Smart Technologies Used in the Home Environment

This section presents the framework of the smart home environment and illustrates a retrofitted smart home scenario for older adults according to technology classifications, functions, and positions (Fig. 2.2).

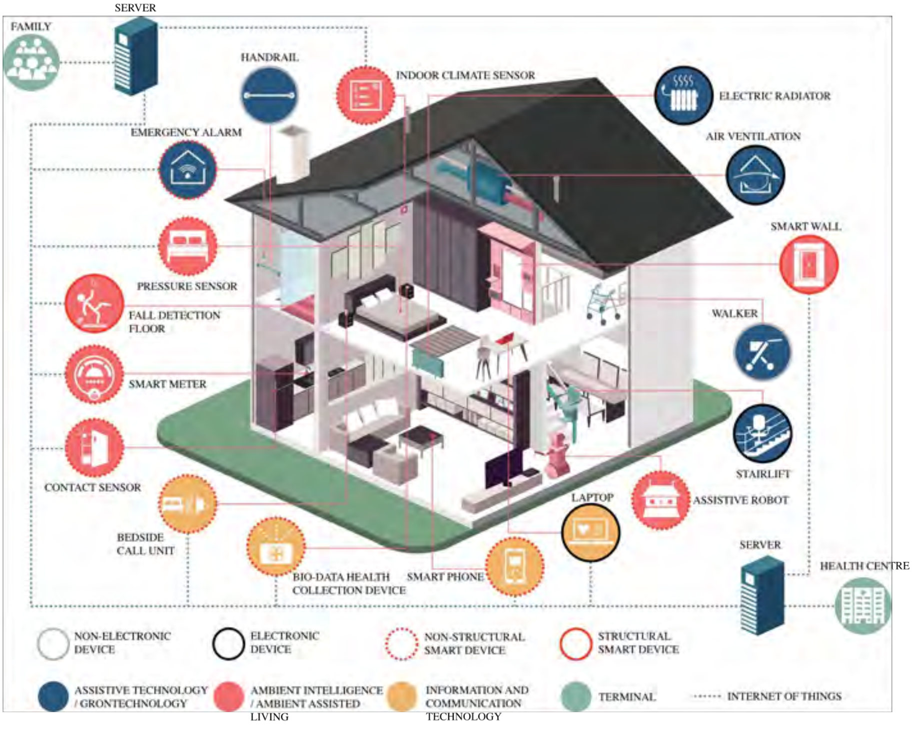


Fig. 2.2 The classification of smart technologies used in the home environment.

Generally designed homes need to be retrofitted to keep older adults safe. Conventional measures, such as replacing the bathtub with a walk-in shower, can provide safer living conditions. In addition to home modification, devices designed for older adults can support their daily activities as well. Non-electronic devices, electronic devices, and smart devices (represented with different coloured circles in Fig. 2.2) are widely used for various purposes. These devices or external parts of smart systems are distributed in the home environment. Most of them are non-structural, which are placed on the surface of architectural components or installed inside the infrastructure and furniture, such as indoor climate sensors on walls or ceilings, pressure sensors under mattresses, water meters on taps, and contact sensors on doors [65–68]. Non-structural technologies make a minimum change of homes and are easier to deploy. However, structural technologies require retrofitting the existing housing structure for specific purposes, such as using fall detection floors to replace slippery floor tiles in risky areas to cope with an occasional emergency.

Furthermore, smart technologies have a more detailed classification of building environments and interactions with users, terminals, and other devices. Assistive technology (AT) has the broadest range of meanings, from low-tech gadgets to complex home automation systems [69]. It could be any product, equipment, or part of a smart technology package designed to support older adults living independently [70]. The primary function of AT is to compensate for the decline of older adults' basic living skills and improve the safety of their daily activities. Older adults with 'architectural disabilities' gradually lose control of their living environment, which can be enhanced by the assistance of AT [71]. AT refers to both non-electronic and electronic devices, including smart assistive devices (blue icons in Fig. 2.2). These technologies or devices designed for older adults are also called 'gerontechnology'. This new term combines gerontology and technology and is an interdisciplinary field of science for creating healthy, comfortable, and safe living spaces with supportive technologies [57]. To this day, AT and gerontechnology are essential equipment in home settings and could be transformed from 'unsmart' objects to smart devices by integrating innovative technologies.

The developments of information and communication technology (ICT) provide solutions for controlling and managing AT in the home environment through interactive modes, such as computerised devices and communication devices (yellow icons in Fig. 2.2) [72]. These interactions make technologies easier for older adults and their caregivers to manage (green icons in Fig. 2.2). E-health, telecare, and more ICT-based technologies offer health care by remotely monitoring and diagnosing. Ambient intelligence (AmI) is also an ICT-related concept in which the home environment consists of the user's data-collecting devices, ICT networks and electronic assistive technology [73]. As a subfield of ambient intelligence, ambient assisted living (AAL) can be defined as an intelligent integration of ICT and sensors into the living environment. It supports the needs of older adults through networked technologies in the physical space (red icons in Fig. 2.2) [74,75]. AAL has a broader application scope. It can be applied in residential buildings, communities, or public buildings [76]. Within the ageing-in-place field, the Internet of Things (IoT) is the foundation for transforming physical components used in AAL into smart components and integrating them into living spaces [77]. IoT forms local networks by connecting things with remote servers (blue dashed lines in Fig. 2.2) [78]. In other words, IoT technology does not refer to a specific device but to technical means linking older adults, their living environment, and information on their health condition to terminals by the network.

As a result of the emergence and development of innovative technologies, the living environment, technologies, objects, and even people are interconnected. Smart homes can be considered as a more comprehensive concept of smart technologies applied in homes. Including the technologies mentioned above, the definition of the smart home is a special kind of house or apartment equipped with sensors and actuators integrated into the infrastructure of the residence, intended to monitor the context of the inhabitant to improve their experience at home [79,80]. Hui pointed out that intelligence is an essential ingredient in smart homes [81]. The function of smart homes is developing from primary data collection to a more intelligent interactive care environment.

2.4 The Smart Home Modification Process for Ageing-in-Place

Smart home modification for ageing-in-place aims to integrate new technologies through physical environment adjustments to provide an intelligent home. This process usually starts after older adults realise their living environment is unsuitable. The modification consists of four phases: Home assessment, technology selection, design strategy, and user evaluation (Fig. 2.3). These phases are consistent with the framework proposed by Mohammadi et al. and Güttler et al. for designing smart home environments [38,82]. Their approaches mainly consist of several practical steps: exploring and translating users' requirements, identifying the necessary technologies and processes, building design concepts, experiments in living labs, and producing and validating the final solutions. The use of the participatory design method is highlighted in these approaches.

Ageing is a dynamic process that requires home modification iterations when homes reach the threshold of unsuitable. Therefore, a comprehensive viewpoint is required to understand the opportunities and challenges associated with implementing smart technologies in the home modification process and promoting ageing-in-place [83]. The following sections focus on the steps of the smart home modification.

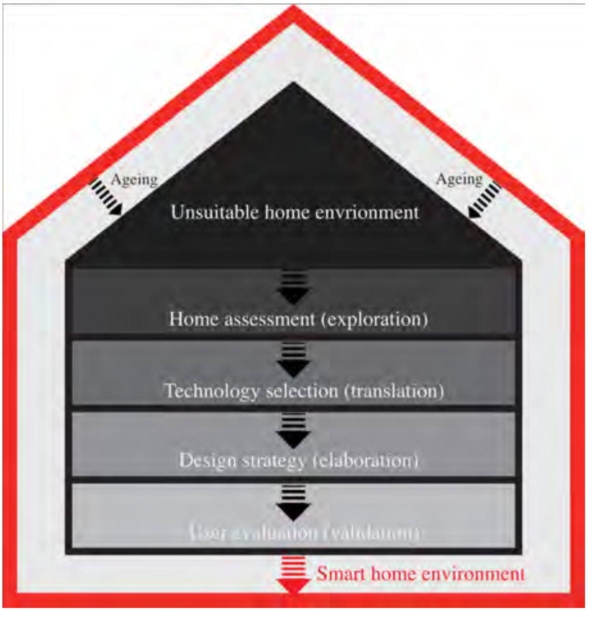


Fig. 2.3 Smart home modification process.

2.4.1 Home Assessment

The home assessment phase is an essential step in smart home modification. Eight studies emphasised the importance of home assessment supporting older adults living independently (see Appendix A). This phase helps identify potential hazards in existing housing stock and contributes to exploring the objective requirements of older adults' daily lives. The home assessment is also the foundation for renovation design and construction. Assessment tools vary from traditional checklists to high-tech technologies such as virtual reality (VR) techniques. The checklist is the simplest method to detect hidden dangers in homes. The contents of checklists vary according to different objectives. Horowitz et al. demonstrated the Home Safety Self-Assessment Tool (HSSAT) to diagnose 66 targeted home hazards in the following locations in the home: entrances to the front door and front yard; entrance to back/side doors; hallways/foyers; living room; kitchen; bedroom; bathroom; staircases; and laundry room/basement, and provided potential solutions [84]. Housing Enabler (HE) is another well-established research-based methodology using checklists for housing accessibility assessment and modification solutions [85]. However, the main limitation of checklists is that they have been designed for an average target user, ignoring the differences between individuals. The prevalence of augmented reality (AR) and VR technologies has overturned traditional methods. These technologies could identify and visualise the harmful indoor features and propose suggestions using a participatory design method in the decision process. Some advanced devices even allow users to experience the simulated scene of renovated homes [86,87].

Home assessment tools concentrate on three aspects of senior housing: Structural modification (increasing accessibility of indoor spaces), layout adjustment (simplifying tasks of daily activities), and device application (supporting activities and compensating living abilities) [54,88]. Current studies mainly explored older adults' functional decline with the impact of domestic features changes, and involved technologies were usually classified as general housing components. The technological effects on users and their living environments have been ignored. Furthermore, older adults' homes are often structurally unsuitable or unprepared for the straightforward installation of smart home systems [89]. Therefore, an assessment tool is required to evaluate the compatibility of smart technologies with existing housing structures before modification design and construction.

2.4.2 Technology Selection

As a heterogeneous group, older adults have various and changing living habits, requirements, and preferences. These differences should always be taken into account in the technology selection phase, which aims to match users' characteristics [90]. As McCreadie and Tinker summarised, the acceptability of smart technologies requires matching both older adults' individuals and housing conditions, and it is also affected by the attributes of the technology itself [71]. Therefore, it is crucial to explore compensation requirements in older adults' daily lives and translate them as selection criteria to match suitable technologies.

The features of smart technologies with higher acceptance are identified as being less intrusive, having lower costs, being user-friendly control, having a user-friendly interface, and having fewer design features [11,89,91]. Agree advocated for the benefits of using universal design for developing standardised devices and systems to ensure they are uniformly accessible or usable by persons of varying abilities [61]. However, the main barrier to promoting smart technologies in the market is the missing common standards in the interoperability and compatibility of these products [89,90,92,93]. Challenges remain for older adults to constantly adapt to non-universal smart systems until these barriers are eliminated.

2.4.3 Design Strategy

Five studies focused on integrating innovative technologies into the domestic environment in different stages, from concept to pilot project (see Appendix A). Röcker and Ziefle proposed combining communication and interaction mechanisms as well as bio-signals with basic architectural elements and building structure. People can directly interact with the smart homecare environment, consisting of an interactive wall, a smart floor, and a medical helper device [94]. Linner et al. developed the concept and prototyped 'robotic micro-rooms' (RmRs), which do not require refurbishment of the existing interior. The concept is based on the 'terminal-wall' approach that pre-embedded assistive devices into modular elements as integrated furniture [95]. Based on the size of the three-dimensional space surrounded by the ceiling panel, wall panels and floor panel, the adjustable smart components can be easily inserted into existing rooms and enable a 'plug-n-play' installation. The integrated robotic devices and furniture, such as ceiling robots, robotic cabinets, and robotic service walls, are also easier to adjust and lower the threshold of older adults managing their daily living [82]. However, real smart home retrofitting projects need to deal with practical problems. The pilot project of Smart Cottage in McKeesport, Pennsylvania, used wireless sensor technologies to solve the design problems caused by setting new data channels inside the walls of the existing house. This approach aims to maintain the aesthetics and neatness of the interior space [96]. Moretti and colleagues reported their experiences installing a smart home system in an existing home. To avoid damaging the housing structure, they used a more secure and traditional (iterative) method of mounting selected external devices by creating custom-made brackets, photographing the site, drafting design drawings, printing the parts, and checking the fitness [97]. This universal customisation approach would normally take longer because interior designs in different homes have little uniformity.

Nine studies described the challenges of creating smart home environments and offered strategies to gain higher user acceptance (see Appendix A). In a review article, Bitterman and Shach-Pinsly pointed out the lack of empirical evidence to prove the effectiveness of using smart technologies in home environments [98]. Most studies remained in the laboratory stage. Hence, universal design, also known as design for all or inclusive design, has been regarded as one of the few guidelines for designing a home environment without architectural barriers [73,99,100]. In the context of smart home design, universal design has another meaning of commonality in technology design and application. The features of universally designed architectural components and devices are convenient to install, modify or remove and more adaptive to coping with older adults' changing daily lives [46]. However, understanding seniors' lives often differs between the age group and young designers. Thus, Iwarsson suggested that designers negotiate with older adults to consider their personal needs and preferences in the design phase instead of proposing generally applicable recommendations [21].

Compared with the top-down design, user-centred design approaches have been proven to be better strategies for understanding the individual experiences of older adults and their requirements [47]. These approaches for designing domestic environments for ageing well come from the Human-Computer Interaction (HCI) and participatory design methods. HCI is an effective solution for developing smart technologies and devices from a user-centred perspective. It contributes to understanding the preferences of older adults concerning smart environments by gathering feedback regarding the interaction between older adults and a smart environment [101]. A series of HCI-inspired design guidelines have been presented, such as HCI technology as a visualisation tool to assist older adults in anticipating changes to their home environments [86]. De Vries and colleagues developed a design system that storages smart architectural components in a database, including the smart wall, kitchen, and furniture. This system allows users to experience smart living in the virtual domestic setting and interact with added technologies [102]. Another study by the Massey University Smart Environment (MUSE) group explored requirements analysis for smart homes and occupants [103]. Researchers introduced 'Use Cases' to assist smart home design for older adults through database-documented discussions and behaviours from a wider smart environment community. These user-centred methods are becoming crucial methods for smart home design research, which can increase the technology acceptance and user experience.

2.4.4 User Evaluation

Smart technologies cannot completely replace the function of a supportive physical environment; in other words, ageing-in-place requires both architectural and technological interventions to keep older adults' living quality at home [104]. The user evaluation is the phase for validating the effectiveness of these interventions and using users' experience to guide future practices. However, the limitation of this research type is that most of the outcomes are based on self-reports and interviews and lack objective performance-based measures [105]. Guiding practices need more scientific data to avoid detours in the modification process. The renovated home is unlikely to be entirely suitable by only one modification, which means more investment and construction cycles. A comprehensive method is needed to analyse the effects of architectural and technological interventions in various types of residential buildings.

In this chapter, we identified seven research projects where recognised systems for evaluating the modified living environment of older adults were developed or tested (see Appendix A). Carnemolla explored her Human/Activity/Space/Technology (HAST) model for ageing-in-place through three case studies in which smart technologies were introduced into senior households and mapped the implications, limitations, and outcomes of the template design. This model evaluated the home environments in four aspects: A person's functional capacity (human), care (activity), the built environment (space), and smart technology (technology) [104]. Cho and Kim proposed a framework of user interface design principles for older adults that helps to evaluate the usability of smart devices in their homes. This framework was based on five evaluation tools for living environments: multiphasic environmental assessment protocol (MEAP), nursing unit rating scale (NURS), professional environmental assessment protocol (PEAP), environmental audit tool (EAT), and evaluation of older adults' living environments (EVOLVE). The framework was characterised by 12 smart devices: six interactive and six supportive properties. It provides a new method for evaluating the built environment and offers a rational basis for selecting alternative proposals [106]. In the research 'Smart Home Independent Residing' enabled by Intelligent Solutions (IRIS), Ocepek's team used the Canadian Occupational Performance Measure (COPM) and the Functional Independence Measure (FIM) to evaluate the older adults' satisfaction and independence with the assistive technology implementation and home modification [107]. Renaut and colleagues investigated French residences for seniors through semi-structured interviews. The study focused on how they construct the space in their home environments and how to fit new devices with the evaluated housing condition. They stressed the importance of involving older adults in the design and construction phase of home modification and the advantages of small repairs and minor changes [108]. In the Housing and Independent Living (HAIL) study, six key themes emerged from the semi-structured interviews: housing choice, attachment to place, financial issues, changes to the home over time, transport, and anticipating the future. The study investigated what the occupants (over 70 years old) had retrofitted to their homes and the expectations for future modification. It discussed the role of assistive technologies, devices or modifications in the home environment and highlighted the importance of housing design in planning a supportive home environment [109]. Lien and her team used the ecological theory of ageing (ETA) and selection, optimisation, and compensation (SOC) model as their theoretical frameworks to understand the adaptive environmental behaviours employed to achieve Person-environment (P-E) fit in older adults' homes. The results could be used to develop and optimise current home modification practices [110]. Bishop et al. reported the first national evaluation of the prevalence of residential assistive devices and modifications among the multiple sclerosis group in America [111]. Although this research is not specific to older adults, multiple sclerosis patients are also a relatively vulnerable group. Researchers used a qualitative analysis method and categorised the indoor changes by rooms or areas identified. This method is instrumental for the specific renovation of each room in the domestic environment.

The above studies show the evaluation tools and results of home modification for frail groups and reveal the prevalence of modified or adapted housing in the housing market. Interestingly, most included projects (6/7) were only equipped with unsmart assistive technology as a functional complement to housing facilities. The limited number of study samples is the main reason for this result, and there needs to be a correlation or uniform standard between the evaluated cases. However, the evaluation tools and methods mentioned can be references for developing specific smart home modification evaluation systems.

2.5 Problems and Countermeasures of Independent Living

Even healthy older individuals encounter challenges due to normal age-related changes. The functional decline of the body often increases the difficulty of activities of daily living (ADLs) and instrumental activities of daily living (IADLs) [112]. Restricting older adults' daily activities is impractical. An effective way to support independent living is to detect and erase the hazards in their living environments. Eight reviewed studies focused on the hazards that could influence older adults' independent living, specifically on fall prevention and accessibility (see Appendix A). A few of them showed the types and extent of home modifications associated with daily activities and the implications of these potential problems on older adults' independence. Although both home modification and smart technology can theoretically enhance independence, the effects and prospects of these interventions in home environments are still being explored.

Falling is one of the most dangerous situations threatening older adults living independently. The common definition of falls is unintentionally coming to impact on the ground, floor, or other lower level [113]. Serious consequences may happen after the falls if they fail to get timely treatment. Falls are the leading cause of injury and death in people over age 65, and the risk is higher following the growth of age. Over 30% of older adults fall each year [88]. Most fall-related injuries (55%) occur inside the home, including falls on stairs and in rooms throughout the house. Hazards of falls are hiding in the domestic environment. 80% of households contain at least one identifiable hazard, and approximately 40% of them contain five hazards or more [20,114]. The majority of the reviewed studies mentioned the dangers of falls among older adults, and five of them investigated how to prevent falls (see Appendix A). The measures include improving older adults' body function by strengthening exercise and optimising the indoor environment. For the indoor environment, action should be taken to start with the housing assessment phase. Checklists are widely used to assess the common hazards in the home environment, even though the results are not intuitive. With the advent of AR technology in recent years, these high-tech devices can scan and visualise problem areas and help older adults better accept home modification design [115]. Fall risk in daily activities cannot be eliminated. Several strategies provided by literature studies for enhancing indoor safety: universal design (reduce indoor barriers and improve the versatility of structures and spaces to facilitate functional expansion and installation); optional fittings (add architectural components such as handrails, ramps, and stairlifts that protect for the daily activities); co-creation design (create an age-friendly home environment according to the specific circumstances of occupants); and smart technology (install fall detection sensors and automatic alarm for detecting dangerous situations and calling rescue) [11,20,86].

Accessibility has a broader definition in the field of smart home research. The scope mainly includes physical accessibility, financial accessibility, technical accessibility, and psychological accessibility [65]. Physical accessibility is the basic premise of independent living, especially for the older group with mobility limitations. Physical accessibility is usually defined as older adults' mobility, reachability, and occupancy in interior spaces or with building components at the architectural design level. Many architectural features impact the physical accessibility of the structure, from the structure to small construction details, including spatial articulation, compactness, available room to manoeuvre, number of floors, and open plan [116]. With the future appliance of assistive devices and smart technologies, the indoor space for device placement and operation also needs to be considered. Currently, the mainstream research is on the technical accessibility of how older adults use smart technology at home and their acceptance of new technologies. Few researchers have tried to investigate the actual physical accessibility of older adults in different living scenarios when they have mobility limitations. Moussaoui et al. proposed experimental research using virtual reality technology for a personalised assessment of the accessibility to a dwelling [87]. They tested the accessibility of mobility, reaching and grasping by modelling a person moved in a wheelchair or with a walker. Using VR technology, they visualised the possible state after modifying the environment and the ability of older adults to control their living spaces. Their research provided an approach to using VR technology as a supplementary method of architectural design. For smart home modification, it is essential to simulate and validate technology application scenarios in the design stage.

2.6 Discussion

2.6.1 Summary of Findings

In the last decade, smart technology development boomed and created a prosperous market. The scenario of smart homes fully supporting ageing-in-place is still far from a reality [117,118]. Older adults choose to live in smart homes depending on intentions to enhance safety and reduce the demand for care. However, the acceptance of 'smart' devices is still lower than expected [119]. Using common assistive technologies to expand housing functions such as grab bars, railings, and stairlifts is still the preference of designers and users when retrofitting homes for ageing well. The barriers to smart home modification are high cost, low trust, stigmatisation, maintenance, ethical problems, and many other aspects of smart technology application [19,92,120–122]. In this chapter, we conclude that the following strategies are crucial: 1) consider the integration with the existing home layout, structure, and materials before deploying smart technologies; 2) minimise the interference to older adults' original living environment; 3) use extensible technologies and design to reduce the frequency of home modification.

Home modification for ageing-in-place follows universal design guidelines for installing, removing, or renewing building features, which is not extraordinarily expensive or complicated. However, adding smart technologies to the housing structure will increase the difficulty of the design and construction. Smart technology requires spaces for installation and operation and changes the indoor environment according to location, material, and appearance [98]. Most studies so far have discussed technology applications at the theoretical level. However, in realistic home environments, many factors will likely lead to mismatches between technology and space usage and deviations between design and application [37]. For instance, some light sensors are designed to be embedded in ceilings. However, users prefer to put the sensor on top of the wardrobe to keep the ceilings neat, influencing data collection accuracy. Furthermore, different building materials, surface reflectance, and indoor obstacles also affect smart devices' operation, such as reinforced walls, which could cause indoor localisation and signal reception malfunction [12,123]. Thus, the effects of installing and using new devices sometimes cannot fulfil expectations if the existing home environment is not properly considered.

From the existing literature, unobtrusive smart technologies are more acceptable [112,124]. These technologies support ageing-in-place while maintaining their dignity, privacy, and familiarity. The preference is to integrate smart technology as an invisible part of the housing instead of highlighting the 'smart' [95,124]. If smart technologies are visible, the products or interior features after the installation should be aesthetically acceptable [92]. An opposing view held by some researchers is that smart technologies can exist in living spaces in a more futuristic way rather than be completely hidden behind the building structure. The concept of ‘plug-n-play’ is a method to simplify the process of technology installation and home modification [82,125]. There is no conflict between these viewpoints. Both ‘hiding’ and ‘plug-n-play’ strategies aim to simplify the modification process and minimise interference to the living environment. The only difference is the degree of integration of technologies and housing conditions, which depends on the user’s acceptance of technology. According to the user’s preference, smart home modification requires a consistent strategy from design to implementation.

Ageing is a dynamic process. There is no concept of adaptability in the field of smart home design for older adults, which varies according to users’ needs and characteristics [65]. Helal and Bull pointed out that to adapt to older adults’ changing needs, integrating smart technology in living spaces should be flexible, adaptive and changeable [117]. With the decline of individuals’ abilities, customisable supports (e.g. assistive technologies and home modifications) are also crucial to keep older adults independent as long as possible [126]. Therefore, the smart home modification design strategy needs to take into account the variables of older adults’ circumstances and their homes to create a long-term plan. Home modification should solve immediate problems and prepare to cope with different situations of future ageing stages. It is often late and risky when older people realise they live in an unsuitable home. Homes renovated by an extensible strategy could be easier to upgrade before reaching ‘unsuitable’ thresholds. Furthermore, along with smart technology development, it is necessary to reserve spaces for technology upgrades and replacement according to housing characteristics.

2.6.2 Limitations

This chapter has some limitations. First, although we used a thorough search strategy and expanded the search scope, only thirty-three studies were identified as relevant to this systematic review topic. Smart home modification is a relatively new and interdisciplinary field that is being developed based on practice. The existing smart home projects designed for older adults are limited. Less than a quarter of thirty-three studies were in the pilot project stage, or involved technologies were widely used (see Appendix A). Second, due to the heterogeneous perspectives of available studies, this chapter was conducted using the thematic analysis method. Not all included studies were based on architecture research. Technologies in some studies were research tools that were not used to support older adults’ independent living. Third, a growing number of innovative technology terms have emerged in recent years. The high-frequency terms found in existing literature were listed and explained in this chapter. Fourth, we built an elementary design framework for smart home modification, described the scenario, and summarised the latest research orientation. The framework needs to be validated with further research and practices.

2.6.3 Implications for Practice

Different from traditional architectural design, smart home modification design for older adults focuses on the ability compensation. It is user-centred rather than concentrating on the building itself. While this chapter presents the basic design flow, strategies, tools, and main design points, there is a need to comprehensively understand and analyse the specific situation of occupants and their living environments. Otherwise, it is difficult to guarantee the effect of home modification. In some cases, home modification could worsen the situation and negatively impact older adults' lives [127,128].

The diversity of smart technology terms, products, and protocols is another challenge for designers and users. Low technology compatibility and fragmentation lead to low adoption rates and user confusion [93]. There is a need to establish a clear and comprehensive classification standard of smart technologies and systems to match their functions to user needs. It could also be helpful to indicate the architectural requirements of technologies (e.g. operation space, building facilities, installation site) as references for the renovation design. User-friendly and application-friendly smart technologies are more likely to be used in seniors' homes.

2.6.4 Future Research

The reviewed studies were mostly conducted in ideal conditions and only provided theoretical data. Knowledge of the actual effects of smart technology and architectural interventions on older adults' health is still missing [129]. More practical projects will bring sufficient application data and tangible user experience that reveal design and application problems in actual environments to accelerate smart technology adoption in the housing market.

In the near future, smart technology in the home environment could be more than a part of the architectural element that will bring innovation to the architectural industry. The function of smart homes will extend beyond traditional housing. It will interact with users, respond to their requirements, and manage their homes. Future studies need to propose different ways to design 'intelligent' homes for older adults [62], bridging the connections between housing structure, smart technology, and occupants.

2.7 Conclusion

This chapter illustrates the innovative technologies used in the home environment, summarises state-of-the-art smart home modification design strategies and identifies problems and countermeasures of independent living. Currently, many categories of innovative technologies can be applied in older adults' homes. In addition to smart devices, other objects, furniture, and even infrastructure in the home environment can be connected to the smart home. Using user-centred design approaches, these supportive technologies can be selected and appropriately deployed in homes. Universal design is an essential design strategy to eliminate the environmental and technical barriers of a smart home environment. However, due to the diversity of individuals and heterogeneity of housing, universal design cannot be entirely applied to the process of home assessment, technology selection, design strategy, and user evaluation. To achieve ageing-in-place, a customised modification scheme and an extensible living environment are required to keep fitting older adults' needs and maximise the effectiveness of smart technology. The approaches to designing and renovating smart homes still need to be explored in future interdisciplinary research and verified in real-life projects.

Chapter 3
Supporting Dementia Care by Monitoring Indoor Environmental Quality in A Nursing Home [2]

Abstract

The indoor environment quality in care facilities impacts residents' daily lives. Sensor technology has been proven useful in evaluating the indoor environment of buildings, but the method of using this information to improve residents' comfort, specifically in the context of nursing homes, is still underdeveloped. Thus, this chapter focuses on monitoring indoor environmental quality in a nursing home in the Netherlands, supported by professional caregivers' insights. A campaign was conducted for one year to monitor eight rooms, and a mixed-method approach was used to collect and analyse the data on local weather, building facility operation, and proxies' responses to residents' comfort. Seventeen care professionals and twenty-two guardians (visitors) answered questions based on their opinions and observations. The results show that the low indoor humidity during heating seasons and high CO_2 concentration at night were the main factors leading to environment-related symptoms of residents and care professionals, such as dry eyes. Furthermore, we found that data outliers can help reveal residents' occupancy, ventilation habits, and activity time, thus showing the application value of environmental sensors in dementia care. We also recommend using non-intrusive sensors for nursing home residents and taking into account room layouts and occupants' conditions before installing sensors.

[2] A previous version of this chapter was published as:
Ma, C., Guerra-Santin, O., Grave, A., and Mohammadi, M. (2023). Supporting dementia care by monitoring indoor environmental quality in a nursing home. Indoor and Built Environment, 32(9), 1843-1861.

3.1 Studies on Indoor Environmental Quality of People with Dementia

According to the World Alzheimer Report 2021, over 55 million people live with dementia globally, and this number is steadily increasing [130]. In the Netherlands, an estimated 280,000 people have been diagnosed with dementia, of which 70,675 lived in care facilities in 2018 [3]. Smart technology development and application contribute to dementia care with health assessment and monitoring, maintenance of functioning, and caregiving management [28]. Over the past decade, many projects in the Netherlands have deployed advanced technologies in homes and care facilities to support people with dementia in their daily activities or social interactions [18,131]. However, most applications were focused on preventing dangerous situations rather than improving well-being or coping with dementia symptoms [132]. Because of the hallmarks of dementia (e.g. cognitive decline, memory loss, and difficulties in learning new tasks), interactive technologies could be unsuitable in practical situations [133]. Technologies for people with dementia usually have simple functions, such as the smart pillbox reminding them to take medicine on time [134]. For privacy protection and ethical issues, users do not readily accept intrusive technologies with surveillance cameras and audio recording devices [45]. Therefore, sensors, as non-intrusive technologies, are widely used in care facilities and tested in dementia studies [135].

People with advanced stages of dementia may have extra demands regarding their indoor environment because they are generally very sensitive to changes in indoor conditions [136]. Also, they are often unable to adjust to uncomfortable situations due to limited cognitive, sensory and verbal abilities that require substantial attention and assistance from caregivers [137,138]. Thus, environmental sensors deployed in care facilities can assist in evaluating indoor environmental quality (IEQ). IEQ is an indicator of the general quality conditions of indoor environments, which comprises multiple subdomains, including indoor air quality, lighting quality, noise levels and thermal comfort [26]. Table 3.1 summarises the recent research using sensors or other monitoring technologies in care facilities that focuses on indoor environmental indicators and their impacts on older adults. Appropriately controlling these indicators could positively impact health, delay dementia progression, and reduce changed behaviours [27]. For instance, constant indoor air temperature can reduce agitation; high-intensity bluish light contributes to managing sleep problems and improving the circadian rhythm; controlling reverberation throughout care facilities is essential in reducing the impact of intruding noise sources and in achieving privacy; and good indoor air quality can reduce the risk of spreading airborne diseases [24,139–141].

Table 3.1 The research used monitoring technologies in care facilities.

Citation	Study area	Focus	Data collection method (tool)	Data analysis method	Main outcome(s)
Garcia-Constantino et al. [142]	UK	ADL	Thermal sensors, contact sensors, PIR sensors, and audio level sensors	-	Most care home buildings were not originally designed to appropriately install ambient sensors, and the installation of sensors should be adapted to the specific care home case.
Guerra Santin et al. [30]	UK	IEQ performance	Indoor environment monitoring transmitter, interview, and questionnaire	Descriptive statistics and PMV	The expected performance of the Passivhaus was unrealistic in terms of energy use.
Zhan et al. [34]	China	IEQ acceptance	Wireless sensor network, questionnaire	Multivariate logistic regression	The air temperature had the greatest impact on the overall IEQ acceptance, while the visual environment and illuminance level had the least influence.
Bankole et al. [31]	USA	Early signs of agitation and environmental triggers	Sensors, questionnaire, and interview	Distributions, assessment of variance or dispersion, and exploration of communality	A valid relationship between the presence of dementia-related agitation and environmental factors.
Feng et al. [143]	USA	Real-time monitor	UbiBot WS1 sensor	PMV-based model	A real-time individualised comfort monitor system.
Yu et al. [33]	China	Thermal comfort	Wireless sensor networks	APMV model	Significant seasonal variations in nursing home thermal environments as well as in the thermal comfort, thermal sensation, and adaptive behaviours of older adults.
Tartarini et al. [144]	Australia	IEQ assessment	RTD PT100, HUMICAP, Type T thermocouple, Omnidirectional probe tip, Micro electromechanical system, and questionnaire	Descriptive statistics and TSV	The IEQ Cart did not significantly affect the agitated behaviours of residents with dementia, which can be used to monitor IEQ factors reliably and accurately in nursing homes.
Raatikainen et al. [145]	Finland	Lighting	MN-ENV-THPL indoor environment sensor	-	A customised intelligent lighting control combined with an indoor environment monitoring system for people with dementia.
Hassanvand et al. [146]	Iran	Particulate matter	GRIMM dust monitors	Simple linear regression and Manne-Whitney U test	People's activity is a major factor in elevating indoor levels of PM_{10}. $PM_{2.5}$ and PM_1 could be significantly affected by outdoor PM concentrations.

Citation	Study area	Focus	Data collection method (tool)	Data analysis method	Main outcome(s)
Konis [147]	USA	Circadian stimulus potential of daylight provided by windows	Mobile spectrometer cart	Circadian stimulus potential, photopic illuminance, and circadian efficacy (M/P ratio)	Regular access to daylit spaces in the morning (within 3 m from windows) can significantly increase the level of the circadian-effective light stimulus.
Childs et al. [148]	UK	Self-reported thermal sensation and extremity skin temperature	Kestrel environmental monitor, Thermoscan device, and medical history	Chi-Square tests and Anova tests	Infrared thermography has clinical utility in identifying residents' satisfaction with indoor environmental conditions.
Aarts et al.[149]	The Netherlands	Dynamic lighting systems	Questionnaire and Konica Minolta Incident Colour Meter type CL-200	A stakeholder approach	Dynamic lighting systems have no positive health effects in care facilities.
Thomas et al.[35]	Belgium	Acoustic performance and comfort	Sensor nodes, semi-structured interview, and focus group	Thematic analysis	Acoustic interventions have direct positive outcomes and both positive and negative outcomes from perceived indirect effects.
Mendes et al.[150]	Portugal	Thermal comfort	TSI 8386A-M-GB thermo-anemometer, Delta Ohm HD 32.1–Data logger, and questionnaire	Mann–Whitney and Kruskal–Wallis tests, PMV, and PPD	The influence of thermal comfort in the winter season on older individuals' quality of life.

Note. ADL: activities of daily living; PMV: predicted mean vote; APMV: adaptive predicted mean vote; TSV: thermal sensation vote; PM: particulate matter; PPD: predicted percentage of dissatisfaction.

Based on the existing literature, the sensory deviation and acceptance threshold amongst people with dementia on indoor environmental factors, such as ventilation frequency and ambient temperature, are still unknown [151]. There is also a lack of information on the effects of indoor environmental indicators on people with different degrees of dementia [27]. The existing knowledge mainly looks at the influence of single indoor environmental indicators on health and comfort and does not take them into account in a holistic way [152]. Indoor environment standards and guidelines, such as EN ISO 7730 and ASHRAE 55 [153,154], focus on healthy adults and are not entirely applicable to frail older groups [32]. Older adults usually spend most of their day (80% to 90%) indoors, and this percentage is likely even higher amongst nursing home residents [24]. Exposing them to unsatisfactory indoor environmental conditions could adversely influence their physical and mental health [155–157]. Furthermore, these health risks increase when people develop a deterioration of cognitive abilities and difficulties expressing themselves [158].

Sensors are widely tested in monitoring the living environments of people with dementia. However, as Table 3.1 shows, the application remained on the data collection level, and the studies rarely bridged connections between sensor data and residents' comfort. The guideline for appropriately deploying environmental sensors in nursing homes is also lacking. Thus, this chapter had a twofold goal. Firstly, we assessed the IEQ in the studied facility and investigated it based on objectively measured data and subjective opinions of people with dementia, their guardians, and care professionals. Secondly, we validated the questionnaire responses with the data analysis results and explored the value of using environmental sensors in real-life dementia care.

3.2 Case Study and Research Methods

3.2.1 Case Study

Fig. 3.1 Floor plans and sensor locations in the nursing home.

The case study was in a small-scale care facility in the Netherlands, which provides 32 bedrooms for 32 older people with dementia (above 65 years old). The red dots show the sensor locations in the nursing home (Fig. 3.1). Each floor of this two-storey building includes two lounges, a central living room, and a nurse station. A spacious green courtyard is on the ground floor. Each bedroom has a private bathroom. Residents can furnish their spaces with personal belongings. Bedrooms are orientated south or southeast. The building has a concrete structure and double glazing to achieve the standardised insulation level of old-age care facilities. The thermoregulating floor system consists of a gas-fired heating system supplying water to the entire building. The water is heated in winter and unheated in summer. The general temperature settings are 23°C during the daytime and 22°C between 6:00 p.m. and 4:00 a.m. all year. The temperature in each room can also be manually controlled by thermostats. One window in each bedroom can be opened for natural ventilation. The central mechanical ventilation has three grades of wind force for common spaces and bedrooms (low, medium, and high airflow) to provide fresh air 24 h. The wind force in bedrooms is usually lower than in common spaces.

3.2.2 Monitoring Campaign

Fig. 3.2 The layout of the bedrooms in the nursing home.

The monitoring campaign was conducted from July 2019 to June 2020, and indoor environmental data was continuously collected from eight rooms in the nursing home. We received consent to monitor the bedrooms of seven residents. In these seven bedrooms, sensors were installed on top of wardrobes, and the receiver sides were towards the beds. The wardrobes were near the entrance or beside the bed (Fig. 3.2). The sensor in the central living room was deployed at the top of the kitchen cabinet. The installation heights of these sensors were 1.8 m to avoid interfering with residents' daily activities.

3.2.3 Sensor Features

The selected multi-functional sensor measures indoor illuminance, relative humidity, air temperature, particulate matter ($PM_{2.5}$ and PM_{10}), CO_2 and total volatile organic compounds (TVOC) concentrations (Table 3.2). The TVOC unit has been converted from ppb to μg/m^3 (4.9 μg/m^3 corresponds to 1 ppb) based on an average molar mass of TVOC molecules proposed by Mølhave et al. [159]. The sensor consists of a thermistor (accuracy: ± 0.4°C), a humidity transmitter (accuracy: ± 3%), a light sensor (optical filtering to match the human eye), an NDIR(LED) CO_2 sensor (accuracy: 30 ppm + 3% of reading), and other modules which support intelligent algorithms to process raw sensor measurements to output a TVOC value. All the sensors were connected to the local Wi-Fi network and sent readings every 5 minutes to the logger.

Table 3.2 Sensor specifications (device: ISensit-Clear Climate Sensor, model: CC1).

Indoor environmental parameters	Range	Resolution
Illuminance	0.01 - 83k lux	0.01 lux
Relative humidity	0 – 100%	0.01%
Air temperature	0 – 60°C	0.01°C
Particulate matter ($PM_{2.5}$, PM_{10})	0 – 500 μg/m^3	0.01 μg/m^3
TVOC	0 – 2000 ppb	0.01 ppb
CO_2	125 – 6000 ppm	0.01 ppm

3.2.4 Data Collection and Analysis

Before the monitoring campaign, possible confounders and modifiers were identified. These were classified into three categories: 1) environmental factors (location-specific weather conditions to which a building is subjected); 2) building characteristics (building quality, design, materials, and facility operation); and 3) human activities and interventions (such as room occupancy and usage of appliances) [160]. Therefore, as

Fig. 3.3 shows, we employed the local weather data from the Royal Netherlands Meteorological Institute (KNMI) database, obtained the building characteristics and building management information by interviewing the technicians, and investigated human factors through related records and interviews with care professionals. These three-category data were collected from September 2020 to February 2021. The possible confounders and modifiers were considered in describing the relationship between IEQ parameters and the comfort of residents with dementia.

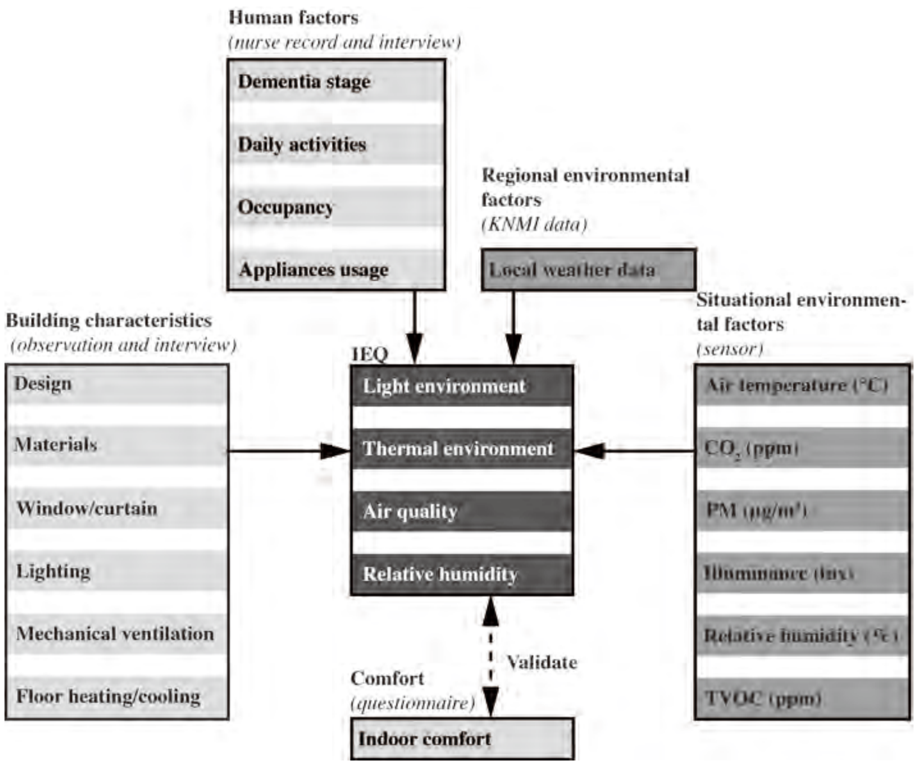


Fig. 3.3 Data types of the case study.

The environmental data collected from seven bedrooms and one central living room were descriptively analysed in SPSS. Box plots were created per room in two seasons (summer and winter) to show the IEQ in the studied facility when the weather changes led the outdoor environment to extreme conditions. The outliers of the data set were compared with the questionnaire responses for validation. Questionnaire responses were summarised in graphs to demonstrate the comfort and preference of different groups.

3.2.5 Participants and Recruitment

The nursing home sent consent forms to residents, residents' guardians, and care professionals and distributed anonymous online questionnaires. All participants were informed about the purpose of the study and signed a consent form. Seven residents gave permission to install sensors and collect data in their bedrooms. Their room numbers were replaced with letters that cannot be linked to specific participants.

Given the vulnerable status of people with dementia during the COVID-19 pandemic, the possibility of physical contact with them in the nursing home was excluded from this study. Thus, two questionnaires (A and B) were designed to obtain information on care professionals', guardians', and residents' comfort in different seasons of the monitored year. The questionnaires consisted of three parts: demographic information, indoor environmental preferences, and indoor comfort (7-point Likert scale). Questionnaire A, filled in by care professionals, focused on their opinions (e.g. what is your thermal comfort in the central living room during the winter? Please rate from 1-very cold to 7-very hot). Questionnaire B was designed for guardians (visitors) and concentrated on the basic information of their family members. The guardians were required to ask residents and fill in their answers to the questionnaire (e.g. in your opinion, what is the thermal comfort of your family member in the bedroom during the summer, or how does the room feel to them? Please rate from 1-very cold to 7-very hot). Questionnaires with less than 50% completion were considered invalid.

3.3 Nursing Home Environment and Indoor Comfort

3.3.1 Questionnaire Responses

The nursing home manager sent out 95 questionnaires to 43 care professionals and 52 guardians (visitors or contact persons) of residents and received 39 valid responses. The number of respondents, their information and response rates are shown in Tables 3.3 and 3.4. The average age of nursing home residents was 84.7 years old, and the proportion of women was more than men (24: 8). During the COVID-19 pandemic, care professionals kept the same working schedule (three shifts a day), but nearly half of the guardians visited less and stayed shorter than before. However, amongst 22 guardian respondents, 32% of them still visited every day, and 36% visited once a week. The visiting time was normally around one hour. Because some residents and their visitors rarely stayed in the central living and spent the most time in bedrooms, their responses about the indoor comfort of central living rooms were excluded for reliability.

Table 3.3 Responses from care professionals (questionnaire A).

Respondent number	Effective response rate	Working in each bedroom per day			Working in the nursing home			
		<0.5 h	0.5-1 h	>1h	< 1 year	1-3 years	3-5 years	>5 years
17	39.5% (17/43)	5	8	4	1	6	3	7

Table 3.4 Responses from guardians (questionnaire B).

Respondent number	Effective response rate	Age of residents			Living in nursing home			
		71-80	81-90	91-100	< 6 months	7 months-1 year	1-2 years	>2 years
22	42.3% (22/52)	9	5	8	2	6	2	12

Table 3.5 specifically lists the information of seven participants who lived in the bedrooms monitored by sensors. They were all female, over 75 years old and had different chronic diseases. Their dementia stages were assessed by the Global Deterioration Scale (GDS) [161], and most of them were at mild or moderate dementia stages. According to the nursing records, Resident B had moderately severe dementia since the study started, and her health condition restricted her daily activities.

Table 3.5 Participants' information.

Participant	**Age**	**Gender**	**Dementia stage**	**Symptoms**	**Other behaviour/illness**
A	83	Female	Alzheimer stage 2	Very mild cognitive decline	Chronic obstructive pulmonary disease
B	90	Female	Alzheimer stage 5	Moderately severe cognitive decline	Pneumonia, heart failure
C	77	Female	Alzheimer stage 2	Very mild cognitive decline	Hypertension, diabetes
D	78	Female	Alzheimer stage 3	Mild cognitive decline	Urinary tract infections, broken hip
E	82	Female	Alzheimer stage 3	Mild cognitive decline	Depression
F	84	Female	Alzheimer stage 4	Moderate cognitive decline	Anxiety disorders
G	86	Female	Alzheimer stage 3	Mild cognitive decline	Cerebral infarction

3.3.2 Thermal Environment

Sensor data shows the temperature in bedrooms was steady between 22-23℃, usually with less than 1℃ standard deviation in different seasons and no significant differences between seasons. The temperature in the central living room was always higher than in the bedrooms (Fig. 3.4), especially during dinner time. Fig. 3.4 also shows that bedroom temperatures were more constant in winter than summer. However, some bedrooms had a risk of overheating, as shown by the outliers of Room A in January. The temperature in Room B was stable all year, around 23℃. Furthermore, unoccupied rooms (Room A in February and Room G in December and January) were 2-3℃ cooler than the other bedrooms in the same period. According to the weather data (KNMI), the local mean monthly temperatures in January and February 2020 were around 6-7℃. It can be seen that residents' activities influenced the indoor air temperature to some extent, and the temperature data reflects the room occupancy.

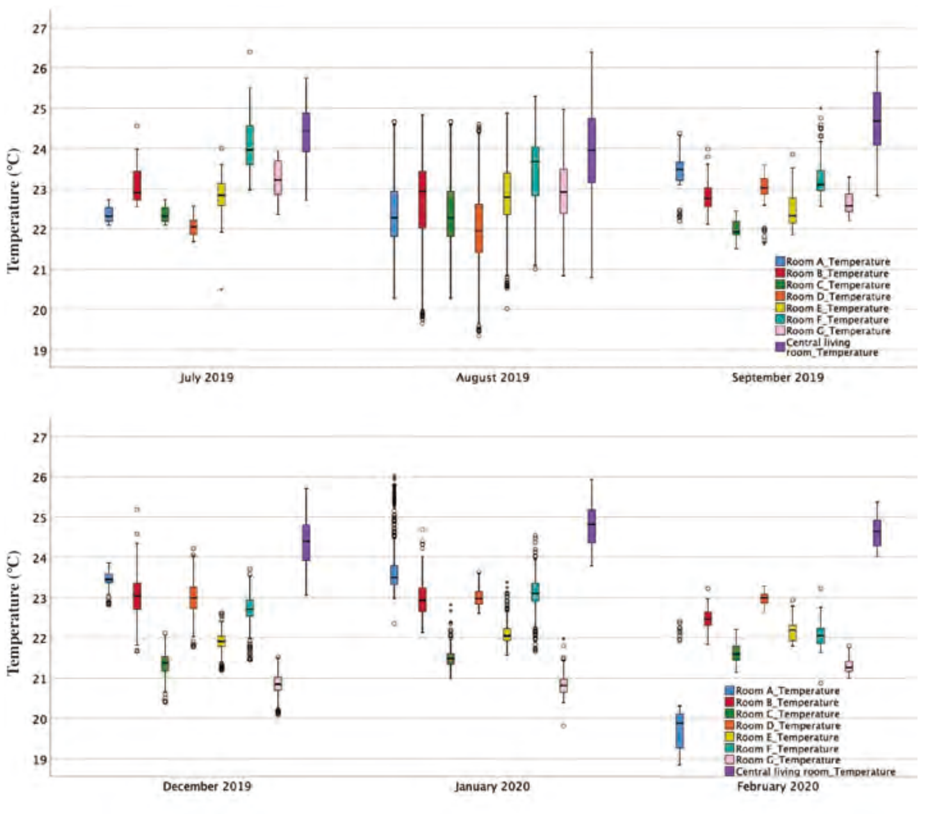


Fig. 3.4 Box plot of indoor air temperature in summer and winter.

Participants had different views on indoor thermal comfort (Fig. 3.5). The thermal sensation votes for bedrooms and the central living room in summer and winter show different patterns. Nearly 40% of care professionals reported that the interior spaces were hot during the summer, and the common areas (central living rooms and lounges) were overheated in winter. According to care professionals' responses, the central living room was the hottest place in the building and had negatively influenced their work. In contrast, the guardians thought their family members were basically satisfied with the indoor thermal environment. Although 63% of the guardians thought the bedrooms were slightly hot in summer or slightly cold in winter, no one reported their family members feeling overheated or cold in the nursing home.

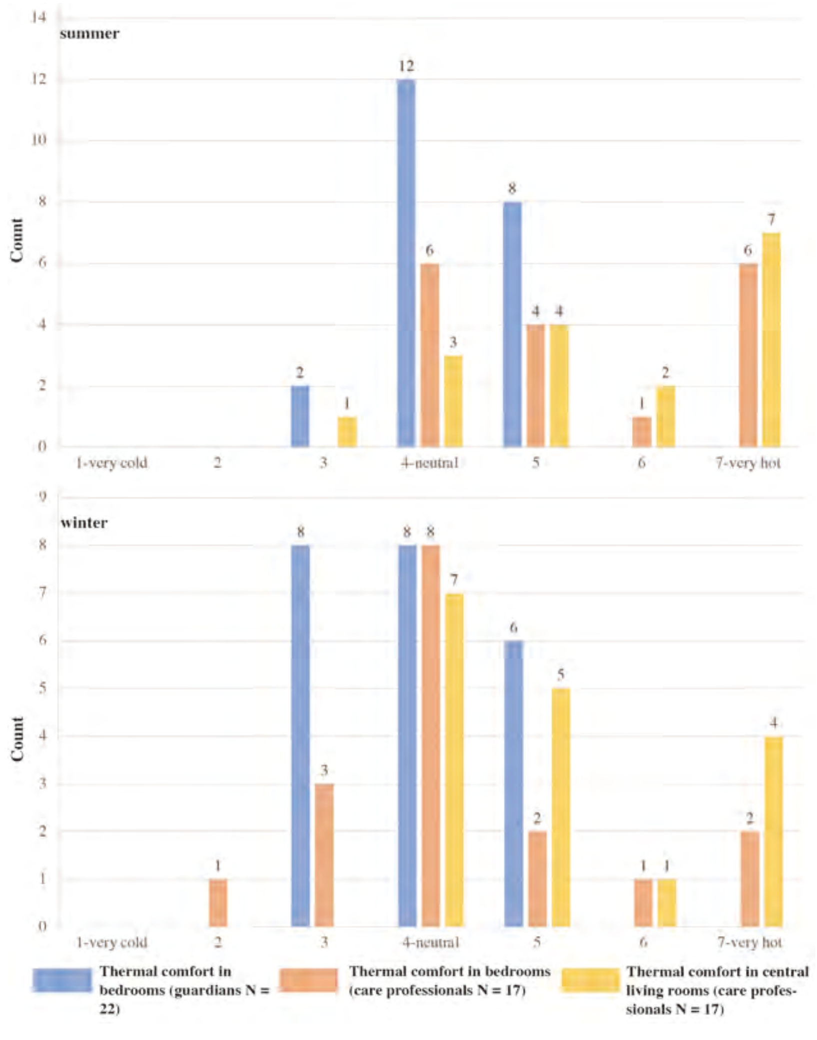


Fig. 3.5 Thermal sensation votes for indoor thermal comfort.

3.3.3 Relative Humidity

Relative humidity is also a seasonal indicator in the studied nursing home. The highest value was detected in July 2019, around 60% in all rooms. From the end of October, humidity levels fell from 50% to 30%, and the levels in the nursing home remained low until May 2020. In seven months, the mean indoor humidity of monitored rooms was lower than 40%. The mean values were lower than 30% in March and April 2020. There was little difference in humidity data amongst all rooms in the same season. The humidity fluctuations were larger in summer than in winter (Fig. 3.6). Because the outdoor humidity is normally higher than indoors in the Netherlands, the outliers of this box plot were related to the natural ventilation frequency of rooms, especially in winter.

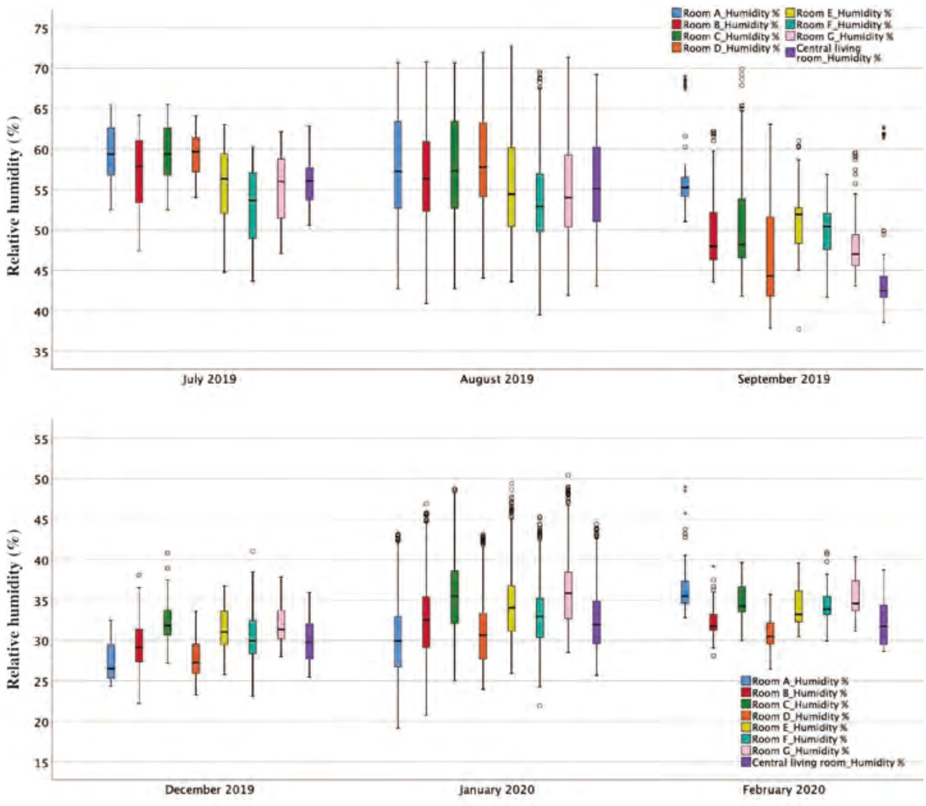


Fig. 3.6 Box plot of relative humidity in summer and winter.

Fig. 3.7 shows how the humidity and temperature changed at the beginning of the heating season. Indoor air temperature data was steady in all rooms between 21-26°C, but the relative humidity decreased significantly since 27th October. The outdoor temperature fell rapidly within one week from 16.4°C on 27th October to -0.7°C on 1st

November. This was paired with the usage of floor heating, which was seen with a sharp decline in indoor humidity, whilst the outdoor humidity levels remained above 80%. Based on the significant humidity difference between indoors and outdoors, humidity data fluctuations reveal the duration of natural ventilation in bedrooms.

Fig. 3.7 Indoor relative humidity and air temperature variations between 21st October to 3rd November.

Questionnaire responses show relative humidity was the most problematic for residents and care professionals. More than half of the care professionals reported the indoor environment was slightly dry, dry, or very dry (Fig. 3.8). Nearly half of the guardians also reported that their family members felt the air was slightly dry in their bedrooms. Spring was the period with higher overall complaints and matched the sensor data. Care professionals also complained that indoor spaces on the upper floor were hotter and drier. People living and working in the nursing home had symptoms, such as being always thirsty, dizziness, headaches, dry eyes, sore throat, and nasal pain, from February to April.

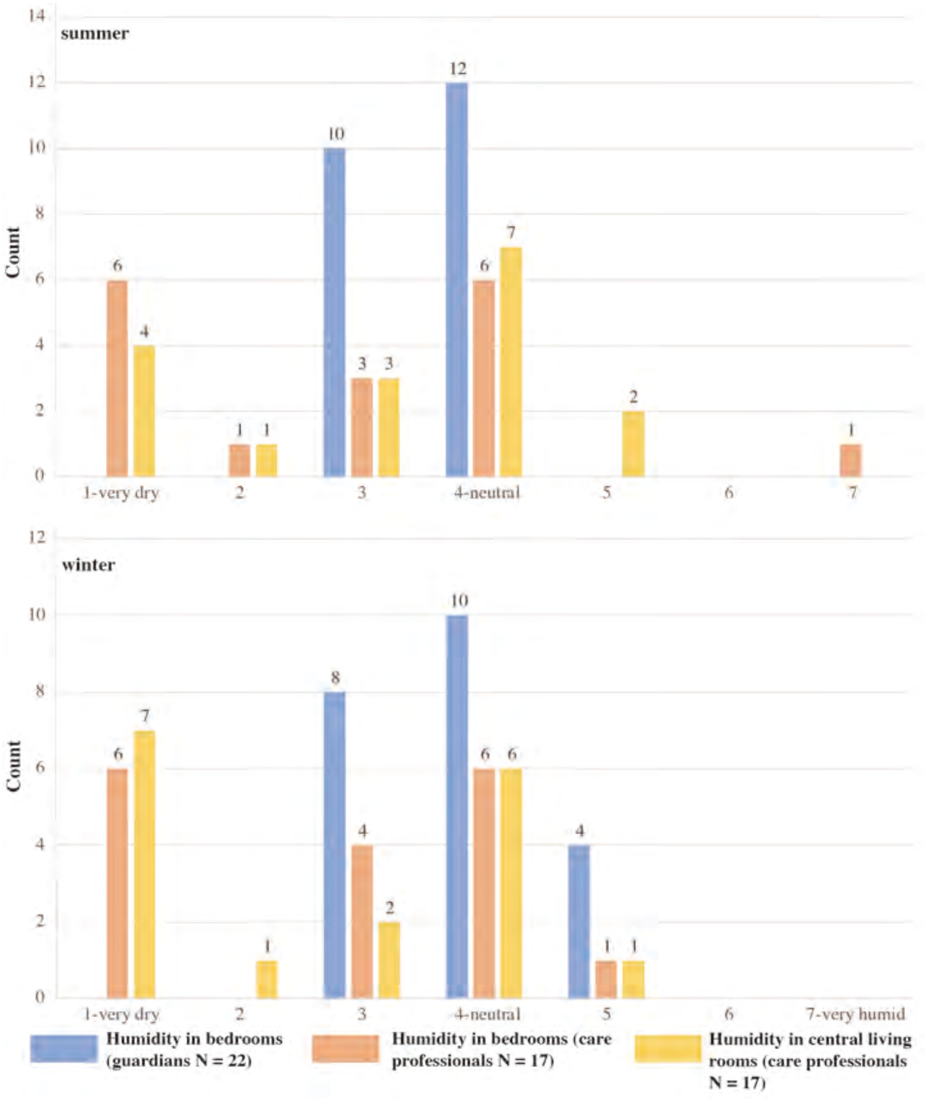


Fig. 3.8 Votes for indoor relative humidity.

3.3.4 Air Quality

The mean CO_2 concentrations in monitored rooms were between 600 and 1000 ppm. However, the values varied significantly every day, increasing at night and decreasing during the daytime. The peak values reached 2000 ppm a few hours at midnight. After the ward round the following day, the care professionals opened windows for natural ventilation, and CO_2 concentrations in bedrooms were back to 400-600 ppm. The data deviations in monitored rooms were 200-400 ppm between rooms during the same season. TVOC value is a measurement for monitoring the overall amount of volatile organic compounds (VOCs) in a given space. TVOC concentrations in the nursing home were under 200 μg/m^3 most of the year. The TVOC variation shows a similar trend as CO_2, which decreased from the peaks at night to lower levels during the daytime. However, the peak values of TVOC concentration (100-200 μg/m^3) were sometimes captured around noon.

Fig. 3.9 presents the CO_2 and TVOC concentration levels of the overall time percentage in the nursing home. The ventilation in the central living room was better than in the bedrooms. The CO_2 concentrations in bedrooms nearly 60% of the time were lower than 800 ppm, 10% were between 800 to 1000 ppm, and almost 30% were over 1000 ppm. This rate is similar in all bedrooms and shows the length of time residents maintain metabolism in a poorly ventilated space at night. TVOC concentrations in bedrooms were less than 10% of the time between 200-300 μg/m^3 or above 300 μg/m^3. However, Room B data reflects that the occupant's activities and ventilation management can still significantly influence indoor air quality.

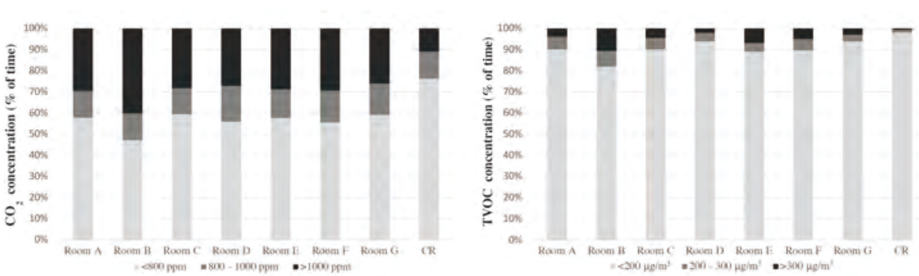


Fig. 3.9 CO_2 and TVOC concentration levels of the overall time percentage.

The indoor $PM_{2.5}$ and PM_{10} concentrations were maintained within the suggested ranges according to World Health Organization (WHO) guidelines (mean value: bedrooms<10 μg/m³ and the central living room<15 μg/m³) [162]. In contrast to CO_2 and TVOC data, particulate matter values were higher in the central living room than in the bedrooms. The peak values were usually captured around dinner time, which could be 20 times higher than the data monitored in the bedrooms. Cooking was the main reason $PM_{2.5}$ and PM_{10} increased over 100 μg/m³ a few hours surrounding the stove and oven.

Residents' guardians and care professionals reported they could smell cooking oil fumes from the central living room. They had similar views on indoor air quality that sometimes felt stale in the building (Fig. 3.10). Nearly a third of guardians thought that their family members were not satisfied with bedroom air quality, and the dissatisfaction rate amongst care professionals was over 50%. The vote for the favourite place was the courtyard, where residents have access to fresh air and more sunlight. They often stay in the courtyard or terraces for one to two hours if the physical conditions and weather allow.

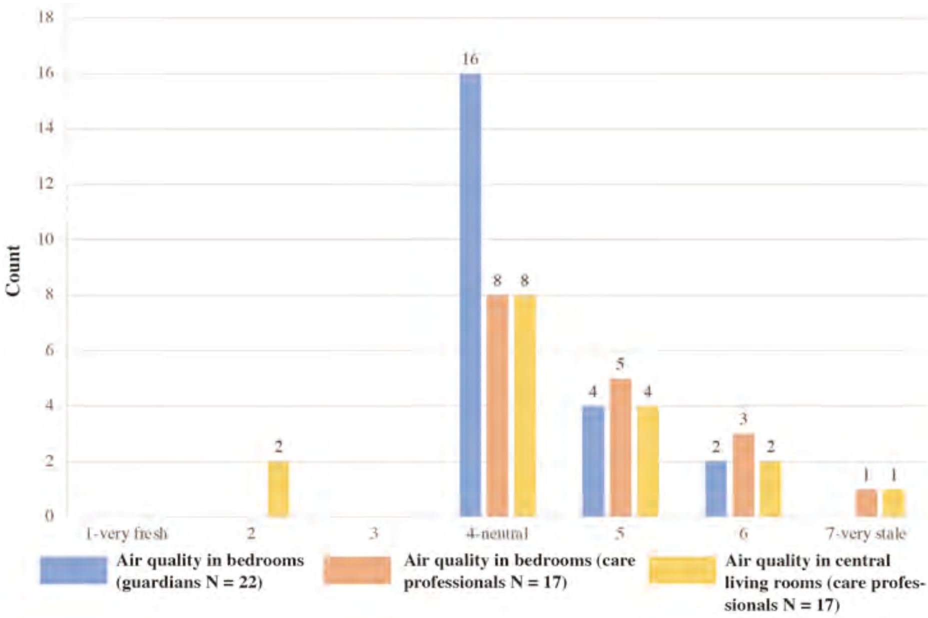


Fig. 3.10 Votes for indoor air quality.

3.3.5 Light Environment

Indoor illuminance is influenced by weather and human factors, and the data varied significantly between rooms. Fig. 3.11 is a sample that selected a sunny day in the summer and a rainy day in winter to show indoor light environments under different conditions. In this heatmap chart, the red areas present the higher values detected on selected days. The illuminance data after sunset (summer 9 p.m., winter 5 p.m.) indicates the activities of residents (e.g. using the bathroom or watching TV). In the daytime, illuminance in bedrooms ranged from tens to hundreds of lux. On sunny days, the sunlight could be sufficient for residents' daily activities or even need sun shading. However, on (winter) rainy days, the sunlight is usually insufficient. Rooms C, D, and E data show the active time residents or caregivers spend using artificial light.

Whether in summer or winter, the central living room was the brightest place in the nursing home, where staff worked earlier in the morning and left later at night. Artificial light maintained the average illuminance of activity time in the central living room at

Date	Room A	Room B	Room C	Room D	Room E	Room F	Room G	CR
8/22/2019 0:00	0	0	0	0	0	0	0	31
8/22/2019 1:00	0	0	2	0	2	0	0	0
8/22/2019 2:00	0	0	0	0	1	0	0	0
8/22/2019 3:00	0	0	0	0	0	0	0	4
8/22/2019 4:00	0	0	0	0	0	0	0	5
8/22/2019 5:00	0	0	0	0	0	0	0	5
8/22/2019 6:00	0	0	0	0	0	0	0	24
8/22/2019 7:00	0	0	0	0	2	0	0	36
8/22/2019 8:00	0	0	0	0	0	0	0	53
8/22/2019 9:00	0	0	0	26	26	10	1	120
8/22/2019 10:00	0	0	2	26	38	18	51	224
8/22/2019 11:00	11	10	8	177	29	16	89	282
8/22/2019 12:00	92	12	13	232	67	38	109	279
8/22/2019 13:00	161	16	21	215	114	68	102	321
8/22/2019 14:00	225	24	32	117	157	95	53	409
8/22/2019 15:00	279	30	40	39	181	112	44	248
8/22/2019 16:00	300	33	44	27	185	108	40	223
8/22/2019 17:00	282	57	43	18	172	98	30	296
8/22/2019 18:00	212	32	35	12	136	80	26	300
8/22/2019 19:00	139	12	27	10	247	107	22	400
8/22/2019 20:00	65	6	13	7	127	50	16	289
8/22/2019 21:00	22	2	5	4	42	14	8	232
8/22/2019 22:00	4	0	2	0	9	2	2	123
8/22/2019 23:00	5	0	0	0	0	0	0	40

Date	Room A	Room B	Room C	Room D	Room E	Room F	Room G	CR
1/18/2020 0:00	0	0	0	0	0	0	0	4
1/18/2020 1:00	0	0	0	0	0	0	0	0
1/18/2020 2:00	0	0	0	0	0	0	0	0
1/18/2020 3:00	0	0	0	0	0	0	0	0
1/18/2020 4:00	0	0	0	0	0	0	0	0
1/18/2020 5:00	0	0	0	0	0	0	0	0
1/18/2020 6:00	0	0	0	0	0	0	0	5
1/18/2020 7:00	0	0	0	0	0	0	0	39
1/18/2020 8:00	0	0	0	0	2	0	0	108
1/18/2020 9:00	0	0	5	2	2	0	0	122
1/18/2020 10:00	10	0	146	35	178	0	16	169
1/18/2020 11:00	36	0	526	285	514	0	154	304
1/18/2020 12:00	39	2	680	322	267	32	141	346
1/18/2020 13:00	46	2	344	172	185	50	65	295
1/18/2020 14:00	47	5	126	144	147	39	24	252
1/18/2020 15:00	39	4	104	146	219	50	19	249
1/18/2020 16:00	30	2	53	22	223	34	11	186
1/18/2020 17:00	11	1	15	5	17	6	2	137
1/18/2020 18:00	0	0	0	0	0	3	0	273
1/18/2020 19:00	0	0	0	0	0	0	0	244
1/18/2020 20:00	0	0	5	0	0	0	0	170
1/18/2020 21:00	0	0	0	3	0	2	0	122
1/18/2020 22:00	9	0	0	0	0	0	2	90
1/18/2020 23:00	3	0	0	0	0	0	0	24

Fig. 3.11 The heatmap chart of indoor illuminance (lux) on a summer day (left) and a winter day (right).

around 300 lux. However, the illuminance data varied significantly in bedrooms due to transient weather changes or variable control of artificial lighting and shading elements. Although 53% of care professionals and 73% of guardians thought that light intensities in bedrooms were neutral for residents (Fig. 3.12), they often adjusted windows and curtains when entering the bedrooms. Room B was at a very low light intensity level all the year, and the maximum value was below 100 lux.

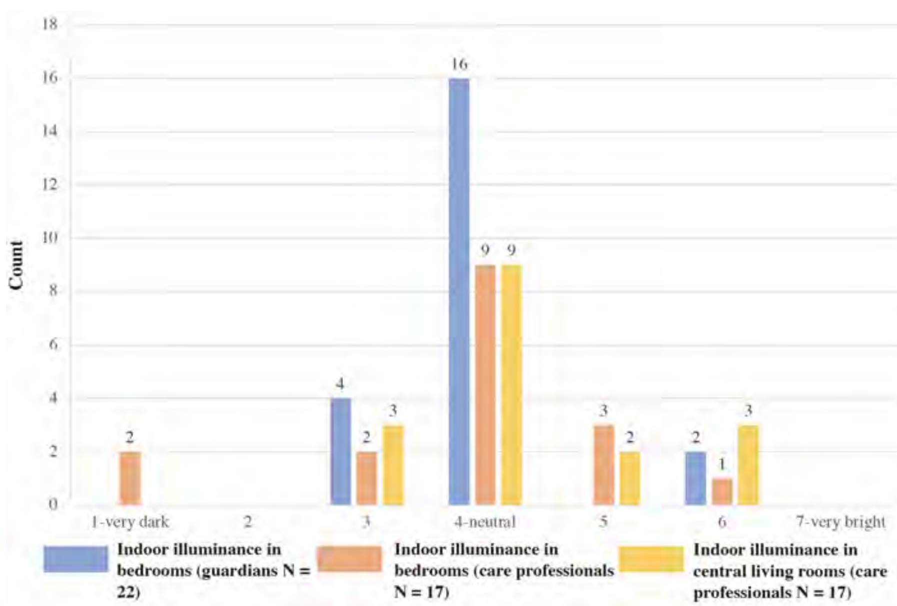


Fig. 3.12 Votes for indoor light environment.

3.4 Influence of Indoor Environmental Factors and Technology Applications

Dementia is a progressive syndrome that changes cognitive, behavioural and psychological functions [163]. People with dementia may have difficulty expressing discomfort and asking for help. Monitoring technologies can be a potential solution to assist dementia care through environmental data. This chapter investigated the IEQ in a nursing home, proxies' responses to residents' comfort, and the reasons for outliers and deviations in the data. To do this, we integrated sensor data analysis with caregivers' opinions to determine the comfort level of people with dementia.

This chapter highlighted the potential use of sensor devices and data to support caring for people with dementia. For example, Resident B was in the moderately severe dementia stage and had heart failure, stayed in bed most of the day, and relied on caregivers to control the indoor environment. Even though this resident did not report dissatisfaction with the indoor environment in her room, the data showed large differences between Room B and the other bedrooms occupied by residents with higher independence. The environmental data does not directly equal indoor comfort, but it could be a reference for caregivers providing care and interventions.

Building and care-related factors, such as insulation, ventilation, heating, and ward round schedule, were consistent for all rooms and participants (residents and their caregivers) in this chapter. The building quality was high, and the facilities were new and operating well. All bedrooms were similar in layout and orientation. Thus, data differences were mainly associated with room occupancy, residents' daily activities, and room facility control. The mechanical ventilation was set lower at night for noise reduction, but it led to CO_2 concentrations above 2000 ppm and TVOC above 300 $\mu g/m^3$ in bedrooms, which were higher than the harmless limits. Many studies have shown a strong correlation between air pollutants and levels of indoor air quality. CO_2, TVOC, and particle matter concentrations are key indicators for measuring indoor air quality [140,151,164]. These indicators in care facilities are usually higher than those found outdoors. Reasons include indoor emission sources (e.g. furnishing), activities (e.g. cooking), low ventilation, and seasonal variations in temperature and humidity [164]. The average outdoor CO_2 concentration level varies from 350 to 575 ppm [165]. Based on existing research, the healthy threshold of CO_2 concentration has been set at 800 ppm, and the harmless limit is 1000 ppm [166]. A high CO_2 concentration could increase Sick Building Syndrome (SBS) symptoms, including eye irritation and upper tract respiratory symptoms reported by care professionals from the studied nursing home [167]. The same symptoms may also be caused by TVOC exposure [168], and its guideline value proposed by the European Commission is 300 μg/m^3, and the comfort range is under 200 μg/m^3 [169]. Low TVOC values were maintained in the nursing home (Fig. 3.9) and thus not the main factor influencing residents' health. However, the TVOC value could sharply increase around noon related to residents' specific activities or nursing services. Airborne particles, another significant air pollutant, primarily affect the human respiratory and cardiovascular systems. According to the WHO guidelines, the 24-h means of $PM_{2.5}$ and PM_{10} are 25 μg/m^3 and 50 μg/m^3, whilst the annual means set for $PM_{2.5}$ and PM_{10} are 10 μg/m^3 and 20 μg/m^3 [162]. Although peak $PM_{2.5}$ values in the central living room were between 150 to 200 μg/m^3 around cooking time, its 24-h mean value was still below 25 μg/m^3.

Indoor relative humidity during the heating season was another problem in the nursing home. Good building insulation, the use of the heating system, and lack of humidifying devices were the reasons indoor relative humidity gradually decreased below 40%. Relative humidity is an indicator related to both thermal comfort and air quality. Maintaining the humidity level in a suitable range is essential for IEQ. Airborne fungi and house dust mites often happen in rooms with prolonged high humidity (>70%), but lower than 40% can cause the symptoms of dryness and irritation of the mucosa [170], which care professionals and residents also complained about similar symptoms. High room humidity with poor ventilation could increase VOCs emissions and reduce indoor air quality [171]. Maintaining relative humidity over 40% could significantly reduce the infectivity of aerosolised viruses [172]. In care facilities, indoor environments are likely too dry in winter due to heating systems [173]. However, in the studied nursing home, the dry environment (< 40%) lasted six months.

Existing studies have pointed out the overheating risk in care facilities during summertime [174], which also remains in the wintertime. Six factors could influence thermal comfort in a particular scenario: metabolic rate, clothing insulation, air temperature, radiant temperature, airspeed, and humidity [154]. Due to the COVID-19 restriction, this study only collected indoor air temperature and relative humidity data. The Dutch design guideline suggests that the maximum indoor air temperature in the general area of nursing homes should be 25.5°C in summer, and the minimum should be 22°C in winter [175]. According to a WHO report, an indoor environment between 18-24°C is the most healthy range for sedentary people [176]. The setting temperature of the nursing home was 23°C during the daytime and 22°C during the night, whilst the medians of temperature data were between this range. However, questionnaire responses show that the thermal comfort of residents differed between individuals and was associated with seasons. Older adults care more about warmer conditions in winter than cooler conditions in summer [177]. Occupation of an overheated room could trigger problems such as agitation and restlessness. Some residents and care professionals felt overheated in winter. For instance, Resident A used an electric radiator in her room during the winter, which caused the indoor temperature to be warmer than 25°C in some periods. In this case, Resident A would need more attention and adaptive actions from caregivers to adjust their thermal comforts (changing clothes, regulating metabolism or operating thermostats) [178].

The impact of the lighting on care home residents' living conditions is significant [179]. People with dementia staying in low-illuminance environments could show more signs of a negative mood, thus impacting their well-being [180]. A comfortable indoor light environment compensates for the deteriorating eyesight of older adults and benefits their quality of life by regulating circadian rhythm and decreasing depression. The suggested ambient light environment of care facilities is 500 lux and can be subdivided according to specific spaces. For general lighting in common spaces, including the entrance hall, corridor and bathroom, the lighting requirement is 300 lux. Lighting for bedrooms is 150 lux, and working and reading places are 750 lux [181]. A minimum illuminance of 1000-2500 lux could positively affect biological rhythms [182]. Older adults with eye diseases need a higher quality of illumination (1500-4000 lux) to compensate for their visual impairments when reading [183]. Unfortunately, the residents' exposure to light in care facilities is often reduced, and the actual light intensity is lower than the standards [145,184]. We found some bedrooms on the ground floor did not have sufficient light during the daytime. These bedrooms were along the street, and thus, the constant passing of pedestrians and vehicles caused residents to close the curtains to protect their privacy. Protecting occupants' privacy whilst maintaining natural ventilation and light should be an important consideration during the design stage.

The major limitations of this chapter were the scale of participants, the lack of direct feedback from people with dementia, and the fact that the data collection was not conducted simultaneously. Thus, we designed questionnaires for care professionals and residents' guardians to investigate their overall evaluation of the nursing home indoor environment for the monitored year. Some responses from different groups were contradictory. For instance, over half of guardians reported their family members were satisfied with the nursing home environment, and no one voted for dissatisfaction, but over 70% of care professionals were unsatisfied. Care professionals felt the common spaces, such as corridors between 21 to 24°C, were hot in winter, whilst 40% of guardians thought the family members felt slightly cold. Although the questionnaire for guardians required them to ask their family members, its accuracy cannot be completely guaranteed. The communication and verbal skills of people with dementia could also affect the results [185]. Thus, acquiring accurate feedback requires more scientific approaches to obtain the information objectively. Also, the limited sample size of residents meant that the relationships between IEQ and comfort could only be assessed qualitatively and not with significance tests.

Sensor placement influences data collection. In the monitoring campaign, sensors were deployed on top of wardrobes in ventilated zones and far from heat sources. However, the measurement requirements are different according to specific indoor environmental indicators. As ASHRAE 55 suggested, measuring the average value of air temperature concerns location and time: the height of the ankle level, the waist level, and the head level in periods between 3 to 15 minutes [154]. Air quality sensors should be positioned at the breathing zone height or on the ceiling in the middle of the room, and the optimal position needs to take into account the room layout [186]. Thus, finding an appropriate position for a multi-functional sensor is difficult. Existing knowledge of sensor placement focuses on standing or seated participants. It has hardly been applied to the characteristics of people with severe dementia who are on extended bed rest. Sensor maintenance is also an important factor. Residents could pull out the plugs of sensors for using other electronic devices and then forget to plug them back in, which leads to sensors intermittently being offline and data loss. Low power consumption and battery-based sensors could be more suitable for long-term monitoring. Care professionals noticed that even the faint light and noise generated by sensors could reduce the acceptance of these devices in private spaces. These interferences could increase the risks of people with dementia's changed behaviours (e.g. agitation). Monitoring technologies used for care facilities need to become completely non-intrusive. Future research is suggested to verify the effectiveness of using these technologies in dementia care from the user's perspective.

3.5 Conclusion

This chapter was conducted in a small-scaled nursing home in the Netherlands for one year to collect indoor environmental data in selected rooms. Its objective was to find the connections between indoor environmental parameters and residents' comfort. Due to the uncertainties of people with dementia answering questionnaires and COVID-19 pandemic restrictions to carry out observations, the online questionnaires were answered by care professionals and residents' guardians. The responses validated the connections of indoor comfort with indoor air temperature, air quality, relative humidity, and illuminance variations to some extent. The relative humidity is the most problematic indicator in the nursing home during the heating season, which could be even drier in spring than in winter in the absence of humidification measures. The stages of dementia affect the independence and behaviour of older adults, which can be revealed by indoor environment data. In this study, stable air temperature but poor air quality and illuminance were seen in the room of the resident with severe dementia compared to the rooms of other residents at mild and moderate dementia stages. The living environments of people with severe dementia who have less independence require more attention and timely adjustment from caregivers. Short-term data fluctuations and long-term trends could assist caregivers in obtaining objective information and assessing the IEQ of people with dementia's living environment. Furthermore, the monitoring technology application in care facilities needs to be non-intrusive to reduce interference with residents' daily lives.

Chapter 4
Exploring the Influence of Indoor Environment and Spatial Layout on Changed Behaviours of People with Dementia in A Nursing Home [3]

Abstract

People with dementia sometimes show changed behaviours such as agitation, hallucination, and wandering during the moderate and severe dementia stages. In addition to individual health factors, contextual factors, such as indoor environment conditions, spatial layout, and human activities, may trigger or influence these behaviours, but there is a lack of solid evidence. We used mixed methods to collect data, including the fly-on-the-wall method to observe the residents' daily lives and deploying environmental sensors to monitor the indoor environments of two central living rooms and ten bedrooms in a nursing home in the Netherlands. A data collection campaign from August to September 2022 focused on the indoor environmental parameters, ventilation control of monitored rooms, the observation of ten participants' locations, activities, clothing levels, and changed behaviours. The data were analysed using Fisher's exact tests and heatmap analysis. The results show that even though the nursing home was well maintained according to existing indoor environmental quality standards, the room conditions of temperature, TVOC, and HCHO levels and contextual factors (main activity and numbers of people in the space) were significantly correlated with locations of changed behaviours. By analysing observation data with spatial layout, participants had larger activity ranges on the days that exhibited changed behaviours than those without. Most of these behaviours were observed at the edge of common spaces, where caregivers need to pay more attention.

[3] A previous version of this chapter was published as:
Ma, C., Guerra-Santin, O., and Mohammadi, M. (2024). Exploring the influence of indoor environment and spatial layout on changed behaviours of people with dementia in a nursing home. Building and Environment, 256, 111452.

4.1 Previous Studies on Indoor Environment and Changed Behaviour of People with Dementia

Dementia is characterised by 'a decline in cognitive faculties and the occurrence of behavioural abnormalities which interfere with an individual's activities of daily living' [163]. Following the dementia progression, people in advanced stages may have severe implications on their daily lives, such as extra demands regarding their indoor environment, as they are generally very sensitive to changes in indoor conditions [25]. However, due to the hallmarks of dementia (limited cognitive, sensory, and verbal abilities), they are often unable to adjust according to discomfort situations and require substantial attention and assistance from caregivers [137,138]. In the Netherlands, an estimated 280,000 people have been diagnosed with dementia, of which 70,675 live in care facilities [3]. If designed or managed incorrectly, care facilities might be overheated in the summer, too dry in winter, air pollutants higher than outdoors, and light intensity lower than required by the standards [145,164,171,184]. Thus, controlling indoor environmental conditions is necessary for dementia care to maintain and improve the living quality of this target group.

The adult population spends 80% to 90% of their day indoors. This percentage is likely even higher among nursing home residents with less independence [24]. Indoor environmental factors (e.g. surroundings that are too hot, cold, or loud) could contribute to behavioural and psychological symptoms of dementia (BPSD) [187]. BPSD include agitation, aberrant motor behaviour, anxiety, elation, irritability, depression, apathy, disinhibition, delusions, hallucinations, and sleep or appetite changes [188]. Existing studies have shown that more than 90% of people with dementia develop at least one BPSD, and more than half will exhibit two or more changed behaviours [189]. The frequent behavioural disturbances and related disorders reported are irritability (64%), tiredness (62%), depression (57%), rapid mood change (57%), anxiety (57%), threat of violence (54%), lack of initiative (44%), and inappropriate social behaviour (26%) [190]. An appropriate indoor environment could positively impact health, ameliorate dementia symptoms, and reduce behavioural changes [27,191]. The specific determinants of the changed behaviours remain unclear. Based on the triadic reciprocal causation model (person, behaviour, and environment) of Bandura's theory [50], besides personal factors of people with dementia, predisposing factors of changed behaviours may include physical and social environment characteristics [192]. Many medical and environmental science studies have explored the patterns of single behaviour in care facilities. For instance, agitation was originally defined as any inappropriate verbal, vocal or motor activity which, according to an outside observer, does not result directly from the needs or the confusion of the agitated person [189]. Screaming in people with dementia is often designated as ‘agitation’, which is related to the experience of vulnerability, suffering, and loss of meaning [193]. Wandering refers to ‘seemingly aimless or disoriented ambulation throughout a facility, often with observable patterns such as lapping, pacing, or random ambulation’ [194]. Hallucination is ‘experiencing visual sensory perception without an external stimulus, seeing something others cannot’ [195]. A growing number of studies concentrate on relationships between indoor environmental factors and the behaviours of people with dementia, using mixed methods and technologies for data collection (Table 4.1). However, there is still a lack of knowledge linking the indoor environment to contextual factors (e.g. building layout and management) and behavioural changes.

Table 4.1 Recent studies on indoor environments and behaviours of residents living in care facilities.

Authors	Year	Focus	Data collection method (tool)	Data analysis method	Findings
Liu et al. [196]	2023	Air-conditioning usage behaviour	Manufacturer monitoring database and Hobo data loggers	Clustering analysis	The inactive usage group with short-term and discrete air-conditioner operation would prefer a fast-cooling setting. The all-day usage group showed that the dynamic cooling demand may exist in older adults’ long-term daily air-conditioner usage.
yoon Yi et al. [197]	2022	Applicability of existing thermal comfort models	Kestrel 3000, thermo-scan device (Model LF 40), micro-bolometer detector (model A-600 series), and questionnaire survey	Logistic regression, independent-samples t-test, and one-way ANOVA	Three approaches (PMV, Adaptive Comfort, and IRT) have limitations in accounting for the distribution of thermal sensations collected from people with dementia.
Zheng et al. [198]	2022	Dynamic thermal comfort demands	Questionnaire survey, temperature and humidity recorder (HOBO UX100-003), globe temperature recorder (HQZY-1), and wind speed recorder (TESTO425)	Linear regression	Older adults in Xi’an were very active in adapting to the indoor thermal environment through behavioural adjustment and had higher acceptance and lower psychological expectations.
Yang et al. [199]	2021	Interior daylight environments	Questionnaire survey and TES-1337 digital illuminometer	RadianceIES module	Older adults have different expectations for sunlight illuminance of different functional spaces.
Zhan et al. [34]	2021	IEQ acceptance levels	Questionnaire survey and wireless sensor network	Multivariate logistic regression	Air temperature had the greatest impact on the overall IEQ acceptance, while visual environment and illuminance level had the least influence.
Bankole et al. [31]	2020	Early signs of agitation and environmental triggers	Sensors, questionnaire, and interview	Assessment of distributions, variance or dispersion, and exploration of communality	A relationship has been validated between the presence of dementia-related agitation and environmental factors.

Authors	**Year**	**Focus**	**Data collection method (tool)**	**Data analysis method**	**Findings**
Leung et al. [200]	2020	IBE- Behaviour model	Dementia care mapping and questionnaire survey	Pearson correlation analysis, Multiple regression analysis, and Structural equation modelling	Factors of the space management component have no impact on the behavioural symptoms of people with dementia; lighting, lifts and water supply influence demented residents' negative emotions, positive emotions, sleeping disturbance and limited mobility; loneliness is affected by the supporting facilities factor of furniture.
Jin et al. [171]	2020	Thermal and humidity comfort and skin condition	Questionnaire survey, Courage-Khazaka MPA-5 Central Multi-probe Unit with the Tewameter TM 300, and Corneometer CM 825	T-test and ANOVA	The stratum corneum hydraulic system showed a significant correlation with indoor absolute humidity.
Thomas et al. [35]	2020	Acoustic performance and comfort	Sensor nodes, semi-structured interview, and focus group	Thematic analysis	Acoustic interventions have direct positive outcomes and both positive and negative outcomes from perceived indirect effects.
Yu et al. [33]	2020	Thermal comfort	Wireless sensor networks	APMV model	Significant seasonal variations are observed in nursing home thermal environments, thermal comfort, thermal sensation, and adaptive behaviours of older adults.
Tartarini et al. [32]	2018	Thermal perceptions, preferences and adaptive behaviours	Questionnaire survey and IEQ Cart	Linear regression (F-tests)	Residents were more tolerant of temperature variations and preferred higher temperatures than non-residents.

Note. PMV-predicted mean vote; APMV-adaptive predicted mean vote; IRT-long wave infrared thermography; IEQ-indoor environmental quality; IBE-indoor building environment.

Existing studies on contextual factors of care facilities and the influences on residents' behaviours are usually from design perspectives. The spatial layout of public and individual rooms in care facilities has been validated as playing a crucial role in influencing residents' navigation ability and BPSD [201]. Early research revealed residents in group-living units with I-shaped corridors experienced a higher degree of dyspraxia, restlessness, lack of vitality, and loss of identity than residents in L-, H- or square-shaped units [201,202]. Nursing homes with long hallways can decrease residents' awareness, orientation, safety, and security [201,203]. The open kitchen/dining room design creates positive sensory stimulation and a supportive built environment, which may encourage residents to gather and influence their daily activities [204]. Transitional spaces between the bedroom and social area maintain the privacy of older adults' social behaviour [205]. The small-scale and homelike-designed special care units have positive effects on the behavioural and psychological symptoms of patients with dementia [206]. These studies mainly focused on the impacts of building design and the wandering behaviour of people with dementia, such as spatial accessibility and frequency of wandering, standing, and socialising [207,208]. People with dementia could exhibit changed behaviours randomly in care facilities, but knowledge of where and how they are influenced by indoor environments is still missing [209]. Furthermore, only a few studies examined whether environmental interventions have benefits or make no difference in the prevalence of BPSD. There remains a dearth of high-quality evidence to conclusively guide the selection of any particular built environment intervention [210]. Thus, this chapter includes:

1) Collect the nursing home residents' information (e.g. dementia stage, illness, and symptoms).

2) Monitor the indoor environmental parameters and record contextual factors (e.g. daily routine of residents, building layout, and facility operation) in the nursing home that may influence changed behaviour occurrence.

3) Record the type, time, location, and surroundings information when the changed behaviour appears.

4) Analyse the data and explore the relevance of these factors on observed changed behaviours.

4.2 Case Study and Research Methods

4.2.1 Case Study

The case study includes a small-scale care facility in the Netherlands that provides thirty-two single rooms for older people with dementia. The building has a concrete structure and double glazing to achieve the standardised insulation level of old-age care facilities. Each floor consists of sixteen bedrooms, two activity rooms, a central living room (with a kitchen), and a nurse station. A spacious green courtyard is on the ground floor, and two semi-opened terraces are on the first floor. The central living rooms are semi-opened spaces located at the junction of the L-shaped floor plan and connect to the courtyard or terraces (Fig. 4.1). Each central living room has a small kitchen, four dining tables, two sofas, some easy chairs, and a television. The elevator and staircase are near the entrance, but the staircase is usually closed for safety reasons. Bedrooms are orientated south or southeast. Each bedroom includes a private bathroom and is furnished with a single bed, cabinet, table, sofa, and television. Most furniture is against the walls to ensure the space for residents using wheelchairs and walkers. Residents can furnish their rooms with personal belongings. The ventilation is centrally controlled, and airflow in common spaces is higher than in bedrooms. The floor heating system supplies hot water during the heating season or cold water to cool down the indoor temperature in summer. The setting temperature for indoor spaces is 23℃ (4 a.m. to 6 p.m.) and 22℃ (6 p.m. to 4 a.m.) throughout the year.

Fig. 4.1 Sensor locations in the case study.

4.2.2 Research Participants

Ten participants voluntarily participated in this research through an ethically approved recruitment process. Five participants lived on the ground floor, and the other five lived on the first floor. Their dementia stages have been assessed according to the Clinical Dementia Rating (CDR) shown in Table 4.2 [211]. All residents kept regular routines in the nursing home, which were not influenced by the study. Researchers collected observation data at a distance from the residents without interfering with their daily activities. Due to residents' ages and dementia stages, they had various degrees of hearing, reading, and writing difficulty. All the residents in the nursing home and their guardians were informed of the research background, methods, and objectives. The consent forms were signed and returned by participants or their families.

Table 4.2 Participants' information from nursing records.

Participant	Gender	Age	Dementia stage (CDR)	Illness or symptoms
A	Female	87	2-moderate	Sleep problems
B	Male	65	2-moderate	
C	Female	75	2-moderate	Frequency of urination
D	Female	81	2-moderate	Wandering
E	Female	89	2-moderate	
F	Female	98	2-moderate	Arthralgia
G	Female	89	2-moderate	
H	Male	85	3-severe	Frequency of urination, sleep problems
I	Female	78	2- moderate	
J	Male	90	3-severe	Wandering, sleep problems

Note. CDR = 0 (Health), CDR = 0.5 (Questionable impairment), CDR = 1 (Mild impairment), CDR = 2 (Moderate impairment), CDR = 3 (Severe impairment).

4.2.3 Research Procedure

Indoor environmental data was continuously monitored by sensors from August to October 2022, and the observation data collection was carried out for fourteen days within the monitoring campaign. The research design and the use of sensors referenced the methods of the studies in Table 4.1. Twelve sensors were deployed in ten participants' bedrooms and two central living rooms (red dots in Fig. 4.1). Sensors in bedrooms were installed 0.8 to 1 m high (the breathing height of sedentary or bedridden people) in their activity zone. The installation height in the central living rooms was 2 m (on the cabinets), and sensor locations were near the kitchen to measure air quality variations during cooking times. Table 4.3 shows the specifications of sensors, including air temperature, relative humidity, CO_2, the total volatile organic compound (TVOC), formaldehyde (HCHO), and particulate matter ($PM_{2.5}$ and PM_{10}). The TVOC unit has been converted from ppb to $\mu g/m^3$ based on an average molar mass of TVOC molecules [212]. All devices were connected to the local Wi-Fi network and sent readings every 5 min to the cloud storage.

Table 4.3 Sensor specifications (device: Edimax AI-2003W).

Parameter	Range	Sensitivity
$PM_{2.5}$	0 - 500 μg/m^3	>100 μg/m^3, ± 20 %
		<100 μg/m^3, ± 15 μg/m^3
PM_{10}	0 - 500 μg/m^3	
Temperature	0 - 80°C	± 1 °C
CO_2	0 - 10000 ppm	± 30 ppm
TVOC	0 - 1000 ppb	± 15%
Humidity	0 - 100%	± 5%
HCHO	0 - 1 mg/m^3	± 10%

The study used the fly-on-the-wall observation method to record the actual behaviour of people with dementia [38,51]. In August and September, researchers selected fourteen days (based on the arrangement of the nursing home and weather conditions) to record the ventilation control of monitored rooms as well as each participant's location, activity, clothing level, and changed behaviour. The observation data was converted into numerical data (e.g. clothing level: 1-short sleeve, 2-pyjamas, 3-shirt, 4-sweater, 5-jacket; activity: 1-sleeping, 2-sitting/napping, 3-reading/watching, 4-chatting/eating, 5-walking, 6-exercising, 7-out of the building). Based on the schedule of participants (they usually were dressed and ready to come out of their bedrooms before 10 a.m. and went back to their bedrooms to rest after supper around 6 p.m.), the observation started from 10:00 till 18:00. The researcher went through the common spaces in the nursing home to check all participants in the different floors and stopped for a few minutes for data logging. The participants were not being continuously observed, and their information was logged every 30 min by filling out the form and using floorplans, pictures (people not included), sketches, and notes as supplementary information. Considering the fly-on-the-wall observation method could influence the residents' activities and behaviours, researchers frequently visited the nursing home before the study started to reduce the strangeness. Ten participants' names and bedroom numbers were coded using letters from A to J. After data collection, both sensor data and observation data were input into SPSS software for analysis.

4.2.4 Data Analysis

In this chapter, we collected three categories of data: 1) participants' background information (age, gender, and dementia stage); 2) indoor environmental data (air temperature, relative humidity, CO_2, TVOC, HCHO, $PM_{2.5}$, and PM_{10}; and 3) observation data (building facility management, participants' locations, clothing levels, daily routines, changed behaviours, number of residents in the rooms, and residents' main activities). We used SPSS Version 26 for data description and Fisher's exact tests to explore the influences of indoor environmental and contextual data on participants' changed behaviours ($p < 0.05$ as significant). In addition, heatmap charts were made to show the participants' locations at some specific moments according to the data analysis results. These charts associated with sensor data are used to describe the environmental conditions when changed behaviours were observed.

4.3 Analysis of Changed Behaviours with Environmental and Contextual Factors

Table 4.4 lists the date, time slot, location, the number of residents and their main activity in the space when a participant exhibited any changed behaviour, and the indoor environmental conditions at the exact moment. The changed behaviours observed in the courtyard were excluded from the data analysis. Most of the observed changed behaviours in the indoor environment were wandering, which half of the participants had. Besides, participants H and J showed more than one behaviour. The wandering behaviour was mostly exhibited but was not limited to common spaces (corridors or central living rooms). Sometimes, the participants were found pacing in their bedrooms. Participants' hallucinatory symptoms can be recognised as participants (A, F, and H) were soliloquising to the air or objects (e.g. dolls). Participant J showed agitated behaviour once on 27th August, lasting for a few minutes. During the observation period, there were no extreme indoor conditions in the nursing home, such as being too cold or hot, too humid or dry, or poor air quality.

Table 4.4 The environmental and contextual data of changed behaviours.

Participant	Date	Time slot	Behaviour	Location	Temperature (°C)	Humidity (%)	CO2 (ppm)	TVOC (μg/m³)	PM2.5 (μg/m³)	HCHO (mg/m³)	People counting	Main activity
A	Aug 25	11:30–12:00	Hallucination	Courtyard	29.00	42.00	–	–	–	–	2	1
C	Sep 17	11:30–12:00	Wandering	Common space	23.33	51.92	558.00	5.88	4.00	0.04	7	1
D	Aug 18	13:00–13:30	Wandering	Common space	22.98	76.28	672.00	8.33	2.00	0.05	6	1
E	Aug 16	11:30–12:00	Wandering	Common space	22.55	76.29	591.00	12.74	4.00	0.08	8	1
	Aug 16	15:30–16:00	Wandering	Common space	23.52	72.68	660.00	13.23	5.00	0.05	5	3
	Aug 18	11:30–12:00	Wandering	Common space	22.63	76.90	653.00	4.41	2.00	0.03	7	1
	Aug 18	15:30–16:00	Wandering	Common space	23.14	74.78	753.00	8.82	2.00	0.04	8	1
	Aug 23	13:00–13:30	Wandering	Common space	22.84	69.49	646.00	8.33	5.00	0.05	3	1
F	Aug 16	11:30–12:00	Hallucination	Bedroom	23.23	69.67	447.00	0.98	3.00	0.02	1	1
	Sep 15	17:30–18:00	Hallucination	Bedroom	22.20	53.22	476.00	1.96	2.00	0.02	1	2
H	Aug 18	11:30–12:00	Wandering	Common space	22.31	74.87	630.00	7.84	2.00	0.06	8	3
	Aug 18	17:00–17:30	Wandering	Common space	23.91	73.21	476.00	3.92	1.00	0.03	4	3
	Aug 23	15:00–15:30	Wandering	Bedroom	23.63	60.93	563.00	2.45	5.00	0.03	1	4
	Aug 23	15:30–16:00	Wandering	Courtyard	29.00	44.00	–	–	–	–	8	3
	Aug 23	16:00–16:30	Hallucination	Common space	24.16	62.73	465.00	2.45	7.00	0.02	7	3
	Aug 27	11:30–12:00	Wandering	Common space	22.60	61.77	499.00	0.98	3.00	0.02	4	1
	Aug 27	15:00–15:30	Wandering	Common space	23.11	61.46	585.00	4.90	2.00	0.03	6	3
	Sept 1	11:30–12:00	Wandering	Common space	24.30	50.18	466.00	2.94	3.00	0.03	7	1
	Sept 3	13:30–14:00	Wandering	Common space	24.79	46.44	495.00	5.88	7.00	0.04	3	1
	Sept 5	14:00–14:30	Wandering	Bedroom	22.88	55.22	538.00	4.90	4.00	0.03	1	4

Parti-cipant	Date	Time slot	Behaviour	Location	Tempera-ture (°C)	Humidity (%)	CO2 (ppm)	TVOC (μg/m³)	PM2.5 (μg/m³)	HCHO (mg/m³)	People counting	Main activity
	Sept 10	11:30–12:00	Wandering	Common space	22.47	73.62	532.00	4.90	7.00	0.04	7	1
	Sept 10	14:00–14:30	Wandering	Common space	22.80	71.83	469.00	3.92	7.00	0.04	1	4
	Sept 22	10:30–11:00	Wandering	Common space	22.88	49.36	656.00	7.84	5.00	0.05	5	1
	Sept 22	13:00–13:30	Wandering	Common space	23.90	50.18	671.00	11.76	5.00	0.06	3	1
J	Aug 23	16:00–16:30	Wandering	Common space	24.16	62.73	465.00	2.45	7.00	0.02	6	3
	Aug 27	12:30–13:00	Agitation	Common space	22.88	62.71	505.00	16.66	2.00	0.11	2	2
	Aug 27	14:00–14:30	Wandering	Common space	22.98	62.90	509.00	3.43	4.00	0.03	3	1
	Aug 27	14:30–15:00	Wandering	Common space	23.70	61.24	531.00	3.43	3.00	0.03	6	1
	Sept 22	14:00–14:30	Wandering	Common space	23.65	49.49	653.00	5.88	7.00	0.04	2	1
	Sept 22	14:30–15:00	Wandering	Common space	23.49	47.69	621.00	5.39	4.00	0.04	2	1

Note. Main activities: 1-siting, 2-reading/watching, 3-eating/chatting, 4-walking.

Table 4.5 Fisher's exact test of changed behaviour types and contextual factors.

Factors	**Exact Sig. (2-sided) (with changed behaviour types)**
Indoor locations	0.086
Time slots	0.057
Ventilation controls	1.000
Clothing levels	0.010*

Note. (*) Significant at $p<0.05$

Table 4.6 The locations of the changed behaviours observed (indoor).

Changed behaviour	**Location**		**Total (count)**
	Bedroom	**Common space**	
Wandering	2	22	24
Hallucination	2	1	3
Agitation	0	1	1
Total (count)	4	24	28

Fisher's exact tests were conducted for data analysis. Table 4.5 shows the relationship between behaviour types and contextual factors. For the test, all variables were categorised: behaviour types (three categories: wandering, hallucination, and agitation), indoor locations (two categories: common spaces and bedrooms), time slots (three categories: morning 10:00 to 12:00, dining time 12:00 to 13:00 and 17:00 to 18:00, and afternoon 13:00 to 17:00), ventilation controls (three categories: natural, mechanical, and both), and clothing levels (four categories: short-sleeve shirt, long-sleeve shirt, sweater, and jacket). The result shows the behaviour types are only statistically correlated with clothing levels. Amongst twenty-eight recorded changed behaviours, twenty-four of them were observed in the common spaces (sixteen in central living rooms and eight in corridors), significantly higher than in bedrooms (Table 4.6). Since the location was not related to the behaviour types, and given that wandering was significantly more often seen than all other behaviours, the changed behaviours were considered as a whole in the subsequent analysis. Table 4.7 shows the relationship between the location of changed behaviour observed (two categories: common spaces and bedrooms) and indoor environmental factors (three categories: higher, approximate, and lower). Due to the lack of knowledge about the range in which people with dementia can perceive the changes of environmental indicators, we define parameter differences, comparing the data of the room changed behaviour observed and the data of other spaces. For this, we consider a difference of less than one average standard deviation (SD) of twelve monitored rooms (fourteen observation days) as approximate (temperature = 0.69, relative humidity = 10.37, CO2 = 55.08, TVOC = 1.62, PM2.5 = 2.81, and HCHO = 0.02) as similar. A difference larger than a standard deviation (±SD) was coded as 'higher' and 'lower' respectively. Additionally, we also investigated with Fisher's exact test, the relationship with the main activity carried out (four categories: sitting, reading/watching TV, eating/chatting, and walking) and the number of residents present (eight categories: one to eight) in the spaces where changed behaviours were observed (Table 4.7). The result shows that room temperature, TVOC, HCHO levels, the number of residents, and their activities statistically correlate with the locations.

The indoor environmental parameters were steady when changed behaviours were observed (temperature mean value (M) = 23.25°C, SD = 0.65; relative humidity M = 62.85%, SD = 10.18; CO_2 M = 563.75 ppm, SD = 84.67; TVOC M = 5.95 μg/m^3, SD = 3.90; $PM_{2.5}$ M = 3.96 μg/m^3, SD = 2.01; HCHO M = 0.04 mg/m^3, SD = 0.02). However, as shown in Fig. 4.2 and 4.3, changed behaviours present a clear pattern for factors statistically related (e.g. temperature), while such distinction cannot be (visually) made for factors not statistically related (e.g. relative humidity). Indoor temperatures (fourteen observation days) of Rooms A to E and the central living room on the ground floor are at the upper part of Fig. 4.2, Rooms F to J and the central living room on the first floor are at the bottom part. Exterior conditions are shown at the top of the figures for each day. The different colours of solid and dotted lines indicate the temperatures in the rooms, and the colour dots accompanying the letters of participants indicate the type of their changed behaviours. On scorching weather days, the average temperature on the first floor was 1℃ higher than on the ground floor. The data deviation of rooms on the first floor was larger than on the ground floor. Most changed behaviours were exhibited in the warmest central living rooms or the coolest Rooms F and H, between 22 and 25℃, which were maintained in the ranges as ASHRAE 55 suggested [154]. The temperature in the central living room rose more significantly during cooking and dining times, while the other rooms had tiny fluctuations.

Table 4.7 Fisher's exact test of changed behaviour locations and indoor environmental or contextual factors.

Factors	Exact Sig. (2-sided) (with changed behaviour locations)
Temperature	0.001*
Humidity	0.270
CO_2	0.057
TVOC	0.022*
$PM_{2.5}$	0.146
HCHO	0.033*
Number of residents in the space	0.004*
Main activities of residents	0.029*

Note. (*) Significant at $p<0.05$

The indoor relative humidity in the nursing home was stable during the daytime (Fig. 4.3). The ranges during the monitoring campaign were from 35 to 85%. Each room variated about 10% during one day. Unlike indoor temperature variations, relative humidity was usually highest in the morning, lowest in the middle of the day, and gradually picked up in the evening. The average humidity level on the first floor (bottom part) was 5% lower than on the ground floor (top part). Based on the simultaneous observation and monitoring, participants' occupancy in bedrooms had tiny influences on the data fluctuation. In Fig. 4.3, the changed behaviour occurrence does not show a clear pattern with the relative humidity trend (not always in the warmest or coolest room), which is consistent with Fisher's exact test results. However, it can be seen from the figure that most of the changed behaviours appeared in the interval of 60 to 75% humidity.

The observation data of participants and environmental data of rooms they stayed in were logged and integrated into floor plans to find the relationships. Fig. 4.4 and Fig. 4.5 compare the participants' daytime activities, movement ranges, the locations of changed behaviours, as well as indoor and outdoor environmental parameters. The purpose is to illustrate the difference between the day with changed behaviours exhibited and the day without. However, since it was not observed a large number of changed behaviours on the same day and two floors, we conducted separate comparisons between the ground floor (three records) on the 18^{th} of August, the first floor (five records) on the 27^{th} of August, and both floors with no records on the 13^{th} of September. These three days were under essentially the same outdoor and indoor conditions, which minimised the influences of environmental factors. In these heatmap charts, the blue areas indicate participants seldom arrived, and the green areas were the places they shortly stayed. In the yellow and orange areas, participants stayed longer than 0.5 and 1 h. For instance, the upper part of Fig. 4.5 shows that Participant H usually talked with others in front of the staircase, so the areas were yellow or orange rather than blue. The red areas mean participants stayed longer than 2 h. The black dots show the time and type of specific participant who exhibited changed behaviour. These charts show that participants (D, E, H, and J) had larger activity ranges on the days with changed behaviours (left) than on the days without (right). The hotspots of the daytime activities were concentrated in central living rooms and bedrooms. Moreover, based on the observation data of other residents' states, we found that they were relatively spread out when participants exhibited changed behaviours. They were sitting or napping on the chairs and had little interaction with each other, so the changed behaviour was seldom intervened.

The routes and extent of wandering were random. Sometimes, the participants paced repeatedly between the doorways of their bedrooms and central living rooms, or they walked to the end of a corridor and then turned back. Although each bedroom door pasted the portrait photo and name tag, participants could still lose their way back. Hallucinatory symptoms usually happened to the participants staying alone. One record in the corridor was participant H soliloquising and gesturing in front of his bedroom. During the observation, agitation was only observed once in the central living room as Participant J yelled at care professionals without signs and pushed away the tableware during lunch. In conjunction with the participant's personal information, the locations of changed behaviours are related to the individual's mobility and degree of dementia. For instance, participant F had mobility limitations, and her changed behaviours were observed in her bedroom. Participants H and J were in the severe dementia stage and exhibited more changed behaviours than others.

Further analysis of the nursing home layout using the DepthmapX software reveals that the changed behaviours exhibited less in the areas of higher visibility and pedestrian flow (red, orange, and yellow colours in Fig. 4.6). Changed behaviours were mostly in areas which could be overlooked (green and blue colours in Fig. 4.6). There were six records (20%) of changed behaviours recorded in bedrooms or outdoor spaces, five (16.7%) were in the centre areas of the building, and nineteen (63.3%) observed in the edge of common spaces, such as at the corners of central living rooms.

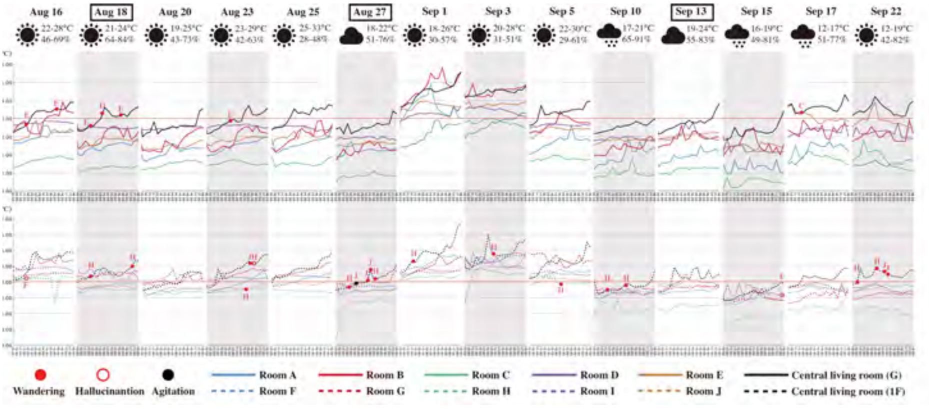


Fig. 4.2 Indoor air temperature, outdoor weather, and participants' changed behaviours on the observation days.

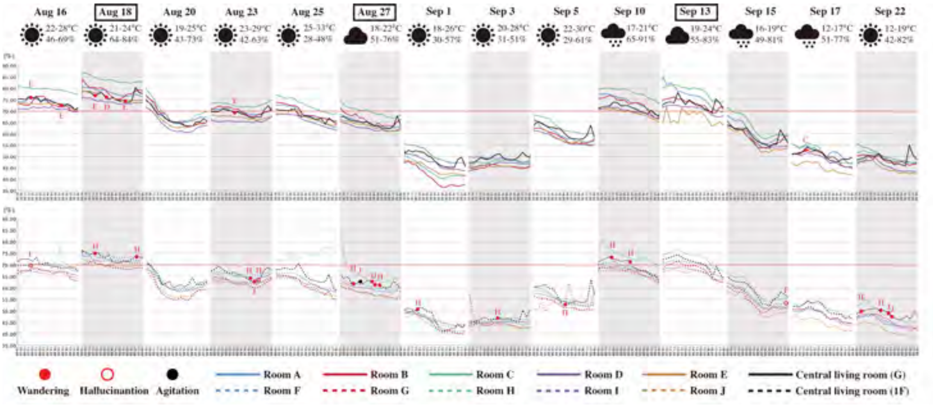


Fig. 4.3 Indoor relative humidity, outdoor weather, and changed behaviours on the observation days.

Fig. 4.4 The heatmap chart of two observation days with (left: 18th August) and without (right: 13th September) changed behaviours on the ground floor.

Fig. 4.5 The heatmap chart of two observation days with (left: 27th August) and without (right: 13th September) changed behaviours on the first floor.

Fig. 4.6 The locations of observed changed behaviours combined with Visibility Graph Analysis.

4.4 Discussion

In this chapter, we investigated the effect of indoor environmental and contextual factors on the behaviours of people with dementia. We focused on the conditions of changed behaviour exhibited and analysed the indoor environmental and contextual factors logged during the period of fly-on-the-wall observation. Thus, we collected different data types to explore these relationships and considered outdoor weather data and participants' clothing levels, activities in common spaces, and building facility operations. Thirty changed behaviours, wandering, hallucination, and agitation, listed in Table 4.4, were from seven participants. Some contextual factors (e.g. clothing levels) remained unchanged during the daytime in this study. However, clothing adjustment is a good way to adapt to environmental changes, which may be beyond the abilities of people with dementia [198]. Thus, these factors could trigger participants' changed behaviours or encourage them to move to other areas.

The floor plans of the studied nursing home are L-shaped. The staircase, elevator, and central living rooms are located at the junction of two corridors, and each corridor is a linear system with one or multiple corners [207]. Corridors play a crucial role in linking the indoor spaces. The availability of different rooms for different purposes, activities, and arrangements impacts residents' preferences to stay and their living qualities [213]. Thus, the L-shaped layout makes the space centripetal, and residents prefer to stay near the central living rooms rather than the activity rooms in corners (Fig. 4.6). The basic typology of wandering patterns is proposed as lapping, pacing, random, and direct individual ambulation episodes, and random has been validated as the most common [214]. However, people with dementia often exhibit more than one pattern. In this study, these patterns are clearly shown in the linear floor plan. Participants' routes were random (pacing in a small area or walking directly to the end of corridors), and the time of wandering start and end was also unpredictable. Sometimes, residents could wander onto the other floors through the elevator because the elevator is easy to access (the staircase was closed). The location of elevators in nursing homes needs to be carefully considered. Another imperfection of the building layout is centralised with the long, straight, materially identical, similar furnishing arrangement corridor. This centralisation of personal and common space instils residents an alienation from spaces they do not often access and gives them a sense of disorientation to their surroundings [215]. Residents were found wandering in the corridors but rarely went to the corner activity rooms.

The building quality of the studied nursing home was high, the facilities were new and operating well, and all bedrooms were similar in layout and orientation. Indoor environmental quality and care-related factors, such as thermal properties of the building, ventilation, cooling and heating systems and care service schedule, were consistent in the studied nursing home [216]. Sensor data shows the temperatures in bedrooms basically fluctuated between 18 and 24°C as the WHO suggests for sedentary people [176], and each room usually had less than 1°C standard deviations during one day. Relative humidity data varied between 35% and 85%, and the fluctuations were around 10% within one day of all monitored rooms. Besides, the air quality was well maintained in the nursing home. Based on existing research, the healthy threshold of CO_2 concentration has been set at 800 ppm, and the harmless limit is 1000 ppm [166]. The TVOC limit proposed by the European Commission is 300 μg/m^3, and the comfort range is under 200 μg/m^3 [169]. WHO air quality guidelines suggest the short-term (24 h) $PM_{2.5}$ and PM_{10} levels are 15 μg/m^3 and 45 μg/m^3, whilst the annual $PM_{2.5}$ and PM_{10} levels are 5 μg/m^3 and 15 μg/m^3 [217]. The guideline value for HCHO of the Netherlands is 0.12 mg/m^3 [218]. The average mean values of CO_2 were around 500 ppm, TVOC mean values were less than 5 μg/m^3, $PM_{2.5}$ mean values were 4 μg/m^3, and HCHO levels were below 0.04 mg/m^3 in the nursing home. Although data analysis results show that the indoor environments were not under extreme indoor conditions, the relationships between room conditions (air temperature, TVOC, and HCHO levels) and the locations of the changed behaviours were significant in this case study. According to the observation records, Fig. 4.7 shows the percentage of the room conditions (changed behaviours observed) that were similar, higher, or lower compared with other spaces on the same floor. In these rooms, temperature had a larger percentage warmer than the average (67.9% in red colour); relative humidity had a larger percentage approximately the average (89.3% in grey colour); and air quality parameters had slightly larger percentages higher, which partly confirms that the thermal environment has a significant impact on nursing home residents [34]. In this study, the proportions of CO_2 and TVOC, as well as $PM_{2.5}$ and HCHO, are consistent, but only TVOC and HCHO are statistically significant. The reason could be the interconnection between indoor environmental indicators (e.g. HCHO negatively correlated with indoor temperature in summer) or specific activity causes indicators to increase (e.g. cooking) [219]. People with dementia's tolerance ranges of these air quality indicators still need to be explored.

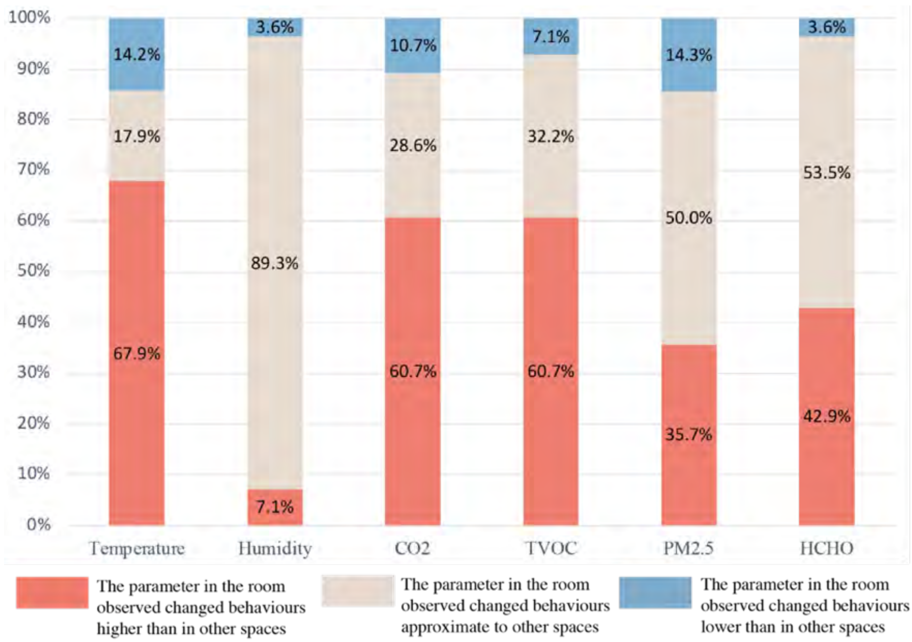


Fig. 4.7 The percentage of indoor environmental conditions when changed behaviours were observed.

This chapter specifically focuses on the relationship between two factors (changed behaviours and indoor environment) of the triadic reciprocal causation model [50]. The findings reveal that indoor environmental factors (temperature, TVOC, HCHO, and activities of other residents) influenced participants' changed behaviours, and the behaviour patterns showed differently in the indoor spaces. Personal factors, such as dementia stage and illness, also influence the occurrences, ranges, and locations of changed behaviours to some extent. However, limitations exist in this study, including the scale of the nursing home, data collection period, and number of participants, which need to be extended and addressed in future research. We observed other changed behaviours from the rest of the residents (e.g. screaming and depression). As they were not participants in the study, their information was not included. Limited sampling sites and participants meant that the relationships between indoor environmental indicators, activities, locations, and behaviours could hardly be assessed quantitatively and did not allow for more general conclusions to be drawn. Considering the heterogeneity of older adults and nursing home conditions, collecting data from more residents living in different nursing homes may bring new challenges for data analysis. People with dementia may have different sensations of indoor environmental changes, and there is no exact perception range of the parameter changes for this group [32,197]. Thus, we categorised and analysed the indoor environmental data according to both observation records and standard deviations of the sensor data for Fisher's exact tests. Furthermore, we had no permission to observe participants at night to check if they had sleep disturbance and restlessness. Some behaviours with no obvious characteristics (e.g. apathy) were excluded from data collection and discussion. Protecting privacy when using the fly-on-the-wall observation method is essential. Participants habitually returned to their bedrooms for napping after lunch and locked the door. In this case, we needed care professionals' help to check the participants' conditions since they were familiar with and brought minimum interference. Moreover, existing research found a high incidence of wandering behaviour around dinner time [220,221], but the changed behaviours more frequently appeared in this study before lunch (nine records of 11:30 to 12:00). Food and medication could also be stimulations, which trigger the changed behaviour but were considered out of the scope of this study. Last, we only collected data during the summer, given that in newly built buildings, it is more difficult to maintain comfortable parameters in the summer (e.g. overheating) than in the winter. We observed very similar indoor parameters in this nursing home in other seasons.

4.5 Conclusion

This chapter was conducted in a small-scaled nursing home in the Netherlands to collect indoor environmental data, contextual data, and details of participants' changed behaviours. Its objective was to explore the relevance of environmental and contextual factors with the occurrences and locations of changed behaviours. Although the excellent building thermal properties and facility operation, the indoor air temperature, humidity, and air quality parameters deviations were small, the room conditions of temperature, TVOC, and HCHO levels could be factors influencing where the changed behaviours were exhibited. However, we also found that the changed behaviour was significantly related to the clothing levels, the number of people present in the space, and their main activities when it happened. Besides the individuals' health conditions, the floor plan and spatial layout impact residents' activity ranges to some extent. If conditions allow, future research is suggested to focus on behavioural changes amongst people with dementia who live in a variable indoor environment, such as older non-renovated buildings, to explore the appropriate indoor environmental conditions that could help to reduce changed behaviours and improve their living quality. Because the changed behaviours of people with dementia are not eliminated by being with others or living in well-maintained indoor environments, the recommendation for nursing home design is to increase the visibility of the indoor spaces and avoid setting common areas at corners. Caregivers are suggested to pay more attention to the edge of common spaces if older adults stay there for a long time. Changed behaviours are likely to be exhibited in these overlooked spaces, which need to be distinguished to prevent serious consequences.

Chapter 5
Social Housing Renovation for Healthy Ageing: An Empathic Design Approach for Creating Immersive Environments through Virtual Reality

Abstract

With the increasing ageing population, there is a shortage of suitable housing stock for the ageing group. One effective way is to renovate the existing housing to improve older adults' living qualities and independence. The development of innovative technologies (e.g. virtual reality) and design approaches (e.g. empathic design) can provide new strategies for housing renovation practices. However, the knowledge of integrating innovative technologies and design approaches remains notably limited, with the potential value yet to be fully recognised. This chapter explores and validates an approach that synergises virtual reality technologies and empathic design within a senior social housing renovation practice, which focuses on three primary aspects: a) translating the data of user requirements and housing assessment into digital models by the empathic design approach, b) developing immersive virtual environments to illustrate design variations, and c) evaluating the renovation design with stakeholders using virtual reality devices. The data analysis of the interview, questionnaire, and experimentation recording revealed that using virtual reality technologies to show customised design scenarios enhances stakeholder engagement and improves the effectiveness of the design process, especially for older adults. Some practical implications on virtual reality application, model design, and empathic approach are provided.

5.1 Innovative Approaches for Architectural Design

According to the latest report of the Central Bureau of Statistics of the Netherlands (CBS), on 1 January 2023, the Netherlands had 3,601,167 inhabitants aged 65 years and over, representing 20.2 % of the population [222]. This percentage is expected to increase to 26% in 2035 [223]. One of the concerns related to population ageing is the issue of ageing-in-place, remaining in individuals' homes and communities safely, independently, and comfortably, regardless of age, income, or ability level [224]. Existing studies suggest that supportive services and features, such as home modification and assistive technologies, can improve older adults' ability to remain at home and promote independence [225,226]. However, over 40,000 Dutch households aged 65 and above still live in an 'unsuitable' home environment [8]. Indoor barriers and hazards are potential safety threats (e.g. staircase), and even large-sized houses could increase the difficulties of their daily lives [227,228]. Thus, the availability of home renovation programmes, which can help older adults adjust their homes to meet their needs, is an important factor for living quality and independence [229,230]. However, traditional design approaches do not intuitively show the renovation benefits after construction. Considering time and costs, home renovation is not always accepted, even if necessary [135]. Furthermore, most existing guidelines for home renovation design reflect a standardised and singular plan. In contrast, personalised and customised design based on older adults' real living conditions always raises their empathy [231]. The empathic design, a user-centred approach that focuses on the user's feelings toward design, is rarely applied in housing renovation projects [48].

Virtual reality (VR) technology plays an essential role in the technical application of architectural design and research, and it has the potential to be an excellent medium for presenting the immersive experience of scenarios designed to be built in the real world [39,135,232,233]. It also allows manipulations of built environments that could not effectively be implemented in the real world, which differs from videos, photographs, and sketches [234]. The advantages of using VR technologies in architectural design include [39,235–238]: 1) Enhanced visualisation: VR allows architects and designers to create immersive 3D visualisations of architectural plans; 2) Cognitive engagement: VR can be used to stimulate cognitive engagement by offering interactive experiences; 3) Accessibility testing: VR test accessibility challenges in design scenarios, which is essential for older adults who may have mobility or sensory impairments. 4) Stress reduction: VR is a tool to reduce the stress and anxiety of modifying individuals' living spaces, provides a safe and familiar environment for them to adapt to proposed architectural changes; and 5) User assessment: Stakeholders can assess the feasibility of design concepts by using VR on how well the ideas addressed in the virtual environments.

Integrating VR with empathic-designed models could provide new architectural design and research directions. Current studies mostly focus on urban development and 3D city modelling [239]. The knowledge of leveraging these tools specifically on the building scale is limited. In the architectural heritage research, Bevilacqua et al. used three case studies to illustrate the reconstructive digital modelling and the prototype of the application of VR. They proposed digital replicas to perceive and understand the close relationship between the physical environment of historical buildings and viewers with VR and Augmented Reality (AR) [240]. Kalantari et al. developed and tested a hybrid physical/digital toolset, 'Ph2D', for architectural prototyping as an innovative tool for the design process. It allowed adjustments in a physical floorplan model to be mirrored and analysed in a digital platform [43]. Najafi et al. have begun to explore using VR in conjunction with healthy ageing principles, assessing age-friendly community designs. However, the full potential to improve the quality of life for older adults has yet to be fully realised [241]. Hou et al. have delved into the emotional impacts of facility environments on older adults [242]. There is still a pressing need for holistic approaches that combine these technological innovations with senior housing design.

In various studies on social housing and older users, VR technologies were often utilised as tools to assess and analyse the home environment, including the size of the rooms, the furniture, and the width of the doors. These assessments were aimed at identifying structural changes that could be made to enhance the accessibility of the older adults' homes and also to help select suitable assistive equipment [232]. Although VR technology can provide virtual environments that are almost close to the real environment, it should focus more on simulating human actions or real conditions rather than on the quality of the rendering [243]. Existing studies show fewer mistakes and better results if older adults participate in the decision-making and design processes [39]. However, in the field of housing renovation for the ageing population, there is a lack of empirical evidence regarding the best design practices for home settings [244,245]. By including older adults as co-researchers, designers can gain valuable insights into their needs and preferences, which inform the design of more inclusive and effective living environments. This chapter seeks to fill this gap, providing new insights into using VR technology to create more immersive and empathic environments for older residents in social housing. It is structured in three distinct phases: the initial phase was focused on assessing the current condition of the social housing in the case study and identifying the residents' requirements for renovation.

The subsequent phase developed immersive virtual environments and scenarios to illustrate design variations. The last phase aimed to gauge the stakeholders' satisfaction and acceptance of the renovation design approach demonstrated through VR. The outcomes of this chapter are anticipated to provide insights for devising an optimal design approach to support creating healthy ageing environments.

5.2 The Research Process on Social Housing Renovation Practice

5.2.1 Case Study

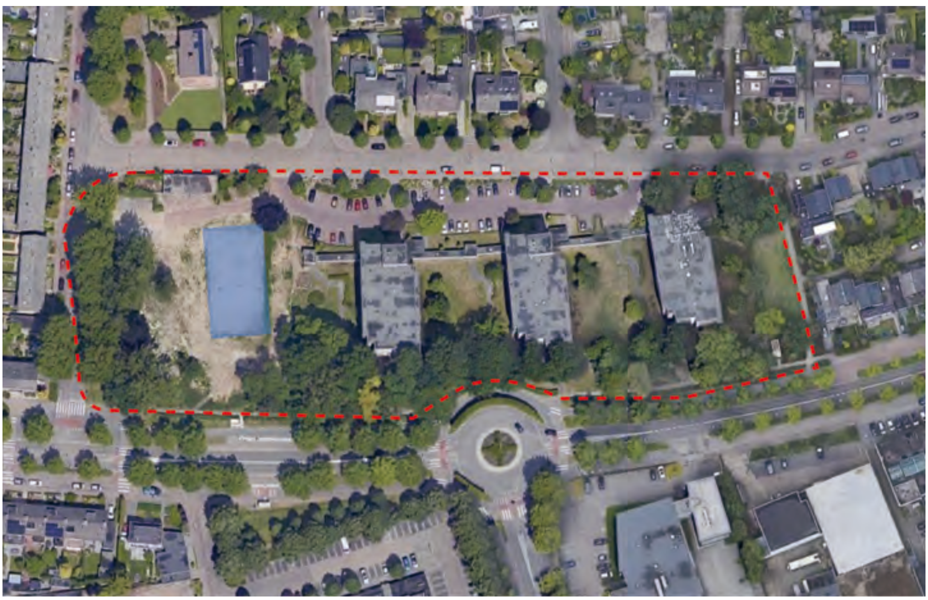


Fig. 5.1 The site plan of the case study.

The subject of this case study is a residential compound in south Eindhoven, the Netherlands, comprising a block of four apartment buildings constructed during the 1970s (the marked area in Fig. 5.1 shows the location of one building demolished in 2020). These structures are interconnected via corridors, facilitating pedestrian circulation and interpersonal interactions among the inhabitants. The central courtyard, interspersed with verdant shrubbery and plane trees, serves as a communal space for the residents. Approximately 140 individuals live in this residential compound. Most of them are over 65 and intent on maintaining their independence for as long as possible. Each five-storey building contains forty residential units, complemented by two staircases, an elevator, and auxiliary spaces in the basement, including storage areas and lounges for social gatherings. The apartments are of two distinct dimensions, with interior spaces measuring 52 m² (two-room flat) and 75 m² (three-room flat), respectively, and feature varying balcony sizes contingent upon their specific locations (Fig. 5.2). The apartments are oriented along an east-west axis, offering advantageous views.

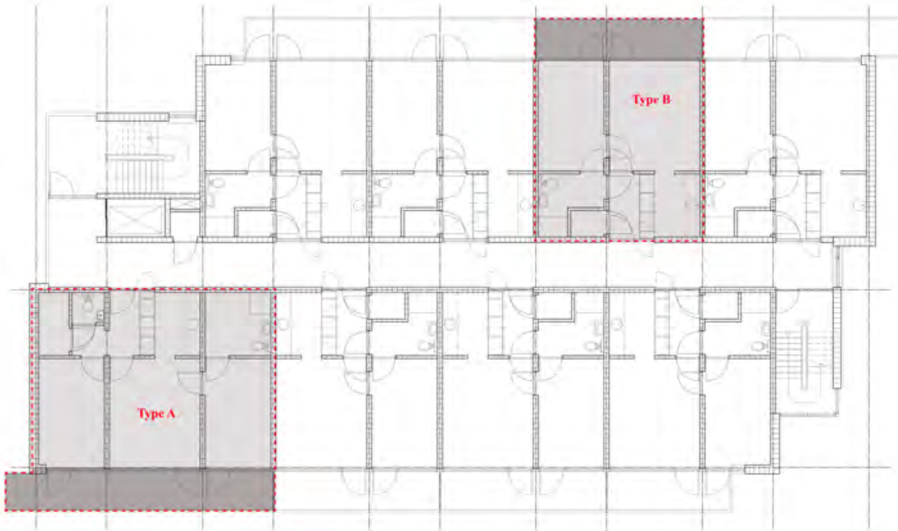


Fig. 5.2 Two apartment types on one floor (Source: Arctitektnburo van de Kerkhof).

5.2.2 Participants Recruitment

The participants were involved in two research phases. Five senior residents (Group Residents) were recruited through an ethically approved recruitment process. They voluntarily participated in the study and were healthy and living independently (four males and one female, between 63 and 82 years old). Before starting, they were informed of the research background, methods, and objectives and signed the consent forms to participate in the interview and VR experimentation. Group Designers include five younger people (designers and the project consultant between 28 and 42 years old). They were invited to participate in the VR experimentation.

5.2.3 Research Design

The chapter followed the empathic design framework [38] and the smart home modification process [135] that used mixed methods for data collection, modelling, and data analysis. The process is shown in Fig. 5.3:

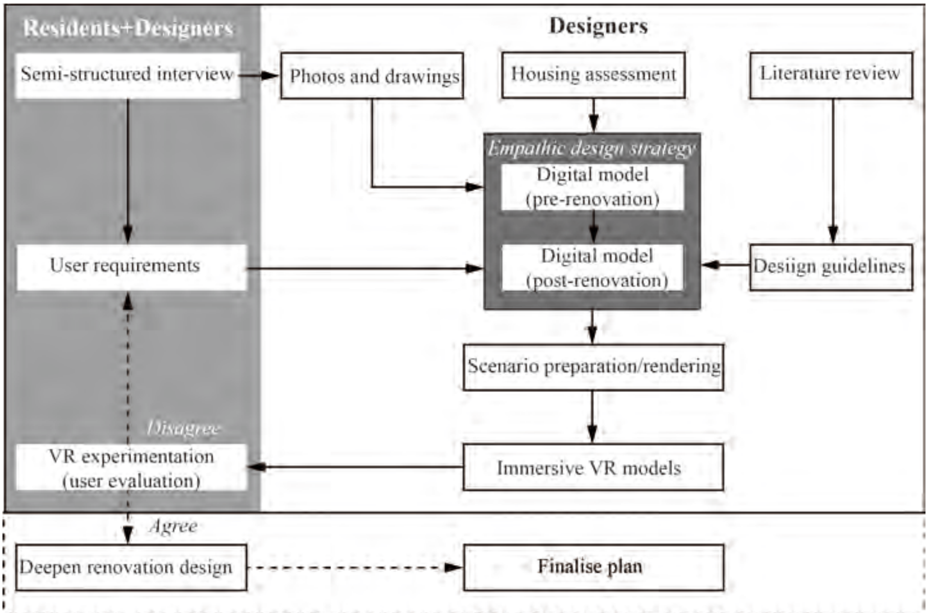


Fig. 5.3 The methodological framework.

5.2.4 Housing Assessment and Residents' Requirement Investigation

To explore the social housing features and residents' requirements for renovation to promote healthy living, this chapter started with the housing assessment and in-depth interviews with Group Residents. The method was based on the Architectural and Psycho-environmental Retrofitting Assessment Method (APRAM) and Housing Enabler (HE). APRAM is useful for building renovation and employs multiple dimensions of analysis to obtain a comprehensive diagnosis. The diagnosis combines an objective dimension, which comes from the technical results of architectural inspections, and a subjective dimension that gathers the social perceptions of residents [246]. HE is an instrument widely used for housing accessibility assessment and analysis, especially in older adults' homes [247]. The interviews also considered five critical factors pertinent to ageing-in-place: building layout, accessibility, comfort, security and health, and use and control, as outlined in existing literature [248,249]. Group Residents expressed their satisfaction levels with their living environments, articulated issues of the residential building, and conveyed their expectations for addressing these challenges. Additionally, details of room layouts and furniture characteristics, documented through photographs and sketches, were gathered during these interviews, providing the basis for creating detailed digital models.

5.2.5 Digital Modelling and Scenario Preparation

The data collected from the housing assessment and interviews were translated and associated with drawings from the architectural firm (Arctitektnburo van de Kerkhof) and measurements of the sites to elaborate the digital model of the studied residential compound. Four components of the current residential compound were developed: 1) the existing residential buildings and connecting corridors, 2) the interior of five interviewees' apartments, 3) the landscaped features of the residential compound, including slopes, pathways, trees, and benches, and 4) the adjacent streets and the broader environment. Creating an accurate model aims to provide empathic environments for participants. Emphasis was placed on accurately replicating the residences of Group Residents, encompassing spatial configurations, furnishings, and textural details, to facilitate the comparison among the renovation options. Twenty renovation scenarios were developed based on the current residential compound prototype (see section 5.3). The modelling process utilised SketchUp and Blender software platforms, which support various file format interactions.

The completed digital model was imported into Unity, a robust and versatile game development engine. Key features of Unity, including real-time lighting and shadow effects, facilitated the creation of a visually immersive and dynamic virtual environment that accurately mirrors the physical counterpart [250]. Unity's diverse camera angles and perspectives enabled users to intuitively navigate the virtual space, gaining a thorough understanding of design details and spatial relationships [251]. Unity also allowed for the seamless integration of sound and other sensory elements, such as haptics, enhancing the realism and engagement of the VR experience [250–252]. The Extended Reality (XR) and Android Software Development Kit (SDK) were used to develop smooth interactivity within the virtual environment, incorporating user input from various sources such as touch, buttons, and cross-platform VR controllers [253,254]. The Universal Render Pipeline (URP) was utilised to render the final models. Its rendering capabilities ensured compatibility across different VR platforms while offering scalability, customisation, and a rich feature set.

User communication was facilitated through Oculus Quest 2, a standalone VR headset. It enables positional tracking in space by offering a per-eye resolution of 1832 * 1920 pixels and supporting 6 degrees of freedom tracking. Its immersive capabilities, ease of use, and ergonomic design minimise physical discomfort, crucial for maintaining engagement among users who may be more sensitive to the physical demands of VR technology. Considering the safety of senior residents, the VR experimentation was designed to employ a sitting mode, allowing them to explore the content while seated and eliminating the need to stand or move around [233].

5.2.6 VR Experimentation

During the validation phase, ten participants (Group Residents and Group Designers) were convened to engage in the VR experience to collect their feedback. This involved the utilisation of the VR headset to navigate virtual tours, showcasing both the common areas and individual apartments pre- and post-renovation. All the participants were informed about the experimentation plan and objectives. They signed the consent forms and understood they could stop the test anytime. Before using VR headsets, we used posters to explain variations of renovation design to start the conversation (Fig. 5.4). Participants discussed the scenarios that they were interested in experiencing with researchers. Experiencing each scenario was around 6 minutes, as the existing study suggested range [255]. They viewed the selected scenarios alternately and could have rest in between.

Fig. 5.4. Poster introduction.

The experimentation process was designed as one participant wearing the VR headset and the view in VR projecting on a screen for the rest of the people (Fig. 5.5). The tour commenced at the main entrance of the residential building model, leading the participants into the lobby. By selecting their apartment number in front of the elevator, they will be teleported to the front of their apartments. Considering that the usage of VR controllers could be complicated for older adults when they were wearing the VR headset, researchers helped them switch the cameras to navigate the VR tour. Several teleport spots were set in the corridor, hallway, living room, balcony, bedroom, and bathroom of the digital models. Participants can tell researchers they would like to move forward or back. During this process, they were free to share ideas and comments, such as which design they liked or disliked and their remarks. The conversations were recorded. Subsequently, each participant filled out a questionnaire developed based on the Technology Acceptance Model (TAM) [256]. The questionnaire was designed using a 5-point Likert scale ranging from 'strongly agree' to 'strongly disagree', including perceived usefulness (e.g. using VR helps me to understand the renovation design), perceived ease of use (e.g. I find it is easy to use VR to communicate the design ideas with designers), attitude toward using (e.g. I think it is interesting to make the objects in VR environments more interactive), and intention to use (e.g. I tend to use VR of the future project updating). The questionnaires were associated with the audio recording transcriptions for data analysis.

Fig. 5.5 VR Experimentation of Group Residents (left) and Group Designers (right).

5.2.7 Data Analysis

As Fig. 5.3 shows, the data were mainly collected in two phases. The first phase included interviews and a literature review conducted for digital modelling, generating design guidelines, and renovation variation design; in the second phase, VR experimentation, we collected questionnaires and discussions by handwritten and audio recordings to gain insight into user evaluation. The interviews were recorded using an audio recorder, and the VR experimentation process was recorded using computer devices. All data were transcribed using MS Word for narrative analysis and descriptive analysis.

Verbatim transcripts are the unfiltered representation of reality. In order to make sense of them, they require classification [257]. To achieve this, the transcription of the interviews and the discussions during VR experimentation were classified by themes. The interviewed themes were classified into two main parts: housing physical conditions and indoor comfort. The data analysis of discussion content associated with questionnaire results generated seven themes: the comfort of using VR, ease of understanding, ease of communicating, scenario interactivity, empathy of customised design, acceptance of technology/approach, and overall satisfaction. These themes are discussed and supported by verbatim extracts from the data to highlight important issues. The aim is to use results to enhance and optimise the renovation design.

5.3 Renovation Design and Evaluation

5.3.1 The Results of the Housing Assessment and Interviews

The renovation design and modelling specifically focused on the residential building and apartment interiors, and the investigation of the exterior surroundings was excluded. By analysing the data collected from interviews and housing assessment, the problems and requirements for renovation were mainly concentrated on the architectural design level.

The common areas of the residential buildings had no accessibility problems. The design of entrance spaces, door width, stairs, walking surfaces, and handrails was well-designed for older adults' usage according to assessment checklists. Each entrance hall was equipped with an elevator, some benches for rest near the letterboxes, and the doors were easily opened or closed (Fig. 5.6).

Fig. 5.6 The common area of one residential building.

Problems in the interviewees' apartments were listed in Tables 5.1 and 5.2. For instance, the hallway is narrow (less than 1.2 m in width) and dark, which could be hazardous for older adults, especially at night. In the I-shaped kitchen, the spaces for operation and the cupboards for tableware are insufficient, and interviewees would prefer an L-shaped kitchen. The bathroom layout of the apartment (Type B) was L-shaped. The space was too narrow to turn around with a wheelchair or walker (the width of some areas was less than 0.9 m). Most residents put a washing machine at the corner and blocked the path. The accessibility problem existed in one interviewee's bedroom. It was crowded, and only on one side of the bed a space over 0.9 m was kept. The privacy issues in the balcony were reported by 3 of 5 interviewees (the transparent material and insufficient height of partitions in balconies). The problems in Table 5.1, related to spatial layout, accessibility, and architectural elements, were considered for renovation design based on established design guidelines [258–261].

Table 5.1 Problems with building layout and accessibility of housing assessment and interview.

Problems	Housing assessment by researchers (APRAM and HE)	Reported by interviewees (count)
Hallway		
• Narrow and dark	Yes	2
Kitchen		
• Insufficient operation spaces	Yes	3
Bathroom		
• Inappropriate design for laundry	Yes	3
• Insufficient manoeuvring spaces	Yes	5
Bedroom		
• Low accessibility for people with mobility limitations	Yes (in one room)	1
Balcony		
• Privacy	Yes	3
• Sun shading	Yes	2
General		
Insufficient spaces for indoor activity, white goods, or storage	No	3
Controls and operable hardware	Yes	3

Note. Yes: the researcher found the according to the assessment tools; No: the researcher didn't find.

According to the housing assessment and interview, some problems related to building insulation and indoor comfort were also found or reported (Table 5.2). Two interviewees reported that their rooms were too bright during the summer day. Three of them complained that the indoor temperature was sometimes hot in summer or cold in winter. The residents thought that the old windows and heating system were the reasons for the poor thermal environment. Most interviewees also had problems with the noise from the old pipelines or neighbours. The ventilation in the kitchen was not operating well because of the outlet location and low fan speed. The smells lingered in the rooms if the windows were not open.

Table 5.2 Problems with building insulation and indoor comfort of housing assessment and interview.

Problems	Housing assessment by researchers (APRAM and HE)	Reported by interviewees (count)
Light environment		
• Too bright or dark during the daytime	No	2
Thermal environment		
• Window insulation	No	3
• Heating control	Yes	3
Noise		
• From pipeline	No	1
• For neighbours	No	4
Air quality		
• Ventilation operation	Yes	3

Note. Yes: the researcher found the according to the assessment tools; No: the researcher didn't find.

5.3.2 Design Variations for VR Experimentation

According to the collected data, we used the empathic design approach to remodel the entire residential compound and five detailed apartments of interviewees. The digital model of the room layout, texture, furniture, ornaments, and outdoor environment was made as realistic as possible for the actual apartment (see Fig. 5.7). The aim is to provide senior residents with home-like environments and reduce their strangeness during the experimentation.

Fig. 5.7 Current indoor scene (left) and empathic designed digital model in Unity (right).

The renovation design variations were based on digital models of the interviewees' apartments and their specific home settings (Fig. 5.8). Variation A is designed based on the drawing of the architectural firm responsible for the project, which will likely be used for future construction. Researchers designed variation B according to the solutions to problems listed in Table 5.1 and renovation design guidelines. The design process considered different interviewee's requirements and their focus on building layout and accessibility problems. So, the variations for each interviewee are slightly different. In variation B, the kitchen is L-shaped for more operation spaces. A minimum turning radius of 1.5 m within the living room, bedroom, and bathroom space. Adjustments in the kitchen and bathroom include reducing the heights of worktops and basins to 0.8 m. The shower stall is larger than 0.9 m x 0.9 m and outfitted with seats and handrails, facilitating ease of use for older adults and considering the possibility of transition from wheelchairs. Additionally, shower doors are designed to open from the outside in emergencies. As interviewees require, the door between the bathroom and bedroom has been replaced with sliding doors. In the bedroom, maintain a minimum gap of 0.9 m between the bed and surrounding walls or furniture to ensure easy access. The living room, bedroom, and balcony, which received fewer complaints, largely retain their current layouts. The main differences between the variations are the bathroom and storage room layout. Except for variation A, the hallway is opened to make a brighter and more accessible kitchen space.

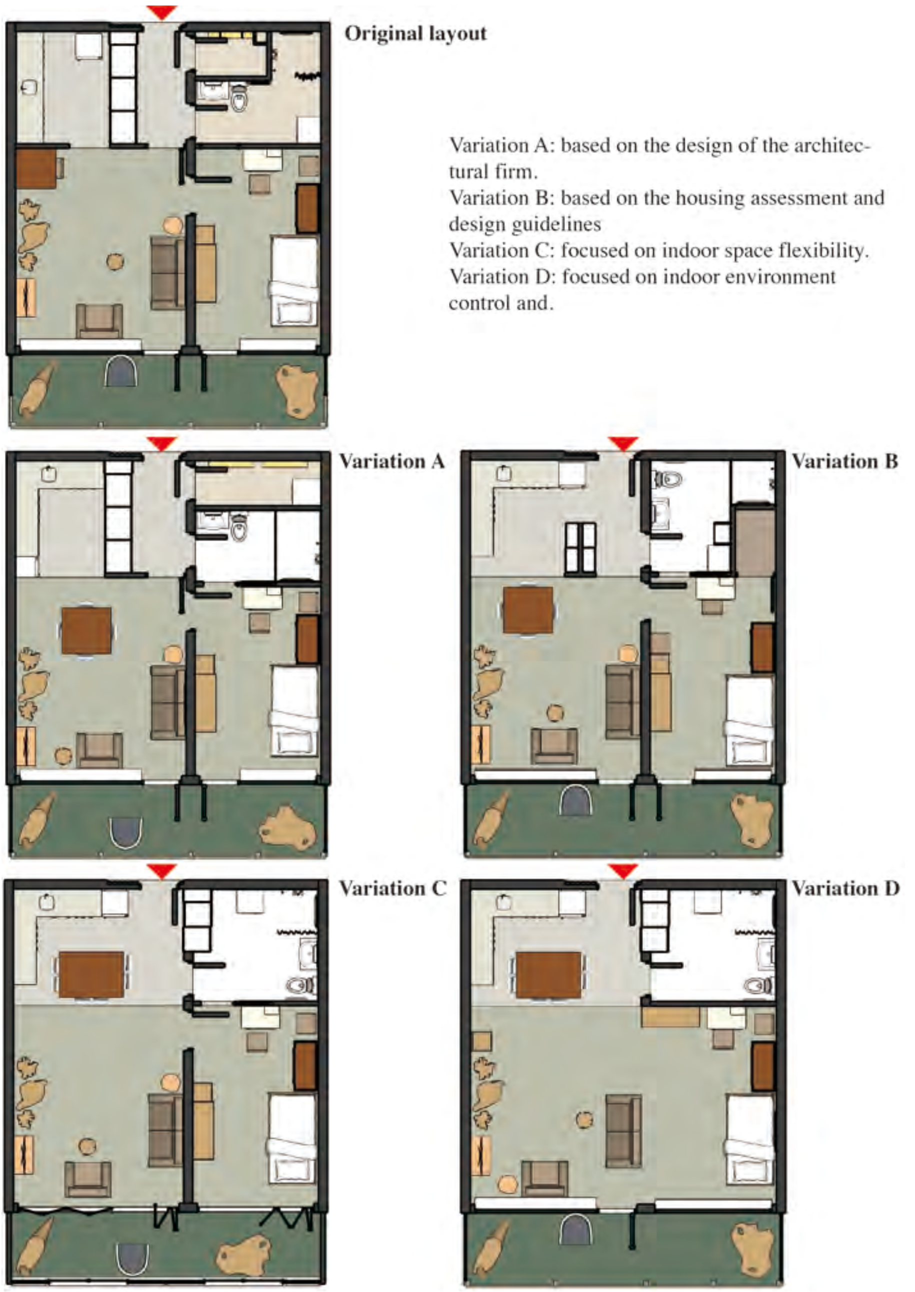
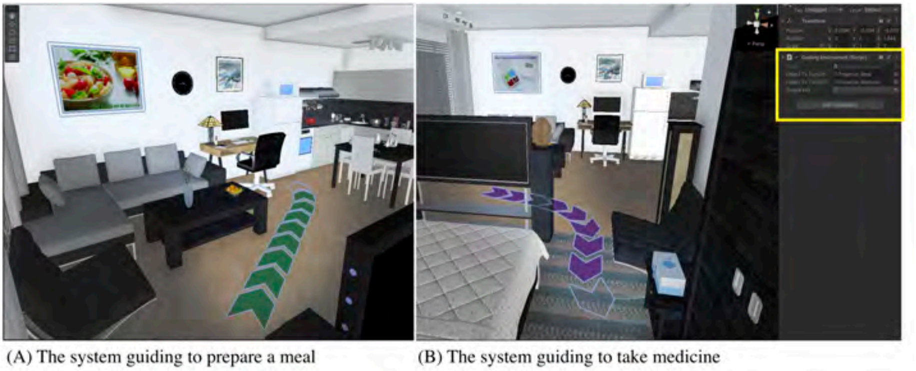


Fig. 5.8 The variations of renovation design.

Variation C was designed to solve the specific requirement of Table 5.1, which more than half of the interviewees reported: insufficient indoor spaces. The original external walls and windows of the living room and bedroom were replaced by sliding doors.

The balcony was sealed by glass windows. Residents can flexibly use the balcony space according to the weather and season as a part of indoor or semi-outdoor space. Furthermore, the storage space merged with the bathroom, making the space larger, which increased the accessibility.

Variation D deepened variation B to improve indoor environment control (Table 5.1) and indoor comfort (Table 5.2), which also considered the situation of older adults having mobility or cognitive limitations in future ageing stages. The wall between the living room and bedroom was removed to simplify the space's complexity and improve visibility. This plan incorporated smart technology interactions (animations were used in the VR to show how the interaction would work), such as an automated lighting system that activates upon entry and deactivates upon exit, a smart system for people with dementia that uses projectors to display time and symbols on walls, reminding older adults to prepare meals (left picture in Fig. 5.9) and take medications (right picture in Fig. 5.9) [262], and a smart housekeeper with embedded sensors and switches control`s the ventilation and heating systems with which the real-time indoor temperature, relative humidity, air quality parameters, and outdoor weather is shown on the TV or tablets. Although creating these smart home scenarios increased the design complexity, it does not require additional operation during the VR experience. Participants just need to enter a space to activate the animation of the smart environment.



(A) The system guiding to prepare a meal (B) The system guiding to take medicine

Fig. 5.9 The animation of the smart system for older adults.

As a result, we designed four variations for each interviewee's apartment with detailed scenarios or animations. Meanwhile, each variation used the empathic design approach that adapted to individuals' different preferences and existing decoration styles. Twenty-seven VR scenarios were created: five original apartments and four variations of each apartment (25 total), one original entrance hall, and one renovated entrance hall.

5.3.3 VR Experimentation and Results

We employed a mixed method to collect and analyse the data from the VR experimentation (audio recording and logfile of the discussion during the experimentation) and participants' self-reporting (questionnaire). The results can be grouped into the following dimensions: a) the quality of the design and immersive environments, b) the evaluation of the design approach with VR application, and c) the experimentation experience.

The experimentation process lasted for a total time of 4.5 hours. The first 0.5 hours were devoted to introducing renovation design variations and a VR tutorial. Then, 3.5 hours were dedicated to experimentation and group discussion (Fig. 5.5). The average experimentation length of Group Residents was about 18 minutes, and Group Designers was about 24 minutes. Group Residents started by viewing the entrance hall and the individual's apartment. Group Designers selected one apartment to start the experience. Most participants selected two or three variations and viewed them using the VR headset (Table 5.3). In the end, participants completed the questionnaire and gave feedback within 0.5 hours.

Table 5.3 The scenarios experienced by participants.

Variation selected	Original Layout	Variation A	Variation B	Variation C	Variation D
Group Residents	5	2	3	3	2
Group Designers	5	3	4	3	5

The transcription of participants' discussion and questionnaire results show that the digital models created by the empathic design approach and presented by VR technologies have impacts on the experience:

1) Comfort of using VR: The comfort includes the comfort level with the VR devices and the experience with immersive environments. Based on the observation and participants' responses, all of them were relaxed and adapted to use the headset and controllers after the tutorial. They didn't report any discomfort from the VR experience. However, the time spent using VR varied between individuals, with Group Residents going through one or two scenarios needing a break, whilst most participants of Group Designers could use the VR device longer. Both groups chose to stop their experience process when they felt they were reaching their stamina and comfort thresholds.

'I'm fine with wearing the VR headset and don't feel dizzy yet. But I think it would be good to rest after viewing the scenario.'-one participant of Group Residents.

2) Easy to understand: All participants agreed that the design shown in the VR was more straightforward than the posters. The design can be easily understood when seeing the three-dimensional spaces, furniture, and ornaments. By switching the pre- and post-renovation scenarios, they compared the differences in spatial changes, added elements, and evaluated the designs. Following the empathic design approach, the variations of each apartment use the same furniture, ornament, textures, and individual decoration style that the participants of Group Residents can concentrate on the design level. Designers also better understood residents' living habits, room conditions, and design preferences through the process.

'VR as a means for demonstrating the renovation plan is an improvement and easier to understand than presenting by floorplans.'-one participant of Group Residents.

3) Easy to communicate: Except for one participant of Group Residents, the rest rated VR as more intuitive for illustrating renovation designs than architectural drawings. During the experimentation, a monitor linked to the VR device simultaneously showed what people saw in the headset. All the participants were involved in discussions about their opinions on renovation design. Meanwhile, researchers or designers made simple adjustments to models according to the discussion that can optimise the design on-site.

'Through the screen, seeing what the resident sees in VR is a different experience. The problem he is pointing out and describing in VR is clear for me to know where to improve. I also can explain timely when he misunderstood the design.'-one participant of Group Designers.

4) Scenario interactivity: In the immersive environment, the interactions include the elevator panel in the entrances, doors, and smart living environment animations. Group Designers showed more enthusiasm, hoping to make quick adjustments or decorate the existing arrangement, such as moving furniture, adding building components, or changing textures. Attitudes of Group Residents were slightly different. Most preferred interactivity in VR, such as interacting with more objects, whilst only one was resistant. In addition, although the experimentation was set in a sitting mode, participants intended to use the walking mode to explore more spaces and check the model details freely.

'The sitting mode is a restriction for me. I understand it is for my safety, but I am curious about some areas I cannot walk into and check more details. Now I have to imagine it. I think it would also be interesting if I could make some changes in the model myself.'-one participant of Group Residents.

5) Feeling empathy for customised design: Group Residents lived in the residential compound for over ten years and were sensitive to slight differences between real-world settings and the virtual environments, even recognised the bedroom wall colour being light grey rather than white. The participants agreed that the empathic design approach enhanced their sense of substitution and familiarity. The familiar settings allowed them to perceive the impact of the renovation on their living environment. However, some 'inaccurate' furniture details, textures, light environments, and shadows have been reported that influenced the immersion. Moreover, two designers familiar with the project also felt disturbed by the undulatory floor textures. Although these slight imperfections had little effect on the design illustration, they still influenced the VR experience.

'The empathic-designed environment is more understandable for me. I feel it more customised because I see my own things in the room.'-one participant of Group Residents.

6) Acceptance of technology/approach: VR and the empathic design approach have relatively higher acceptance in the two groups. Participants expressed the hope of continuing to use VR to evaluate empathetic designed scenarios in future project updates. They also had different concerns of disagreement. The main barrier for senior residents was the unfamiliarity with VR technology and operation. When discussing some scenarios, we found that senior residents were not easily pointed at the right objects because the controllers were hard to control. Designers thought that the empathic design approach needed to spend more time on the customisation of each household.

'I think the customised design is helpful for clients to understand the changes in renovation designs. But I'm not sure how long the modelling will take, such as making those antique wooden furniture, which looks important for the owner.'-one participant of Group Designers.

7) Overall satisfaction: Through the observation and questionnaire results, most participants were satisfied with the experimentation process. One senior resident rated VR as neutral and did not fully accept the VR technology. For many people, especially older adults, wearing VR devices, using controllers, and roaming in immersive virtual environments were still a burden for them. Although the digital model was made based on the reality of the existing buildings and apartments of the case study, there was still a gap between the experience effect and the real world due to the textures. Many issues, such as light environments, model details, rendering effects, and camera movement delay, were reported during the experimentation and were caused by hardware. In the end, Group Residents emphasised the importance of collaborative engagement in the activity room of the residential compound, which improved the satisfaction of the experimentation.

Table 5.4 The questionnaire results of two groups.

VR Experience	Group	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
Comfort of using VR	Residents	-	3	2	-	-
	Designers	-	4	1	-	-
Ease of understanding	Residents	1	4	-	-	-
	Designers	3	2	-	-	-
Ease of communicating	Residents	1	3	1	-	-
	Designers	2	3	-	-	-
Scenario interactivity	Residents	1	2	1	1	-
	Designers	2	3	-	-	-
Empathy of customised design	Residents	1	2	1	1	-
	Designers	-	3	-	2	-
Acceptance of technology/approach	Residents	1	3	-	1	-
	Designers	1	2	1	1	-
Overall satisfaction	Residents	2	2	1	-	-
	Designers	2	3	-	-	-

Table 5.4 shows the responses of two participant groups, including comfort, satisfaction, and questions based on TAM. In the experimentation process, we observed that participants devoted a large portion of time to discussing the model details. These were intertwined with intervals of comparing with reality during discussions (e.g. ‘Do you really have the treadmill in your room?’ and ‘This wooden horse in the model is smaller than mine in the real world.’). Senior residents had a strong empathy for their home models but a weaker empathy for the designs of their neighbours’ homes. In addition, although the existing hallway is narrow and dim, they insisted on preserving it due to the vernacular characteristics and living habits. Variation C was the favourite amongst Group Residents. They cared more about utilising indoor spaces because sealing the balcony provided more options for space usage according to weather and season. The sliding doors in variation C as ‘movable walls’ decreased the boundaries of rooms and provided flexible indoor layouts. In contrast, variation D of smart systems providing supportive living environments was welcomed by Group Designers. Different age groups considered the practical and economic renovation benefits that can be brought to the residents from different perspectives.

5.4 Lessons Learned from the VR Experimentation

In this chapter, we used mixed methods to collect and integrate data into the renovation design. Then, we invited stakeholders to experience the designs in VR for their feedback on satisfaction and acceptance of the empathic design approach demonstrated through VR. The communication recordings and questionnaires can be translated and elaborated to refine digital models of the practical project in an iterative design process. The findings underscore the importance of empathic design in enhancing user experiences in immersive environments. The observation and communication of the experimentation process were congruent with the TAM questionnaire responses, positing that the perceived ease of use significantly affects technology adoption [263]. The chapter corroborated and expanded upon the findings of those who demonstrated the positive impact of engaging senior users' empathy in familiar environments [38,264]. Crucially, we further illustrated that such familiarity and empathy not only bolster engagement but also cultivate trust in emerging technologies like VR, an essential factor for their acceptance and incorporation into everyday life. Furthermore, the findings indicate that VR applications intended for this demographic should emphasise ease of use, gradual familiarisation, and instinctive manoeuvrability, thereby underscoring the principles proposed by Norman [265]. Moreover, three pivotal factors are suggested to be taken into account to augment VR experiences for older adults:

- **Familiar environments:** As creating familiar virtual environments of empathic design, conducting experiments within environments familiar to participants also bolsters receptivity and mitigates technological anxiety [233]. This understanding is supported by Zhao et al. [266], who discerned that environmental familiarity and group participation in VR contexts could yield positive outcomes and cultivate a supportive atmosphere for older users. Moreover, it is observed that positioning VR experiments within the familiar boundaries of the participants' own living spaces significantly increases their trust in the experimental process, especially for those experiencing VR technologies for the first time. It is emphasised that the selection of recognisable settings plays a crucial role in boosting participants' confidence, thus enabling their participation in the VR experiment from a stance of heightened openness.
- **Familiar participants:** Compared to individual tests, incorporating grouped older adults into VR experimentation has shown the potential to enhance participation degree and confidence [267]. The findings show that older adults with friends or neighbours in group settings cultivate a supportive atmosphere that mitigates technology-related apprehension. The empathic design could reinforce

familiarity and relaxation because they have empathy in their shared living environment, facilitating communication and improving the efficacy of the experimentation process.

- **Familiar communication ways:** The findings indicate that communication between designers and residents during the VR experience effectively facilitates the project. We found that participants preferred speaking rather than textual communication. They chose to communicate in familiar ways, such as using the local language. These familiarities are vital for the empathic designed environment and VR experiences, and the perception of the surrounding presence, the subtleties of the environmental changes, and the characteristics of the VR devices also influence the zeal for communication [236].

The inclusion of older adults in studies of virtual environments has been a challenge. Some of them had difficulty with using innovative technologies. Consequently, there is a lack of knowledge regarding the potential of immersive and engaging virtual technologies to enhance older adults' lives [268]. The current research method has some limitations. Most residents reside in apartments with similar layouts, and a standardised design approach disregarding individual preferences in texture, furniture, and decoration could result in a lack of empathy and a diversion of attention. We designed and modelled according to each senior resident through empathic design, but it does not cause empathy for others. We observed that Group Residents focused on the renovation scenarios for their homes and emphasised personal needs and spatial arrangements. In contrast, Group Designers exhibited a greater concern for specific furniture and textures, thereby overlooking the essence of the design because the models and scenarios were not specifically designed for them. Despite being instructed that the dimensions and location of items within the VR were based on the current settings of the apartments, the participants still spent significant time exploring the realism of the floor plan scale and the size of furniture items in the context of scenarios. They deemed this important because they believed the empathic design for immersive environments would hold little value to either party without correct scales and sizes [269]. Moreover, adding certain items of furniture or equipment (e.g., treadmills) was considered a part of privacy, whereas incorporating indoor plants and green spaces gave them a feeling of relaxation [270]. Customised modelling and variations of renovation design need to entail a significant investment of time in the renovation design process to consider each senior resident's actual circumstances appropriately, which is the main reason for the limited number of participants involved in this chapter. The empathic design approach could provide better design quality and communication effectiveness whilst being time-consuming and suitable for fewer clients. Thus, there is an urgent requirement for a methodology that effectively merges spatial renovation with individual preferences, facilitating the rapid empathic design process.

The advancement of VR technologies, such as supporting real-time design between designers and clients within interactive models, could provide innovative methods for architectural design and practical projects. The scale, texture, accuracy, and rendering of interactive digital models are often constrained by the limitations of the hardware, which also influences the software selection and application. Ideally, the liberty afforded by virtual environments for creative exploration enables more efficient design or research processes [271]. VR contributes to the communication between designers and older adults and can evaluate design concepts at early stages, minimising rework and quickly relaying changes to clients [244]. The quality of the design communication and data interaction through VR was deemed satisfactory, especially in a relatively complex environment [272]. The user experience was reported as enjoyable and met with approval from all participants. However, this chapter has many variables and involves empathy, aesthetics, and personal subjective preferences. There is a lack of scientific data collection and analysis methods, such as measuring spatial preferences by analysing participants' electroencephalogram data [242]. Therefore, more future research is needed to establish a quantitative study of experience in complex VR environments.

5.5 Conclusion

This chapter provides a preliminary exploration of the empathic design approach using VR for a social housing renovation project. Drawing on responses from ten participants involved in the project, they had relatively similar perspectives and focused on the variations of renovation design and VR experiences. Immersive scenarios helped stakeholders understand spatial changes, living environment improvements, and technology implementation. The insights of designers and senior residents can be used as a reference for applying VR to ageing groups:

- **Duration management:** Considering older users' cognitive and physical capacities is imperative in determining the optimal duration for VR engagement. We noticed a relative engagement threshold, typically around 10 minutes each time for wearing the VR headset. Exceeding this may result in fatigue or discomfort. Such time limitations are crucial to preserving the attentiveness and comfort of older adults, avoiding overstimulation and enhancing the overall VR experience.

- **Mode selection:** In designing VR scenarios for older adults, it is essential to prioritise comfort and gradual acclimatisation to the virtual environment. While ambulatory modes might deepen immersion and navigational skills, it is recommended that older users engage in seated navigation to ensure a secure and focused experience. This measure is intended to diminish the risk of disorientation and discomfort.
- **Preparatory session:** It is advisable to conduct a brief, comprehensive orientation before older adults engage with VR, preparing them adequately for the experience. The introduction of VR scenarios should begin with a familiar, pleasant, and simple immersive environment, which facilitates a smooth transition from the real to the virtual world. Besides, for complex scenarios, other materials, such as posters, are helpful for older users to prepare what they will view in the virtual environment, enhancing participant readiness and confidence.
- **Empathic design:** Adopting an empathic design approach is crucial as VR technology progresses and virtual environments become increasingly realistic. This approach involves creating familiar, relatable settings within digital models, allowing users to concentrate on the design level rather than being distracted by vast, unfamiliar elements. Although empathic design demands more significant consideration of individual needs and more extensive time investment, it has the potential to yield valuable feedback in the design process.

Incorporating these considerations is paramount in developing VR experiences for older adults. By emphasising empathic design and communication in the design process, VR can foster collaboration and understanding between designers and clients. Future research is suggested to validate the integration of innovative technologies with empathic design in various case studies to improve the housing renovation process and quality.

Chapter 6
Conclusions and Recommendations

6.1 Research Statement

This PhD research explores and validates the approach to integrating smart technologies into home environments for ageing well within the context of the increasing ageing population and age-friendly housing shortage in the Netherlands. The research is conducted from multiple perspectives, including technology applications, indoor environmental quality, changed behaviour, and architectural design. The mixed-methods data collection and analysis show holistic experience in improving home environments for older adults, particularly in nursing homes and social housing.

Different data types were collected and analysed from previous literature and case studies. The knowledge of applying smart technologies in home environments from existing literature was systematically collected from various databases, such as Scopus, Web of Science, Engineer Village, Google Scholar, and Crossref, to define the state-of-the-art and compare the findings. Indoor environmental parameters (temperature, humidity, carbon dioxide, total volatile organic compound, formaldehyde, particulate matter, and illuminance) were monitored by sensors. The residents' demographic information, comfort, daily routines, and behaviours were collected quantitatively with questionnaires (proxies' responses of care professionals and residents' guardians), observations, and nursing reports. The building facility management, residents' daily activities, and requirements were collected through semi-structured interviews. Building characteristics were collected with checklists, field surveys, drawings of the buildings, and photographs. All these data were utilised to map the essential elements for healthy ageing environments, including technology applications and interactions between human factors, indoor environmental factors, and behavioural factors. From case studies and practical projects, these factors were studied consecutively from the perspectives of the designer, caregiver, and older adults. The collected data was analysed using various techniques corresponding to the sub-questions, including descriptive statistics, Fisher's exact tests, narrative analysis, and descriptive analysis. A complete and in-depth understanding of home renovation on a broad range of different types of variables.

This chapter presents the conclusions and recommendations derived from the thesis. Firstly, the sub-questions are answered, followed by the answer to the main question. Then, the limitations of this research are discussed, and finally, the recommendations for future research are presented.

6.2 Overview of the Research Questions and Contributions

This thesis is elaborated into four sub-research questions. Discussed below are the brief responses to the four sub-questions, which are also refined as four interconnected strands representing the main contributions of the PhD research. Next, research findings are discussed to answer the main question: How can smart technologies be integrated into home settings to enhance older adults' living qualities?

6.2.1 Sub-question (Chapter 2)

- **How are state-of-the-art design strategies and technologies used in smart home studies and projects to support older adults ageing-in-place?**

This chapter summarised the state-of-the-art design strategies and technologies used in home renovation for ageing-in-place, illustrating the technology application scenario in home settings. Identifying possible knowledge gaps in the relative research projects is essential. Therefore, a systematic literature review based on 33 of 2594 articles presents three perspectives: the framework of the smart home environment for ageing-in-place, the home modification process, and problems and countermeasures of independent living.

Creating age-friendly home environments involves conventional modifications (e.g. walk-in showers) for safety and technology implementation (e.g. fall detection sensors embedded in housing structures). Assistive technologies, from low-tech gadgets to home automation, aid older adults in independent living. Information and Communication Technology facilitates interactive management of assistive technology, including e-health and telecare. Ambient assisted living, a subset of ambient intelligence, integrates Information and Communication Technology and sensors for older adults' needs. The Internet of Things transforms physical components into smart ones, linking older adults, their environments, and health information. Smart homes with sensors and actuators monitor inhabitants' living environments to enhance their living experience. Intelligence is crucial in smart homes, advancing from data processing to intelligent interaction.

The home renovation process for senior households integrates technologies with physical adjustments. The process typically follows four phases: home assessment, technology selection, design strategy, and user evaluation. Home assessment tools range from traditional checklists to advanced virtual reality technologies, focusing on identifying hazards and user requirements. Technology selection considers older adults' diverse needs and preferences as well as technology acceptance, usability, and compatibility of their home structures. Design strategies are provided by current research on how to design or install smart technologies or systems according to various housing conditions. User evaluation validates renovation effectiveness and guides future practices, often utilising frameworks of existing acceptance models and evaluation tools. Challenges include standardising smart technology interoperability and ensuring user-centred design. Despite limitations, these approaches offer valuable insights into creating age-friendly environments.

Hazards in domestic environments need to be addressed, particularly related to falls and accessibility. Existing research predominantly focuses on fall prevention and the technical accessibility of devices while neglecting the growing need to address the physical accessibility and mobility challenges of older adults. Technologies like virtual reality for personalised accessibility assessments and simulating technology application scenarios can assist in the design process. Addressing hazards and enhancing accessibility is vital for supporting older adults' independence and safety in their homes.

6.2.2 Sub-question (Chapters 3 and 4)

To find how indoor environmental and contextual factors affect older adults' comfort, activities, and behaviours, case studies were conducted in a Dutch nursing home from 2020 to 2022. Environmental sensors were deployed in the central living rooms and participants' bedrooms to monitor indoor environmental parameters. In Chapter 3, the building characteristics were collected through drawings, building inspection, and a semi-structured interview with the nursing home manager. The perceptions of nursing home residents were collected from an online questionnaire poxily answered by 39 care professionals and residents' guardians. The questionnaire included demographic information, indoor comfort, satisfaction with indoor environmental quality, and environmental control. Chapter 4 investigated the influences of indoor environmental and contextual factors on when, where, and how the changed behaviours occurred. Ten participants' behaviours, activities, and room conditions were observed and analysed. This chapter explored, translated, and elaborated the triadic reciprocal causation model (human, behaviour, and environment) by sensors [50].

- **How can sensor technologies be applied to collect environmental data and information on older adults' comfort, activities, and living conditions?**

Chapter 3 explores the method of using sensors to assist in ageing care by analysing indoor environmental quality in a Dutch nursing home. Integrating sensor data with caregiver feedback assesses residents' comfort, highlighting disparities in indoor environmental parameters among residents with varying degrees of dementia severity. Building design, facility management, and heating influence indoor environmental quality and residents' well-being. Indoor air quality, particularly carbon dioxide, total volatile organic compounds, and particulate matter, are noted, with implications for residents' respiratory health. Additionally, indoor relative humidity poses challenges, with dry environments prevailing during the heating season, potentially exacerbating respiratory symptoms. Thermal comfort and lighting are also crucial, with residents preferring warmer temperatures in winter and adequate lighting to mitigate mood disturbances. Sensor placement and maintenance present challenges, necessitating non-intrusive monitoring technologies for accurate data collection. This chapter underscores the importance of understanding residents' living conditions, suggests personalised interventions based on indoor environmental data, and offers knowledge of care facility management.

- **How do indoor environmental and contextual factors influence the behavioural changes of older adults?**

Chapter 4 examines the influence of indoor environmental and contextual factors on changed behaviours (wandering, hallucination, and agitation) of people with dementia in the nursing home. Data on changed behaviour (the types, timeslots, and locations) were collected and analysed alongside indoor environmental conditions and participants' activities through fly-on-the-wall observation. The heatmap charts were made to show conditions of changed behaviour exhibited with the building layout and spatial characteristics. Although the nursing home boasted high-quality construction and maintenance, indoor environmental parameters (temperature, total volatile organic compound, and formaldehyde) correlated with changed behaviours. Additionally, factors such as clothing levels, the presence of other residents, and ongoing activities influenced behavioural changes. The findings suggest that spatial layout plays a significant role in residents' daily activities and living environments. Recommendations for nursing home design include increasing visibility in indoor spaces and avoiding corner spaces in common areas to prevent overlooked spaces where changed behaviours might occur. It is essential to understand the impact of variable indoor environments on behavioural changes amongst people with dementia, with potential implications for improving living quality and care strategies in nursing homes.

6.2.3 Sub-question (Chapter 5)

- **How can innovative technologies and design approaches be used in the housing renovation design process to meet the requirements of older adults for healthy ageing?**

Chapter 5 elaborates and validates the application of innovative technologies in the social housing renovation design process, mainly focusing on enhancing user experiences for older adults through empathic design and virtual reality. The findings emphasise the importance of providing familiar and immersive environments for older users and extend previous research by emphasising empathy feeling and group engagement to cultivate trust and reduce technological anxiety among them. Simplicity in interaction modalities, user-centred design principles, and customisable design are suggested. Moreover, familiarity with the environments, participants, and ways of communicating in the design process is highlighted. This chapter facilitates technology adoption among older adults by addressing these considerations, ultimately contributing to a more effective and age-friendly approach to improve design processes and fostering senior residents' participation, understanding, and acceptance of home renovation.

6.3 Answer to the Main Research Question

- **How can smart technologies be integrated into home settings to enhance older adults' living qualities?**

Integrating smart technologies into (nursing) home settings holds immense potential for enhancing the living qualities of older adults and supporting healthy ageing. By leveraging state-of-the-art design strategies and smart technologies, customisable solutions can be developed to address older adults' specific needs and preferences. These solutions encompass a range of technological interventions, from traditional modifications to smart technology applications. Additionally, insights from studies examining indoor environments in a Dutch nursing home shed light on the complex interactions between environmental factors, indoor comfort, and behaviour changes, providing guidance for crafting age-friendly environments.

The study into the application of the empathic design framework and virtual reality for the social housing renovation project shows user-centred importance. The communication between older adults and designers during the design process is crucial for the design process and facilitating technology acceptance.

In conclusion, integrating smart technologies into home settings requires a holistic approach that considers not only technological solutions but also the physical environment, indoor environmental quality, residents' comfort, living habits, and preferences. Addressing these considerations makes it possible to create supportive environments for ageing well and enhance older adults' living qualities.

6.4 Limitations

This PhD research focuses on crafting healthy home environments for older adults, from the design concept to the practical project. However, the effects of design strategies and technology implementations are still under development. Several limitations remain in gaining more comprehensive insights.

The scope of this research is limited to simple home settings, which only partially represent the diversity of building types and complex technology applications. The domain of smart home design and renovation is nascent and interdisciplinary. Its development needs more research and experimentation to provide scientific evidence. The limited literature is from different research fields, and the application stages and target groups of smart technologies are also very diverse, so there is a lack of systematic methods and guidelines. Furthermore, a growing number of innovative technology terms have emerged in recent years, which cannot be fully included in this research. A basic design framework for smart home renovation is delineated in this research, encompassing the knowledge of technology applications in a nursing home and social housing renovation project. However, the validation of this framework requires further empirical validation and practical implementation.

The case studies of Chapters 3 and 4 were conducted during the COVID pandemic and encountered many challenges, including sample scale, absence of direct feedback from people with dementia, and non-concurrent data collection. To address these issues, care professionals and residents' guardians proxy answered questionnaires for nursing home residents. Responses revealed discrepancies between groups, such as contrasting satisfaction levels reported by guardians and care professionals. The accuracy of feedback from guardians, particularly regarding people with dementia, was compromised by potential communication challenges. Limited participants and sampling sites could hardly be assessed quantitatively and did not allow for more general conclusions to be drawn. In Chapter 4, observations at night were not permitted, and data on sleep disturbance and restlessness recorded in the nurse report was not collected. Protecting residents' privacy is important when using the observation method, and assistance from care professionals is usually needed.

In the practical phase, research method limitations still exist in the design process, particularly regarding differing preferences between senior residents and designers. In the empathic designed virtual environment, the residents prioritise personal needs and spatial arrangements, whilst designers could be distracted by specific furniture and textures, overlooking essential design elements. Traditional design approaches may neglect individual preferences, leading to a lack of empathy and diverting attention.

Customisable designs that are unique to individuals require significant time investment, limiting the size of participants. Moreover, the scenarios presented by virtual reality offer creative exploration opportunities, but software limitations influence their realism on detail rendering. Virtual reality can enhance the design process by providing more intuitive solutions and eliciting valuable input from participants. However, there needs to be more reference in quantifying the effects of complex immersive environments, particularly concerning empathy, aesthetics, and subjective preferences.

6.5 Recommendations for Future Research

The application of smart technologies in domestic environments is increasing, but the device operations and interactions with users, especially older adults, are much more complex in actual living scenarios. To better enhance the effectiveness of smart technology implementation in senior households, it is necessary to focus on user-centred design approaches. This includes creating customised, empathic, and more realistic scenarios, considering individual and environmental factors, and applying appropriate design strategies and technologies for specific use scenarios. By continuously optimising and deepening these approaches, the feasibility and effectiveness of smart homes can be better used and verified in real life. Therefore, further research can focus on smart technology standardisation, user-centred design, and data usage.

6.5.1 Smart Technology Standardisation

Currently, the incompatibility between smart technologies, building structures, and system platforms is hindering its application and promotion. To ensure smart technology can be widely used in home environments, it is necessary to establish standards, such as the standardisation of the devices, standardisation of data formats, compatibility with platforms and building components, consistency of installation process, and consideration of the collaboration between product models and building models (e.g. Building Information Model). Only by establishing a unified standard can the development and application of smart technology be better promoted, which is also beneficial for designers and users.

6.5.2 User-centred Design

User-centred design is essential in design studies, and further investigation is still needed to explore more efficient methods. Combining emerging technologies such as augmented reality, virtual reality, and artificial intelligence could contribute to the collaboration between designers, researchers, and older adults on home renovation design. Furthermore, machine learning can be utilised to understand users' requirements based on their data and assist designers with complex projects.

6.5.3 Data usage

Many existing studies and projects deploy smart technologies in (nursing) home environments, and it's essential to delve into how data, particularly environmental and health data collected by these technologies, can offer valuable insights into their lives. On the one hand, these technologies can track older adults' activities like movement patterns, indoor environmental parameter variations, or even changes in energy consumption, providing clues about their daily routines, health conditions, and overall well-being. Caregivers can use the data to understand their habits, detect deviations from their usual behaviour, which might indicate health issues or emergencies, and adjust their caregiving approach accordingly. On the other hand, technology usage should address the technical aspects of data storage and security. As more personal data is collected through technology devices, it becomes paramount to ensure its safe storage and protection from unauthorised access. This involves exploring encryption methods, powerful authentication mechanisms, and secure data storage protocols to safeguard sensitive information. By addressing these technical challenges, trust can be built among older adults, their caregivers, and technology developers, encouraging wider adoption of smart technology solutions and promoting better care outcomes.

References

[1] WHO, The Global strategy and action plan on ageing and health 2016–2020: towards a world in which everyone can live a long and healthy life, World Heal. Assem. 73. 20 (2020) 1–24.

[2] S. Long, C. Benoist, W. Weidner, World Alzheimer Report 2023, (2023).

[3] Ministry of Health Welfare and Sport, National Dementia Strategy 2021 - 2030, (2020).

[4] K.K.B. Peetoom, M.A.S. Lexis, M. Joore, C.D. Dirksen, L.P. De Witte, Literature review on monitoring technologies and their outcomes in independently living elderly people, Disabil. Rehabil. Assist. Technol. 10 (2015) 271–294. https://doi.org/10.3109/17483107.2014.961179.

[5] United Nations, World Population Ageing 2019: Highlights, 2019. https://doi.org/10.5860/choice.40-1307.

[6] R.J.J. Gobbens, M.A.L.M. Van Assen, Associations of Environmental Factors with Quality of Life in Older Adults, Gerontologist. 58 (2018) 101–110. https://doi.org/10.1093/geront/gnx051.

[7] D. Verbeek-Oudijk, I. Koper, Summary - Life in a nursing home, (2019). https://repository.scp.nl/handle/publications/60.

[8] M. de Klerk, D. Verbeek-Oudijk, I. Plaisier, M. den Draak, Zorgen voor thuiswonende ouderen, (2019) 103.

[9] G. Marquardt, D. Johnston, B.S. Black, A. Morrison, A. Rosenblat, C.G. Lyketsos, Q.M. Samus, A descriptive study of home modifications for people with dementia and barriers to implementation, J. Hous. Elderly. 25 (2011) 258–273. https://doi.org/10.1080/02763893.2011.595612.

[10] M. Mohammadi, Automated assisted homes for the elderly, I-CREATe 2008 - Int. Conv. Rehabil. Eng. Assist. Technol. 2008. (2008) 266–270.

[11] M. Chabot, L. Delaware, S. McCarley, C. Little, A. Nye, E. Anderson, Living In Place: the Impact of Smart Technology, Curr. Geriatr. Reports. (2019). https://doi.org/10.1007/s13670-019-00296-4.

[12] N. Labonnote, K. Høyland, Smart home technologies that support independent living : challenges and opportunities for the building industry – a systematic mapping study, 8975 (2017). https://doi.org/10.1080/17508975.2015.1048767.

[13] M.E. Morris, B. Adair, E. Ozanne, W. Kurowski, K.J. Miller, A.J. Pearce, N. Santamaria, M. Long, C. Ventura, C.M. Said, Smart technologies to enhance social connectedness in older people who live at home, Australas. J. Ageing. 33 (2014) 142–152. https://doi.org/10.1111/ajag.12154.

[14] Y. Lu, C. Valk, J. Steenbakkers, T. Bekker, T. Visser, G. Proctor, O. Toshniwal, H. Langberg, Can technology adoption for older adults be co-created?, Gerontechnology. 16 (2017) 151–159. https://doi.org/10.4017/gt.2017.16.3.004.00.

[15] D. Marikyan, S. Papagiannidis, E. Alamanos, A systematic review of the smart home literature: A user perspective, Technol. Forecast. Soc. Change. 138 (2019) 139–154. https://doi.org/10.1016/j.techfore.2018.08.015.

[16] K. Bouchard, B. Bouchard, A. Bouzouane, Practical Guidelines to Build Smart Homes : Lessons Learned, (2014) 1–38.

[17] S.E.L. Jaouhari, E.J. Palacios-Garcia, A. Anvari-Moghaddam, A. Bouabdallah, Integrated management of energy, wellbeing and health in the next generation of smart homes, Sensors (Switzerland). 19 (2019) 1–24. https://doi.org/10.3390/s19030481.

[18] M. Mohammadi, DomoticaKompas Inzichten uit een decennium slimme zorgprojecten in Nederland, 2014.

[19] J.K.W. Wong, J. Leung, M. Skitmore, L. Buys, Technical requirements of age-friendly smart home technologies in high-rise residential buildings: A system intelligence analytical approach, Autom. Constr. 73 (2017) 12–19. https://doi.org/10.1016/j.autcon.2016.10.007.

[20] J. Pynoos, B.A. Steinman, A.Q.D. Nguyen, Environmental Assessment and Modification as Fall-Prevention Strategies for Older Adults, Physiol. Behav. (2010). https://doi.org/10.1016/j.physbeh.2017.03.040.

[21] S. Iwarsson, Housing Adaptations and Home Modifications, 2015. https://doi.org/10.1007/978-3-319-08141-0.

[22] D. Ding, R.A. Cooper, P.F. Pasquina, L. Fici-pasquina, Maturitas Sensor technology for smart homes, Maturitas. 69 (2011) 131–136. https://doi.org/10.1016/j.maturitas.2011.03.016.

[23] G. Dewsbury, M. Rouncefield, K. Clarke, I. Sommerville, Depending on digital design: Extending inclusivity, Hous. Stud. 19 (2004) 811–825. https://doi.org/10.1080/0267303042000249224.

[24] F. Tartarini, P. Cooper, R. Fleming, M. Batterham, Indoor Air Temperature and Agitation of Nursing Home Residents with Dementia, Am. J. Alzheimers. Dis. Other Demen. 32 (2017) 272–281. https://doi.org/10.1177/1533317517704898.

[25] R. Woodbridge, M.P. Sullivan, E. Harding, S. Crutch, K.J. Gilhooly, M.L.M. Gilhooly, A. McIntyre, L. Wilson, Use of the physical environment to support everyday activities for people with dementia: A systematic review, Dementia. 17 (2018) 533–572. https://doi.org/10.1177/1471301216648670.

[26] M.J. Rodrigues, O. Postolache, F. Cercas, Physiological and behavior monitoring systems for smart healthcare environments: A review, Sensors (Switzerland). 20 (2020) 1–26. https://doi.org/10.3390/s20082186.

[27] J.K.W. Wong, M. Skitmore, L. Buys, K. Wang, The effects of the indoor environment of residential care homes on dementia suffers in Hong Kong: A critical incident technique approach, Build. Environ. 73 (2014) 32–39. https://doi.org/10.1016/j.buildenv.2013.12.001.

[28] A.J. Astell, N. Bouranis, J. Hoey, A. Lindauer, A. Mihailidis, C. Nugent, J.M. Robillard, Technology and Dementia: The Future is Now, Dement. Geriatr. Cogn. Disord. 47 (2019) 131–139. https://doi.org/10.1159/000497800.

[29] A. Grave, S. Robben, M. Oey, S. Ben Allouch, M. Mohammadi, Requirement Elicitation and Prototype Development of an Intelligent Environment to Support People with Early Dementia, 2021 17th Int. Conf. Intell. Environ. IE 2021 - Proc. (2021) 1–8. https://doi.org/10.1109/IE51775.2021.9486462.

[30] O. Guerra Santin, A. Grave, S. Jiang, C. Tweed, M. Mohammadi, Monitoring the performance of a Passivhaus care home: Lessons for user-centric design, J. Build. Eng. 43 (2021). https://doi.org/10.1016/j.jobe.2021.102565.

[31] A. Bankole, M.S. Anderson, N. Homdee, R. Alam, A. Lofton, N. Fyffe, H. Goins, T. Newbold, T. Smith-Jackson, J. Lach, BESI: Behavioral and Environmental Sensing and Intervention for Dementia Caregiver Empowerment—Phases 1 and 2, Am. J. Alzheimers. Dis. Other Demen. 35 (2020) 1–15. https://doi.org/10.1177/1533317520906686.

[32] F. Tartarini, P. Cooper, R. Fleming, Thermal perceptions, preferences and adaptive behaviours of occupants of nursing homes, Build. Environ. 132 (2018) 57–69. https://doi.org/10.1016/j.buildenv.2018.01.018.

[33] J. Yu, M.T. Hassan, Y. Bai, N. An, V.W.Y. Tam, A pilot study monitoring the thermal comfort of the elderly living in nursing homes in Hefei, China, using wireless sensor networks, site measurements and a survey, Indoor Built Environ. 29 (2020) 449–464. https://doi.org/10.1177/1420326X19891225.

[34] H. Zhan, J. Yu, R. Yu, Assessment of older adults' acceptance of IEQ in nursing homes using both subjective and objective methods, Build. Environ. 203 (2021) 108063. https://doi.org/10.1016/j.buildenv.2021.108063.

[35] P. Thomas, F. Aletta, K. Filipan, T. Vander Mynsbrugge, L. De Geetere, A. Dijckmans, D. Botteldooren, M. Petrovic, D. Van de Velde, P. De Vriendt, P. Devos, Noise environments in nursing homes: An overview of the literature and a case study in Flanders with quantitative and qualitative methods, Appl. Acoust. 159 (2020) 1–33. https://doi.org/10.1016/j.apacoust.2019.107103.

[36] K. Vlot-Van Anrooij, J. Naaldenberg, T.I.M. Hilgenkamp, L. Vaandrager, K. Van Der Velden, G.L. Leusink, Towards healthy settings for people with intellectual disabilities, Health Promot. Int. 35 (2020) 661–670. https://doi.org/10.1093/heapro/daz054.

[37] E. Allameh, M. Heidari, Smart Homes From Vision To Reality : Eliciting Users ' Preferences of Smart Homes By a Virtual Experimental Method, (2013).

[38] L.P.G. van Buuren, O. Guerra-Santin, M. Mohammadi, Evaluating Three Validation-Methods for an Architectural Intervention for Seniors with Dementia in the Empathic Design Framework, a Case Study, 2019. https://doi.org/10.1007/978-3-030-33540-3.

[39] E. Lach, I. Benek, K. Zalewski, P. Skurowski, A. Kocur, A. Kotula, M. Macura, Z. Pamuła, M. Stankiewicz, T. Wyrobek, Immersive Virtual Reality for

Assisting in Inclusive Architectural Design, Adv. Intell. Syst. Comput. 1061 (2020) 23–33. https://doi.org/10.1007/978-3-030-31964-9_3.

[40] A. Almusaed, I. Yitmen, Architectural Reply for Smart Building Design Concepts Based on Artificial Intelligence Simulation Models and Digital Twins, Sustain. 15 (2023). https://doi.org/10.3390/su15064955.

[41] B. Tekinerdogan, C. Verdouw, Systems architecture design pattern catalog for developing digital twins, Sensors (Switzerland). 20 (2020) 1–20. https://doi.org/10.3390/s20185103.

[42] S.H. Khajavi, N.H. Motlagh, A. Jaribion, L.C. Werner, J. Holmstrom, Digital Twin: Vision, benefits, boundaries, and creation for buildings, IEEE Access. 7 (2019) 147406–147419. https://doi.org/10.1109/ACCESS.2019.2946515.

[43] S. Kalantari, S. Pourjabar, T.B. Xu, J. Kan, Developing and user-testing a "Digital Twins" prototyping tool for architectural design, Autom. Constr. 135 (2022) 104140. https://doi.org/10.1016/j.autcon.2022.104140.

[44] T. Tannou, T. Lihoreau, M. Gagnon-Roy, M. Grondin, N. Bier, Effectiveness of smart living environments to support older adults to age in place in their community: An umbrella review protocol, BMJ Open. 12 (2022) 1–6. https://doi.org/10.1136/bmjopen-2021-054235.

[45] A. Lotfi, C. Langensiepen, S.M. Mahmoud, M.J. Akhlaghinia, Smart homes for the elderly dementia sufferers: Identification and prediction of abnormal behaviour, J. Ambient Intell. Humaniz. Comput. 3 (2012) 205–218. https://doi.org/10.1007/s12652-010-0043-x.

[46] S. Ahrentzen, E. Tural, The role of building design and interiors in ageing actively at home, Build. Res. Inf. 43 (2015) 582–601. https://doi.org/10.1080/09613218.2015.1056336.

[47] J. Durick, Linda Leung, Designing Augmented, Domestic Environments to Support Ageing in Place, 2018. https://doi.org/10.1007/978-981-10-6404-3.

[48] T. Mattelmäki, K. Vaajakallio, I. Koskinen, What Happened to Empathic Design?, Des. Issues. 30 (2014) 67–77. https://doi.org/10.1162/DESI_a_00249.

[49] J. Van Houwelingen-Snippe, S. Ben Allouch, T.J.L. Van Rompay, Virtual Reality Representations of Nature to Improve Well-Being amongst Older Adults: a Rapid Review, J. Technol. Behav. Sci. 6 (2021) 464–485. https://doi.org/10.1007/s41347-021-00195-6.

[50] A. Bandura, Social Cognitive Theory of Mass Communication, Media Psychol. 3 (2001) 265–299. https://doi.org/10.1207/S1532785XMEP0303_03.

[51] J. Zeisel, Observing Environmental Behavior-- in Inquiry by design: tools for environment- behavior research / J. Zeisel., (2016) Chaper 8.

[52] OECD, The Netherlands Highlights from A Good Life in Old Age? Monitoring and Improving Quality in Long-Term Care, OECD Publishing, 2013, (2013). https://www.oecd.org/els/health-systems/Netherlands-OECD-EC-Good-Time-in-Old-Age.pdf.

[53] K. Leidelmeijer, Monitor Investeren in de toekomst, (2017). www.rigo.nl.

[54] M. Braubach, A. Power, Housing conditions and risk: Reporting on a European study of housing quality and risk of accidents for older people, J. Hous. Elderly. 25 (2011) 288–305. https://doi.org/10.1080/02763893.2011.595615.

[55] J. Kwok, W. Wong, J.K.L. Leung, Modelling factors influencing the adoption of smart-home technologies, (2016). https://doi.org/10.1108/F-05-2016-0048.

[56] P. Udupa, S.S. Yellampalli, Smart home for elder care using wireless sensor, Circuit World. 44 (2018) 69–77. https://doi.org/10.1108/CW-12-2017-0072.

[57] L. Liu, E. Stroulia, I. Nikolaidis, A. Miguel-Cruz, A. Rios Rincon, Smart homes and home health monitoring technologies for older adults: A systematic review, Int. J. Med. Inform. 91 (2016) 44–59. https://doi.org/10.1016/j.ijmedinf.2016.04.007.

[58] B. Reeder, E. Meyer, A. Lazar, S. Chaudhuri, H.J. Thompson, G. Demiris, Framing the evidence for health smart homes and home-based consumer health technologies as a public health intervention for independent aging: A systematic review, Int. J. Med. Inform. 82 (2013) 565–579. https://doi.org/10.1016/j.ijmedinf.2013.03.007.

[59] S.-Y. Rieh, Post-occupancy evaluation of urban public housing in Korea: Focus on experience of elderly females in the ageing society, Indoor Built Environ. 29 (2018). https://doi.org/10.1177/1420326X18782578..

[60] P. Carnemolla, C. Bridge, A scoping review of home modification interventions – Mapping the evidence base, Indoor Built Environ. 29 (2020) 299–310. https://doi.org/10.1177/1420326X18761112.

[61] E.M. Agree, The potential for technology to enhance independence for those aging with a disability, Disabil. Health J. 7 (2014) S33–S39. https://doi.org/10.1016/j.dhjo.2013.09.004.

[62] L.N. Lee, M.J. Kim, A Critical Review of Smart Residential Environments for Older Adults With a Focus on Pleasurable Experience, Front. Psychol. 10 (2020) 1–15. https://doi.org/10.3389/fpsyg.2019.03080.

[63] D. Pal, T. Triyason, S. Funikul, Smart Homes and Quality of Life for the Elderly: A Systematic Review, Proc. - 2017 IEEE Int. Symp. Multimedia, ISM 2017. 2017-Janua (2017) 413–419. https://doi.org/10.1109/ISM.2017.83.

[64] J. Rafferty, C.D. Nugent, J. Liu, L. Chen, From Activity Recognition to Intention Recognition for Assisted Living Within Smart Homes, IEEE Trans. Human-Machine Syst. 47 (2017) 368–379. https://doi.org/10.1109/THMS.2016.2641388.

[65] Q. Lê, H.B. Nguyen, T. Barnett, Smart Homes for Older People: Positive Aging in a Digital World, Futur. Internet. 4 (2012) 607–617. https://doi.org/10.3390/fi4020607.

[66] Q. Ni, A.B.G. Hernando, I.P. de la Cruz, The elderly's independent living in smart homes: A characterization of activities and sensing infrastructure survey to facilitate services development, 2015. https://doi.org/10.3390/s150511312.

[67] M.Z. Uddin, W. Khaksar, J. Torresen, Ambient sensors for elderly care and independent living: A survey, Sensors (Switzerland). 18 (2018) 1–31. https://doi.org/10.3390/s18072027.

[68] P. Visutsak, M. Daoudi, The smart home for the elderly: Perceptions, technologies and psychological accessibilities: The requirements analysis for the elderly in Thailand, ICAT 2017 - 26th Int. Conf. Information, Commun. Autom. Technol. Proc. 2017-Decem (2017) 1–6. https://doi.org/10.1109/ICAT.2017.8171625.

[69] G. Gibson, C. Dickinson, K. Brittain, L. Robinson, The everyday use of assistive technology by people with dementia and their family carers: A qualitative study, BMC Geriatr. 15 (2015). https://doi.org/10.1186/s12877-015-0091-3.

[70] B.R. Beech, D. Roberts, Assistive technology and older people, SCIE Res. Brief. 28 (2008) 1–12. http://www.scie.org.uk/publications/briefings/briefing28/.

[71] C. McCreadie, A. Tinker, The acceptability of assistive technology to older people, Ageing Soc. 25 (2005) 91–110. https://doi.org/10.1017/S0144686X0400248X.

[72] T. Heart, E. Kalderon, Older adults: Are they ready to adopt health-related ICT?, Int. J. Med. Inform. 82 (2013) e209–e231. https://doi.org/10.1016/j.ijmedinf.2011.03.002.

[73] B. Kerbler, An innovative built environment form for dwellings for the elderly, Metu J. Fac. Archit. 31 (2014) 119–137. https://doi.org/10.4305/METU.JFA.2014.1.6.

[74] K. Kasugai, M. Ziefle, C. Röcker, P. Russell, Creating Spatio-Temporal Contiguities Between Real and Virtual Rooms in an Assistive Living Environment, (2010). https://doi.org/10.14236/ewic/create2010.8.

[75] A. Grgurić, M. Mošmondor, D. Huljenić, The SmartHabits: An Intelligent Privacy-Aware Home Care Assistance System, Sensors (Basel). 19 (2019). https://doi.org/10.3390/s19040907.

[76] R. Li, B. Lu, K.D. McDonald-Maier, Cognitive assisted living ambient system: a survey, Digit. Commun. Networks. 1 (2015) 229–252. https://doi.org/10.1016/j.dcan.2015.10.003.

[77] E.I. Konstantinidis, G. Bamparopoulos, A. Billis, P.D. Bamidis, Internet of Things for an Age-Friendly Healthcare, Stud. Health Technol. Inform. 210 (2015) 587–591. https://doi.org/10.3233/978-1-61499-512-8-587.

[78] I. Azimi, A.M. Rahmani, P. Liljeberg, H. Tenhunen, Internet of things for remote elderly monitoring: a study from user-centered perspective, J. Ambient

Intell. Humaniz. Comput. 8 (2017) 273–289. https://doi.org/10.1007/s12652-016-0387-y.

[79] G. Demiris, M. Skubic, M.J. Rantz, K.L. Courtney, M.A. Aud, H.W. Tyrer, Z. He, J. Lee, Facilitating interdisciplinary design specification of “smart” homes for aging in place, Stud. Health Technol. Inform. 124 (2006) 45–50.

[80] V. Frisardi, B.P. Imbimbo, Gerontechnology for demented patients: Smart homes for smart aging, J. Alzheimer’s Dis. 23 (2011) 143–146. https://doi.org/10.3233/JAD-2010-101599.

[81] T.K.L. Hui, R.S. Sherratt, D.D. Sánchez, Major requirements for building Smart Homes in Smart Cities based on Internet of Things technologies, Futur. Gener. Comput. Syst. 76 (2017) 358–369. https://doi.org/10.1016/j.future.2016.10.026.

[82] J. Güttler, C. Georgoulas, T. Linner, T. Bock, Towards a future robotic home environment: A survey, Gerontology. 61 (2015) 268–280. https://doi.org/10.1159/000363698.

[83] A. Engineer, E.M. Sternberg, B. Najafi, Designing Interiors to Mitigate Physical and Cognitive Deficits Related to Aging and to Promote Longevity in Older Adults: A Review, Gerontology. 85721 (2018) 612–622. https://doi.org/10.1159/000491488.

[84] B.P. Horowitz, S.M. Nochajski, J.A. Schweitzer, Occupational Therapy Community Practice and Home Assessments: Use of the Home Safety Self-Assessment Tool (HSSAT) to Support Aging in Place, Occup Ther Heal. Care. (2013). https://doi.org/10.3109/07380577.

[85] M. Haak, B. Slaug, F. Oswald, S.M. Schmidt, J.M. Rimland, S. Tomsone, T. Ladö, T. Svensson, S. Iwarsson, Cross-national user priorities for housing provision and accessibility — Findings from the european innovage project, Int. J. Environ. Res. Public Health. 12 (2015) 2670–2686. https://doi.org/10.3390/ijerph120302670.

[86] M. Lo Bianco, S. Pedell, G. Renda, A. Kapoor, HCI methods for empowering discussion on person-centered fall prevention with older adults, OzCHI 2015 Being Hum. - Conf. Proc. (2015) 255–263. https://doi.org/10.1145/2838739.2838767.

[87] A. Moussaoui, A. Pruski, C. Maaoui, Virtual reality for accessibility assessment of a built environment for a wheelchair user, Technol. Disabil. 24 (2012) 129–137. https://doi.org/10.3233/TAD-2012-0341.

[88] C.A. Chase, K. Mann, S. Wasek, M. Arbesman, Systematic review of the effect of home modification and fall prevention programs on falls and the performance of community-dwelling older adults, Am. J. Occup. Ther. 66 (2012) 284–291. https://doi.org/10.5014/ajot.2012.005017.

[89] L. Normie, Technology for Ageing in Place, Glob. Ageing Issues Action. 7 (2011) 45–53. https://doi.org/S0003-2697(09)00518-1 [pii]\r10.1016/j.ab.2009.07.031.

[90] J. Jännes, P. Hämäläinen, J. Hanski, M. Lanne, Homelike Living for Elderly People: A Needs-Based Selection of Technological Solutions, Home Heal. Care Manag. Pract. 27 (2015) 64–72. https://doi.org/10.1177/1084822314543798.

[91] S.M. Golant, A theoretical model to explain the smart technology adoption behaviors of elder consumers (Elderadopt), J. Aging Stud. 42 (2017) 56–73. https://doi.org/10.1016/j.jaging.2017.07.003.

[92] M. Mohammadi, Empowering Seniors through domotics homes: integrating intelligent technology in senior citizen` home by the perspectives of demand and supply, 2010. main problem.

[93] L.A. Phan, T. Kim, Breaking down the compatibility problem in smart homes: A dynamically updatable gateway platform, Sensors (Switzerland). 20 (2020). https://doi.org/10.3390/s20102783.

[94] C. Röcker, M. Ziefle, E-Health, Assistive Technologies and Applications for Assisted Living: Challenges and Solutions., (2011). http://www.igi-global.com/bookstore/titledetails.aspx?TitleId=45952.

[95] T. Linner, C. Georgoulas, T. Bock, Advanced building engineering: Deploying mechatronics and robotics in architecture, 2012 Proc. 29th Int. Symp. Autom. Robot. Constr. ISARC 2012. (2012). https://doi.org/10.4017/gt.2012.11.02.158.711.

[96] R. Behr, M. Sciegaj, R. Walters, J. Bertoty, R. Dungan, Addressing the Housing Challenges of an Aging Population: Initiatives by Blueroof Technologies in McKeesport, Pennsylvania, J. Archit. Eng. 17 (2010) 162–169. https://doi.org/10.1061/(asce)ae.1943-5568.0000033.

[97] G. Moretti, S. Marsland, D. Basu, G. Sen Gupta, Towards a monitoring smart home for the elderly: One experience in retrofitting a sensor network into an existing home, J. Ambient Intell. Smart Environ. 5 (2013) 639–656. https://doi.org/10.3233/AIS-130233.

[98] N. Bitterman, D. Shach-Pinsly, Smart home - A challenge for architects and designers, Archit. Sci. Rev. 58 (2015) 266–274. https://doi.org/10.1080/00038628.2015.1034649.

[99] M. Gabriel, C. Stirling, D. Faulkner, B. Lloyd, Future housing and support needs of people with dementia, 2014.

[100] R. Bamzar, Assessing the quality of the indoor environment of senior housing for a better mobility: a Swedish case study, Springer Netherlands, 2019. https://doi.org/10.1007/s10901-018-9623-4.

[101] C.S. Jacelon, A. Hanson, Older adults' participation in the development of smart environments: An integrated review of the literature, Geriatr. Nurs. (Minneap). 34 (2013) 116–121. https://doi.org/10.1016/j.gerinurse.2012.11.001.

[102] B. De Vries, E. Allameh, M. Heidari Jozam, Smart-BIM (Building Information Modeling), 2012 Proc. 29th Int. Symp. Autom. Robot. Constr. ISARC 2012. (2012). https://doi.org/10.4017/gt.2012.11.02.044.00.

[103] P. Lyons, A.T. Cong, H.J. Steinhauer, S. Marsland, J. Dietrich, H.W. Guesgen, Exploring the responsibilities of single-inhabitant Smart Homes with Use Cases, J. Ambient Intell. Smart Environ. 2 (2010) 211–232. https://doi.org/10.3233/AIS-2010-0076.

[104] P. Carnemolla, Ageing in place and the internet of things – how smart home technologies, the built environment and caregiving intersect, Vis. Eng. 6 (2018). https://doi.org/10.1186/s40327-018-0066-5.

[105] H.Y. Cho, M. MacLachlan, M. Clarke, H. Mannan, Accessible home environments for people with functional limitations: A systematic review, Int. J. Environ. Res. Public Health. 13 (2016). https://doi.org/10.3390/ijerph13080826.

[106] M.E. Cho, M.J. Kim, Characterizing the interaction design in healthy smart home devices for the elderly, Indoor Built Environ. 23 (2014) 141–149. https://doi.org/10.1177/1420326X14521229.

[107] J. Ocepek, A.E.K. Roberts, G. Vidmar, Evaluation of treatment in the smart home IRIS in terms of functional independence and occupational performance and satisfaction, Comput. Math. Methods Med. 2013 (2013). https://doi.org/10.1155/2013/926858.

[108] S. Renaut, J. Ogg, S. Petite, A. Chamahian, Home environments and adaptations in the context of ageing, Ageing Soc. 35 (2015) 1278–1303. https://doi.org/10.1017/S0144686X14000221.

[109] L. Mackenzie, C. Curryer, J.E. Byles, Narratives of home and place: Findings from the Housing and Independent Living Study, Ageing Soc. 35 (2015) 1684–1712. https://doi.org/10.1017/S0144686X14000476.

[110] L.L. Lien, C.D. Steggell, S. Iwarsson, Adaptive strategies and person-environment fit among functionally limited older adults aging in place: A mixed methods approach, Int. J. Environ. Res. Public Health. 12 (2015) 11954–11974. https://doi.org/10.3390/ijerph120911954.

[111] M. Bishop, K.L. Dennis, L.A. Bishop, K. Sheppard-Jones, F. Bishop, M. Frain, The prevalence and nature of modified housing and assistive devices use among Americans with multiple sclerosis, J. Vocat. Rehabil. 42 (2015) 153–165. https://doi.org/10.3233/JVR-150732.

[112] V.K. Ravishankar, W. Burleson, D. Mahoney, Smart home strategies for user-centered functional assessment of older adults, Int. J. Autom. Smart Technol. 5 (2015) 233–242. https://doi.org/10.5875/ausmt.v5i4.952.

[113] S.E. Lamb, E.C. Jørstad-Stein, K. Hauer, C. Becker, Development of a common outcome data set for fall injury prevention trials: The Prevention of Falls Network Europe consensus, J. Am. Geriatr. Soc. 53 (2005) 1618–1622. https://doi.org/10.1111/j.1532-5415.2005.53455.x.

[114] S.E. Carter, E.M. Campbell, R.W. Sanson-Fisher, W.J. Gillespie, Accidents in older people living at home: A community-based study assessing prevalence, type, location and injuries, Aust. N. Z. J. Public Health. 24 (2000) 633–636. https://doi.org/10.1111/j.1467-842X.2000.tb00532.x.

[115] M. Lo Bianco, S. Pedell, G. Renda, Augmented reality and home modifications: A tool to empower older adults in fall prevention, Proc. 28th Aust. Comput. Interact. Conf. OzCHI 2016. (2016) 499–507. https://doi.org/10.1145/3010915.3010929.

[116] I. Van Steenwinkel, B. Dierckx de Casterlé, A. Heylighen, How architectural design affords experiences of freedom in residential care for older people, J. Aging Stud. 41 (2017) 84–92. https://doi.org/10.1016/j.jaging.2017.05.001.

[117] S. Helal, C.N. Bull, From smart homes to smart-ready homes and communities, Dement. Geriatr. Cogn. Disord. 47 (2019) 157–163. https://doi.org/10.1159/000497803.

[118] M. Peruzzini, M. Germani, Design of a service-oriented architecture for AAL, Int. J. Agil. Syst. Manag. 9 (2016) 154–178. https://doi.org/10.1504/IJASM.2016.078582.

[119] S. Arthanat, J. Wilcox, M. Macuch, Profiles and Predictors of Smart Home Technology Adoption by Older Adults, OTJR Occup. Particip. Heal. 39 (2019) 247–256. https://doi.org/10.1177/1539449218813906.

[120] J.M. Robillard, A.W. Li, S. Jacob, D. Wang, X. Zou, J. Hoey, Co-creating emotionally aligned smart homes using social psychological modeling, ACM Int. Conf. Proceeding Ser. Part F1319 (2017). https://doi.org/10.1145/3134230.3134242.

[121] K. Storey, Smart houses and smart technology: Overview and implications for independent living and supported living services, Intellect. Dev. Disabil. 49 (2011) 50–55. https://doi.org/10.1352/1934-9556-49.1.50.

[122] S. Wang, K. Bolling, W. Mao, J. Reichstadt, D. Jeste, H.-C. Kim, C. Nebeker, Technology to Support Aging in Place: Older Adults' Perspectives, Healthcare. 7 (2019) 60. https://doi.org/10.3390/healthcare7020060.

[123] Y. Schikhof, I. Mulder, S. Choenni, Who will watch (over) me? Humane monitoring in dementia care, Int. J. Hum. Comput. Stud. 68 (2010) 410–422. https://doi.org/10.1016/j.ijhcs.2010.02.002.

[124] M.J. Kim, M.W. Oh, M.E. Cho, H. Lee, J.T. Kim, A critical review of user studies on healthy smart homes, Indoor Built Environ. 22 (2013) 260–270. https://doi.org/10.1177/1420326X12469733.

[125] T. Linner, J. Güttler, T. Bock, C. Georgoulas, Assistive robotic micro-rooms for independent living, Autom. Constr. 51 (2015) 8–22. https://doi.org/10.1016/j.autcon.2014.12.013.

[126] E.T. Remillard, C.B. Fausset, W.B. Fain, Aging with long-term mobility impairment: Maintaining activities of daily living via selection, optimization,

and compensation, Gerontologist. 59 (2019) 559–569. https://doi.org/10.1093/geront/gnx186.

[127] F. Thomése, M. Broese van Groenou, Adaptive strategies after health decline in later life: Increasing the person-environment fit by adjusting the social and physical environment, Eur. J. Ageing. 3 (2006) 169–177. https://doi.org/10.1007/s10433-006-0038-9.

[128] S.M. Trecartin, S.M. Cummings, Systematic review of the physical home environment and the relationship to psychological well-being among community-dwelling older adults, J. Gerontol. Soc. Work. 61 (2018) 567–582. https://doi.org/10.1080/01634372.2018.1463339.

[129] C. Hammink, N. Moor, M. Mohammadi, A systematic literature review of persuasive architectural interventions for stimulating health behaviour, Facilities. 37 (2019) 743–761. https://doi.org/10.1108/F-07-2017-0065.

[130] Alzheimer's Disease International, M. University, World Alzheimer Report 2021, 2021. http://www.alz.co.uk/research/files/WorldAlzheimerReport.pdf.

[131] N. Moor, M. Mohammadi, Grey Smart Societies: Supporting the Social Inclusion of Older Adults by Smart Spatial Design, in: Data-Driven Multivalence Built Environ., Springer Science and Business Media LLC: Berlin/Heidelberg, Germany, 2019;, 2020: pp. 157–180. http://link.springer.com/10.1007/978-3-030-12180-8.

[132] N. Nijhof, eHealth for people with dementia in home-based and residential care, 2013. http://purl.org/utwente/doi/10.3990/1.9789036534550.

[133] R. Orpwood, C. Gibbs, T. Adlam, R. Faulkner, D. Meegahawatte, The design of smart homes for people with dementia - User-interface aspects, Univers. Access Inf. Soc. 4 (2005) 156–164. https://doi.org/10.1007/s10209-005-0120-7.

[134] J. Evans, M. Brown, T. Coughlan, G. Lawson, M.P. Craven, A systematic review of dementia focused assistive technology, Lect. Notes Comput. Sci. (Including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics). 9170 (2015) 406–417. https://doi.org/10.1007/978-3-319-20916-6_38.

[135] C. Ma, O. Guerra-Santin, M. Mohammadi, Smart home modification design strategies for ageing in place: a systematic review, J. Hous. Built Environ. 37 (2022) 625–651. https://doi.org/10.1007/s10901-021-09888-z.

[136] J. Van Hoof, H.S.M. Kort, J.L.M. Hensen, M.S.H. Duijnstee, P.G.S. Rutten, Thermal comfort and HVAC design for people with dementia, 9th Int. Conf. Exhib. - Heal. Build. 2009, HB 2009. (2009).

[137] B. Klimova, K. Kuca, Speech and language impairments in dementia, J. Appl. Biomed. 14 (2016) 97–103. https://doi.org/10.1016/j.jab.2016.02.002.

[138] S.I.M. Janus, J. Kosters, K.A. Van Den Bosch, T.C. Andringa, S.U. Zuidema, H.J. Luijendijk, Sounds in nursing homes and their effect on health in dementia: A systematic review, Int. Psychogeriatrics. 33 (2021) 627–644. https://doi.org/10.1017/S1041610220000952.

[139] M.J. Hayne, R. Fleming, Acoustic design guidelines for dementia care facilities, INTERNOISE 2014 - 43rd Int. Congr. Noise Control Eng. Improv. World Through Noise Control. (2014) 1–10.

[140] M. Kulve, M. Loomans, E. Huisman, H. Kort, Indoor air in long term care facilities and spread of infectious diseases, Indoor Air 2014 - 13th Int. Conf. Indoor Air Qual. Clim. (2014) 579–587.

[141] J. van Hoof, M.P.J. Aarts, C.G. Rense, A.M.C. Schoutens, Ambient bright light in dementia: Effects on behaviour and circadian rhythmicity, Build. Environ. 44 (2009) 146–155. https://doi.org/10.1016/j.buildenv.2008.02.005.

[142] M. Garcia-Constantino, C. Orr, J. Synnott, C. Shewell, A. Ennis, I. Cleland, C. Nugent, J. Rafferty, G. Morrison, L. Larkham, S. McIlroy, A. Selby, Design and Implementation of a Smart Home in a Box to Monitor the Wellbeing of Residents With Dementia in Care Homes, Front. Digit. Heal. 3 (2021) 1–13. https://doi.org/10.3389/fdgth.2021.798889.

[143] Y. Feng, N. Wang, J. Wang, Design of Real-Time Individualized Comfort Monitor System Used in Healthcare Facilities, Springer International Publishing, 2020. https://doi.org/10.1007/978-3-030-59987-4_19.

[144] F. Tartarini, P. Cooper, R. Fleming, Thermal Environment and Thermal Sensations of Occupants of Nursing Homes: A Field Study, Procedia Eng. 180 (2017) 373–382. https://doi.org/10.1016/j.proeng.2017.04.196.

[145] M. Raatikainen, R. Ciszek, J. Närvainen, J. Merilahti, S. Siikanen, T. Ollikainen, I. Hallikainen, J.P. Skön, System architecture of customized intelligent lighting control and indoor environment monitoring system for persons with mild cognitive impairment or dementia, 2016 IEEE 18th Int. Conf. e-Health Networking, Appl. Serv. Heal. 2016. (2016). https://doi.org/10.1109/HealthCom.2016.7749463.

[146] M.S. Hassanvand, K. Naddafi, S. Faridi, M. Arhami, R. Nabizadeh, M.H. Sowlat, Z. Pourpak, N. Rastkari, F. Momeniha, H. Kashani, A. Gholampour, S. Nazmara, M. Alimohammadi, G. Goudarzi, M. Yunesian, Indoor/outdoor relationships of PM10, PM2.5, and PM1 mass concentrations and their water-soluble ions in a retirement home and a school dormitory, Atmos. Environ. 82 (2014) 375–382. https://doi.org/10.1016/j.atmosenv.2013.10.048.

[147] K. Konis, Field evaluation of the circadian stimulus potential of daylit and non-daylit spaces in dementia care facilities, Build. Environ. 135 (2018) 112–123. https://doi.org/10.1016/j.buildenv.2018.03.007.

[148] C. Childs, J. Elliott, K. Khatab, S. Hampshaw, S. Fowler-Davis, J.R. Willmott, A. Ali, Thermal sensation in older people with and without dementia living in residential care: New assessment approaches to thermal comfort using infrared thermography, Int. J. Environ. Res. Public Health. 17 (2020) 1–23. https://doi.org/10.3390/ijerph17186932.

[149] M.P.J. Aarts, M.B.C. Aries, J. Straathof, J. Van Hoof, Dynamic lighting systems in psychogeriatric care facilities in the Netherlands: A quantitative and qualitative analysis of stakeholders responses and applied technology, Indoor

Built Environ. 24 (2015) 617–630. https://doi.org/10.1177/1420326X14532387.

[150] A. Mendes, A.L. Papoila, P. Carreiro-Martins, L. Aguiar, S. Bonassi, I. Caires, T. Palmeiro, Á.S. Ribeiro, P. Neves, C. Pereira, A. Botelho, N. Neuparth, J.P. Teixeira, The Influence of Thermal Comfort on the Quality of Life of Nursing Home Residents, J. Toxicol. Environ. Heal. - Part A Curr. Issues. 80 (2017) 729–739. https://doi.org/10.1080/15287394.2017.1286929.

[151] W. Wang, J. Chen, X. Jin, Y. Ping, C. Wu, Association between indoor ventilation frequency and cognitive function among community-dwelling older adults in China: results from the Chinese longitudinal healthy longevity survey, BMC Geriatr. 22 (2022) 1–9. https://doi.org/10.1186/s12877-022-02805-1.

[152] P. Bluyssen, M. Oostra, D. Meertins, Understanding the Indoor Environment : How To Assess and Improve Indoor Environmental Quality of People ?, Proc. CLIMA 2013 11th REHVA World Congr. 8th Int. Conf. IAQVEC "Energy Effic. Smart Heal. Build. (2013) 1–10. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.952.9874&rep=rep1&type=pdf.

[153] I. ISO, 7730: Ergonomics of the thermal environment Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, Management. 3 (2005) e615.

[154] ANSI/ASHRAE, ANSI/ASHRAE Standard 55-2017 : Thermal Environmental Conditions for Human Occupancy, ASHRAE Inc. 2017 (2017) 66.

[155] N.Y. Torres-Soto, V. Corral-Verdugo, N.S. Corral-Frías, The relationship between self-care, positive family environment, and human wellbeing, Wellbeing, Sp. Soc. 3 (2022) 100076. https://doi.org/10.1016/j.wss.2022.100076.

[156] N.Y. Torres-Soto, F.G. Rascón-Arriaga, J.A. Medina-Fernández, R.A. García-Mira, E. Poblete-Trujillo, G.R. García-Vargas, Home habitability, perceived stress and antisocial behaviour (Habitabilidad de la vivienda, estrés percibido y conducta antisocial), Int. J. Soc. Psychol. 00 (2023) 1–24. https://doi.org/10.1080/02134748.2022.2158592.

[157] F. Tartarini, Impact of temperature and indoor environmental quality in nursing homes on thermal comfort of occupants and agitation of residents with dementia, (2017).

[158] M. yung Leung, C. Wang, I.Y.S. Chan, A qualitative and quantitative investigation of effects of indoor built environment for people with dementia in care and attention homes, Build. Environ. 157 (2019) 89–100. https://doi.org/10.1016/j.buildenv.2019.04.019.

[159] L. Mølhave, G. Clausen, B. Berglund, J. De Ceaurriz, A. Kettrup, T. Lindvall, M. Maroni, A.C. Pickering, U. Risse, H. Rothweiler, B. Seifert, M. Younes, Total Volatile Organic Compounds (TVOC) in Indoor Air Quality Investigations*, Indoor Air. 7 (1997) 225–240. https://doi.org/https://doi.org/10.1111/j.1600-0668.1997.00002.x.

[160] H. Sharma, U. Vaidya, B. Ganapathysubramanian, A transfer operator methodology for optimal sensor placement accounting for uncertainty, Build. Environ. 155 (2019) 334–349. https://doi.org/10.1016/j.buildenv.2019.03.054.

[161] B. Reisberg, S. Ferris, M. De Leon, T. Crook, Lent of Primary, Gerontologist. 139 (1982) 1136–1139.

[162] WHO, WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide, (2006).

[163] H. Fadil, A. Borazanci, E. Ait Ben Haddou, M. Yahyaoui, E. Korniychuk, S.L. Jaffe, A. Minagar, Chapter 13 Early Onset Dementia, 1st ed., Elsevier Inc., 2009. https://doi.org/10.1016/S0074-7742(09)00413-9.

[164] K. Lee, J.H. Choi, S. Lee, H.J. Park, Y.J. Oh, G.B. Kim, W.S. Lee, B.S. Son, Indoor levels of volatile organic compounds and formaldehyde from emission sources at elderly care centers in Korea, PLoS One. 13 (2018) 1–15. https://doi.org/10.1371/journal.pone.0197495.

[165] E. Hasselaar, H. Priemus, Health performance of housing: indicators and tools, IOS Press. 2006.

[166] A. Schieweck, E. Uhde, T. Salthammer, L.C. Salthammer, L. Morawska, M. Mazaheri, P. Kumar, Smart homes and the control of indoor air quality, Renew. Sustain. Energy Rev. 94 (2018) 705–718. https://doi.org/10.1016/j.rser.2018.05.057.

[167] P. Kermeci, A study of the implications for the health of UK passive houses: Investigating indoor climate and indoor air quality and understanding occupants' practices, (2018).

[168] J. Belo, P. Carreiro-Martins, A.L. Papoila, T. Palmeiro, I. Caires, M. Alves, S. Nogueira, F. Aguiar, A. Mendes, M. Cano, M.A. Botelho, N. Neuparth, The impact of indoor air quality on respiratory health of older people living in nursing homes: spirometric and exhaled breath condensate assessments, J. Environ. Sci. Heal. - Part A Toxic/Hazardous Subst. Environ. Eng. 54 (2019) 1153–1158. https://doi.org/10.1080/10934529.2019.1637206.

[169] Commission of the European Communities, Indoor Air Quality & its Impact on Man, 1992.

[170] CIBSE, CIBSE Guide A: Environment Design, 2008. https://doi.org/10.1016/b978-0-240-81224-3.00016-9.

[171] Y. Jin, F. Wang, M. Carpenter, R.B. Weller, D. Tabor, S.R. Payne, The effect of indoor thermal and humidity condition on the oldest-old people's comfort and skin condition in winter, Build. Environ. 174 (2020) 106790. https://doi.org/10.1016/j.buildenv.2020.106790.

[172] J.D. Noti, F.M. Blachere, C.M. McMillen, W.G. Lindsley, M.L. Kashon, D.R. Slaughter, D.H. Beezhold, High Humidity Leads to Loss of Infectious Influenza Virus from Simulated Coughs, PLoS One. 8 (2013) 2–9. https://doi.org/10.1371/journal.pone.0057485.

[173] F. Wang, R. Olej, A. Nioi, A survey on indoor comfort and energy consumption in a care home, Proc. 33rd PLEA Int. Conf. Des. to Thrive, PLEA 2017. 1 (2017) 1336–1343.

[174] R. Gupta, A. Howard, M. Davies, A. Mavrogianni, I. Tsoulou, E. Oikonomou, P. Wilkinson, Examining the magnitude and perception of summertime overheating in London care homes, Build. Serv. Eng. Res. Technol. 42 (2021) 653–675. https://doi.org/10.1177/01436244211013645.

[175] College bouw ziekenhuisvoorzieningen, Binnenmilieu en installatietechniek in de zorgsector Bouwmaatstaven voor nieuwbouw, 2003.

[176] D. Ormandy, V. Ezratty, Health and thermal comfort: From WHO guidance to housing strategies, Energy Policy. 49 (2012) 116–121. https://doi.org/10.1016/j.enpol.2011.09.003.

[177] M. Giamalaki, D. Kolokotsa, Understanding the thermal experience of elderly people in their residences: Study on thermal comfort and adaptive behaviors of senior citizens in Crete, Greece, Energy Build. 185 (2019) 76–87. https://doi.org/10.1016/j.enbuild.2018.12.025.

[178] O. Kinnane, T. Grey, M. Dyer, Perceptions of thermal environments in dementia friendly dwellings, 9th Wind. Conf. Mak. Comf. Relev. (2016) 7–10.

[179] J. Mu, J. Kang, S. Zheng, Evaluating the objective and subjective physical environments of residential care facilities, Indoor Built Environ. 0 (2023) 1–18. https://doi.org/10.1177/1420326X231152561.

[180] I. Goudriaan, L.C. van Boekel, M.E.A. Verbiest, J. van Hoof, K.G. Luijkx, Dementia enlightened?! a systematic literature review of the influence of indoor environmental light on the health of older persons with dementia in long-term care facilities, Clin. Interv. Aging. 16 (2021) 909–937. https://doi.org/10.2147/CIA.S297865.

[181] J. De Lepeleire, A. Bouwen, L. De Coninck, F. Buntinx, Insufficient Lighting in Nursing Homes, J. Am. Med. Dir. Assoc. 8 (2007) 314–317. https://doi.org/10.1016/j.jamda.2007.01.003.

[182] E.V. Ellis, E.W. Gonzalez, D.L. McEachron, Chronobioengineering indoor lighting to enhance facilities for ageing and Alzheimer’s disorder, Intell. Build. Int. 5 (2013) 48–60. https://doi.org/10.1080/17508975.2013.807764.

[183] M.M. Sinoo, Light conditions in nursing homes : visual comfort and visual functioning of residents, 2016.

[184] E.S. Van Der Ploeg, D.W. O’Connor, Methodological challenges in studies of bright light therapy to treat sleep disorders in nursing home residents with dementia, Psychiatry Clin. Neurosci. 68 (2014) 777–784. https://doi.org/10.1111/pcn.12192.

[185] F. Marx, D. Rétfalvi, People with Dementia as Active Participants in Studies Related to the Built Environment: A Systematic Review, J. Aging Environ. 35 (2021) 77–87. https://doi.org/10.1080/26892618.2020.1793440.

[186] J. Waeytens, S. Sadr, Computer-aided placement of air quality sensors using adjoint framework and sensor features to localize indoor source emission, Build. Environ. 144 (2018) 184–193. https://doi.org/10.1016/j.buildenv.2018.08.012.

[187] A. Kolanowski, M. Boltz, E. Galik, L.N. Gitlin, H.C. Kales, B. Resnick, K.S. Van Haitsma, A. Knehans, J.E. Sutterlin, J.S. Sefcik, W. Liu, D. V. Petrovsky, L. Massimo, A. Gilmore-Bykovskyi, M. MacAndrew, G. Brewster, V. Nalls, Y.L. Jao, N. Duffort, D. Scerpella, Determinants of behavioral and psychological symptoms of dementia: A scoping review of the evidence, Nurs. Outlook. 65 (2017) 515–529. https://doi.org/10.1016/j.outlook.2017.06.006.

[188] J. Cerejeira, L. Lagarto, E.B. Mukaetova-Ladinska, Behavioral and psychological symptoms of dementia, Front. Neurol. MAY (2012). https://doi.org/10.3389/fneur.2012.00073.

[189] S.S. Khan, B. Ye, B. Taati, A. Mihailidis, Detecting agitation and aggression in people with dementia using sensors—A systematic review, Alzheimer's Dement. 14 (2018) 824–832. https://doi.org/10.1016/j.jalz.2018.02.004.

[190] A. Stéfan, J.F. Mathé, the SOFMER group Service, What are the disruptive symptoms of behavioral disorders after traumatic brain injury? A systematic review leading to recommendations for good practices, Ann. Phys. Rehabil. Med. 59 (2016) 5–17. https://doi.org/10.1016/j.rehab.2015.11.002.

[191] M. yung Leung, C. Wang, I.O. Famakin, Integrated model for indoor built environment and cognitive functional ability of older residents with dementia in care and attention homes, Build. Environ. 195 (2021) 107734. https://doi.org/10.1016/j.buildenv.2021.107734.

[192] Washington (DC): National Academies Press (US), Reducing the Impact of Dementia in America: A Decadal Survey of the Behavioral and Social Sciences, 2021. https://pubmed.ncbi.nlm.nih.gov/34613684/.

[193] A. Bourbonnais, F. Ducharme, The meanings of screams in older people living with dementia in a nursing home, Int. Psychogeriatrics. 22 (2010) 1172–1184. https://doi.org/10.1017/S1041610209991670.

[194] G. Cipriani, C. Lucetti, A. Nuti, S. Danti, Wandering and dementia, Psychogeriatrics. 14 (2014) 135–142. https://doi.org/10.1111/psyg.12044.

[195] S. Renouf, D. ffytche, R. Pinto, J. Murray, V. Lawrence, Visual hallucinations in dementia and Parkinson's disease: A qualitative exploration of patient and caregiver experiences, Int. J. Geriatr. Psychiatry. 33 (2018) 1327–1334. https://doi.org/10.1002/gps.4929.

[196] M. Liu, Y. Zhai, X. Qiu, X. Xie, Z. Liu, L. Zhu, Y. Lei, Z. Li, Air-conditioning usage behaviour of the elderly in caring home during the extremely hot summer period: An evidence in Chongqing, Build. Environ. 244 (2023) 110828. https://doi.org/10.1016/j.buildenv.2023.110828.

[197] C. yoon Yi, C. Childs, C. Peng, D. Robinson, Thermal comfort modelling of older people living in care homes: An evaluation of heat balance, adaptive

comfort, and thermographic methods, Build. Environ. 207 (2022) 108550. https://doi.org/https://doi.org/10.1016/j.buildenv.2021.108550.

[198] W. Zheng, T. Shao, Y. Lin, Y. Wang, C. Dong, J. Liu, A field study on seasonal adaptive thermal comfort of the elderly in nursing homes in Xi'an, China, Build. Environ. 208 (2022) 108623. https://doi.org/10.1016/j.buildenv.2021.108623.

[199] H. Yang, B. Guo, Y. Shi, C. Jia, X. Li, F. Liu, Interior daylight environment of an elderly nursing home in Beijing, Build. Environ. 200 (2021) 107915. https://doi.org/https://doi.org/10.1016/j.buildenv.2021.107915.

[200] M. yung Leung, C. Wang, X. Wei, Structural model for the relationships between indoor built environment and behaviors of residents with dementia in care and attention homes, Build. Environ. 169 (2020) 106532. https://doi.org/10.1016/j.buildenv.2019.106532.

[201] H. Chaudhury, H.A. Cooke, H. Cowie, L. Razaghi, The Influence of the Physical Environment on Residents with Dementia in Long-Term Care Settings: A Review of the Empirical Literature, Gerontologist. 58 (2018) e325–e337. https://doi.org/10.1093/geront/gnw259.

[202] S. Elmståhl, L. Annerstedt, O. Åhlund, How should a group living unit for demented elderly be designed to decrease psychiatric symptoms?, Alzheimer Dis. Assoc. Disord. 11 (1997) 47–52. https://doi.org/10.1097/00002093-199703000-00008.

[203] D.G. Morgan, N.J. Stewart, K.C. D'Arcy, L.J. Werezak, Evaluating rural nursing home environments: Dementia special care units versus integrated facilities, Aging Ment. Heal. 8 (2004) 256–265. https://doi.org/10.1080/13607860410001666796.

[204] B. de Boer, H.C. Beerens, M.A. Katterbach, M. Viduka, B.M. Willemse, H. Verbeek, The physical environment of nursing homes for people with dementia: Traditional nursing homes, small-scale living facilities, and green care farms, Healthc. 6 (2018). https://doi.org/10.3390/healthcare6040137.

[205] A.C.H. Yang, N. Lau, J.C.F. Ho, The role of bedroom privacy in social interaction among elderly residents in nursing homes: An exploratory case study of Hong Kong, Sensors (Switzerland). 20 (2020) 1–21. https://doi.org/10.3390/s20154101.

[206] J.S. Kok, M.J.G. Van Heuvelen, I.J. Berg, E.J.A. Scherder, Small scale homelike special care units and traditional special care units: Effects on cognition in dementia; A longitudinal controlled intervention study, BMC Geriatr. 16 (2016) 1–9. https://doi.org/10.1186/s12877-016-0222-5.

[207] L.P.G. van Buuren, M. Mohammadi, Dementia-Friendly Design: A Set of Design Criteria and Design Typologies Supporting Wayfinding, Heal. Environ. Res. Des. J. 15 (2022) 150–172. https://doi.org/10.1177/19375867211043546.

[208] C. Hou, G. Marquardt, Spatial layout and spontaneous behaviour for people with dementia: A study of adult day-care centres, SSS 2015 - 10th Int. Sp. Syntax Symp. (2015) 1–15.

[209] S. Mueller-Schotte, E. Huisman, C. Huisman, H. Kort, The influence of the indoor environment on people displaying challenging behaviour: A scoping review, Technol. Disabil. 34 (2022) 133–140. https://doi.org/10.3233/TAD-210352.

[210] L.J.J. Soril, L.E. Leggett, D.L. Lorenzetti, J. Silvius, D. Robertson, L. Mansell, J. Holroyd-Leduc, T.W. Noseworthy, F.M. Clement, Effective use of the built environment to manage behavioural and psychological symptoms of dementia: A systematic review, PLoS One. 9 (2014) 1–12. https://doi.org/10.1371/journal.pone.0115425.

[211] J.C. Morris, Clinical Dementia Rating: A reliable and valid diagnostic and staging measure for dementia of the Alzheimer type, Int. Psychogeriatrics. 9 (1997) 173–176. https://doi.org/10.1017/S1041610297004870.

[212] M. Kharel, S. Chalise, B. Chalise, K.R. Sharma, D. Gyawali, H. Paudyal, B.B. Neupane, Assessing volatile organic compound level in selected workplaces of Kathmandu Valley, Heliyon. 7 (2021) e08262. https://doi.org/10.1016/j.heliyon.2021.e08262.

[213] F. Kelly, A. Innes, O. Dincarslan, Improving care home design for people with dementia, J. Care Serv. Manag. 5 (2011) 147–155. https://doi.org/10.1179/175016811x13020827976726.

[214] D.L. Algase, C. Antonakos, E.R.A. Beattie, C.A. Beel-Bates, L. Yao, Empirical derivation and validation of a wandering typology, J. Am. Geriatr. Soc. 57 (2009) 2037–2045. https://doi.org/10.1111/j.1532-5415.2009.02491.x.

[215] R.L. Burke, A. Veliz-Reyes, Socio-spatial relationships in design of residential care homes for people living with dementia diagnoses: a grounded theory approach, Archit. Sci. Rev. (2021). https://doi.org/10.1080/00038628.2021.1941749.

[216] C. Ma, O. Guerra-Santin, A. Grave, M. Mohammadi, Supporting dementia care by monitoring indoor environmental quality in a nursing home, Indoor Built Environ. 0 (2023) 1–19. https://doi.org/10.1177/1420326X231175340.

[217] WHO, WHO global air quality guidelines, Coast. Estuar. Process. (2021) 1–360.

[218] Commission of the European Communities, Indoor Air Pollution by Formaldehyde in European Countries, 1990.

[219] H. Zong, L. Tian, Z. Cao, M. Luo, Exposure of Elderly People to Indoor Air Pollutants in Wanxia Nursing Home, Buildings. 13 (2023). https://doi.org/10.3390/buildings13092135.

[220] K. Makimoto, Eun Ah Lee, Y. Kang, M. Yamakawa, N. Ashida, Kyung Rim Shin, Temporal patterns of movements in institutionalized elderly with dementia during 12 consecutive days of observation in Seoul, Korea, Am. J. Alzheimers. Dis. Other Demen. 23 (2008) 200–206. https://doi.org/10.1177/1533317507312625.

[221] L. Van Buuren, M. Mohammadi, Design for enabling movement behavior of seniors with dementia : design (process) requirements based upon person-centered behavioral mapping technique, (2022).

[222] Centraal Bureau voor de Statistiek, Elderly people: How many elderly are there in the Netherlands?, 2023. https://www.cbs.nl/en-gb/visualisations/dashboard-population/age/elderly-people.

[223] C.H.M. Smits, H.K. Van Den Beld, M.J. Aartsen, J.J.F. Schroots, Aging in the Netherlands: State of the art and science, Gerontologist. 54 (2014) 335–343. https://doi.org/10.1093/geront/gnt096.

[224] Centers for Disease Control and Prevention, Healthy places terminology: Aging in place, (2017). https://www.cdc.gov/healthyplaces/terminology.htm.

[225] Y.J. Choi, Understanding Aging in Place: Home and Community Features, Perceived Age-Friendliness of Community, and Intention Toward Aging in Place, Gerontologist. 62 (2022) 46–55. https://doi.org/10.1093/geront/gnab070.

[226] M. Mohammadi, S. Agyefi-Mensah, User participation in housing supply for spatial comfort, in: & C.L. L. Villegas, O. Ural, V. Abrantes, I. Lombillo (Ed.), Proceedings of the 37th IAHS World Congress on Housing, 26-29 October 2010, Santander, Spain Universidad de Cantabria., 2010.

[227] E.B. Hansen, G. Gottschalk, What makes older people consider moving house and what makes them move?, Housing, Theory Soc. 23 (2006) 34–54. https://doi.org/10.1080/14036090600587521.

[228] P. de Jong, J. Rouwendal, A. Brouwer, Staying put out of choice or constraint? The residential choice behaviour of Dutch older adults, Popul. Space Place. 28 (2022). https://doi.org/10.1002/psp.2553.

[229] M. Mohammadi, Teaching existing homes to be connected, in: I-CREATe 2011 - Int. Conv. Rehabil. Eng. Assist. Technol., 2011: pp. 152–155.

[230] W. Jagroep, J.M. Cramm, S. Denktaș, A.P. Nieboer, Are neighbourhoods age-friendly? Experiences of older Surinamese adults in the Netherlands during the COVID-19 pandemic, Cities. 137 (2023) 104322. https://doi.org/10.1016/j.cities.2023.104322.

[231] S. Valipoor, S. Ahrentzen, R. Srinivasan, F. Akiely, J. Gopinadhan, M.S. Okun, A. Ramirez-Zamora, A.A. Wagle Shukla, The use of virtual reality to modify and personalize interior home features in Parkinson's disease, Exp. Gerontol. 159 (2022) 111702. https://doi.org/10.1016/j.exger.2022.111702.

[232] N.K. Hwang, S.H. Shim, Use of virtual reality technology to support the home modification process: A scoping review, Int. J. Environ. Res. Public Health. 18 (2021). https://doi.org/10.3390/ijerph182111096.

[233] K. Ijaz, T.T.M. Tran, A.B. Kocaballi, R.A. Calvo, S. Berkovsky, N. Ahmadpour, Design Considerations for Immersive Virtual Reality Applications for Older Adults: A Scoping Review, Multimodal Technol. Interact. 6 (2022). https://doi.org/10.3390/mti6070060.

[234] J. Yin, N. Arfaei, P. MacNaughton, P.J. Catalano, J.G. Allen, J.D. Spengler, Effects of biophilic interventions in office on stress reaction and cognitive function: A randomized crossover study in virtual reality, Indoor Air. 29 (2019) 1028–1039. https://doi.org/10.1111/ina.12593.

[235] R.S. Baragash, H. Aldowah, S. Ghazal, Virtual and augmented reality applications to improve older adults' quality of life: A systematic mapping review and future directions, Digit. Heal. 8 (2022). https://doi.org/10.1177/20552076221132099.

[236] S. Kalantari, T.B. Xu, A. Mostafavi, B. Kim, A. Dilanchian, A. Lee, W.R. Boot, S.J. Czaja, Using Immersive Virtual Reality to Enhance Social Interaction Among Older Adults: A Cross-Site Investigation, Innov. Aging. 7 (2023) 1–15. https://doi.org/10.1093/geroni/igad031.

[237] S. McGarry, A. Brown, M. Gardner, C. Plowright, R. Skou, C. Thompson, Immersive virtual reality: An effective strategy for reducing stress in young adults, Br. J. Occup. Ther. (2023). https://doi.org/10.1177/03080226231165644.

[238] K.C. Tseng, D.T.N. Giau, A feasibility study of using virtual reality as a pre-occupancy evaluation tool for the elderly, Autom. Constr. 134 (2022) 104037. https://doi.org/10.1016/j.autcon.2021.104037.

[239] M. Matthys, L. De Cock, L. Mertens, K. Boussauw, P. De Maeyer, N. Van de Weghe, Rethinking the Public Space Design Process Using Extended Reality as a Game Changer for 3D Co-Design, Appl. Sci. 13 (2023). https://doi.org/10.3390/app13148392.

[240] M.G. Bevilacqua, M. Russo, A. Giordano, R. Spallone, 3D Reconstruction, Digital Twinning, and Virtual Reality: Architectural Heritage Applications, Proc. - 2022 IEEE Conf. Virtual Real. 3D User Interfaces Abstr. Work. VRW 2022. (2022) 92–96. https://doi.org/10.1109/VRW55335.2022.00031.

[241] P. Najafi, M. Mohammadi, P.M. Le Blanc, P. Van Wesemael, Experimenting a Healthy Ageing Community in Immersive Virtual Reality Environment: The Case of World's Longest-lived Populations, 2021 17th Int. Conf. Intell. Environ. IE 2021 - Proc. (2021). https://doi.org/10.1109/IE51775.2021.9486595.

[242] K. Hou, X. Liu, Z. Kong, H. Wang, M. Lu, S. Hu, Impacts of corridor design: An investigation on occupant perception of corridor forms in elderly facilities, Front. Archit. Res. 12 (2023) 1047–1064. https://doi.org/10.1016/j.foar.2023.09.002.

[243] Y. Zhang, R. Codinhoto, Developing a visually impaired older people Virtual Reality (VR) simulator to apply VR in the aged living design workflow, Proc. Int. Conf. Inf. Vis. 2020-Septe (2020) 226–235. https://doi.org/10.1109/IV51561.2020.00045.

[244] S. Liddicoat, C. Newton, Older Adults as Co-researchers for Built Environments: Virtual Reality as a Means of Engagement, in: B.B. Neves, F. Vetere (Eds.), Ageing Digit. Technol. Des. Eval. Emerg. Technol. Older Adults,

Springer Singapore, Singapore, 2019: pp. 151–169. https://doi.org/10.1007/978-981-13-3693-5_10.

[245] P. Wang, M.R. Miller, E. Han, C. DeVeaux, J.N. Bailenson, Understanding virtual design behaviors: A large-scale analysis of the design process in Virtual Reality, Des. Stud. 90 (2024) 101237. https://doi.org/10.1016/j.destud.2023.101237.

[246] A. Serrano-Jiménez, M.L. Lima, M. Molina-Huelva, Á. Barrios-Padura, Promoting urban regeneration and aging in place: APRAM – An interdisciplinary method to support decision-making in building renovation, Sustain. Cities Soc. 47 (2019) 101505. https://doi.org/10.1016/j.scs.2019.101505.

[247] S. Iwarsson, B. Slaug, A.M. Fänge, The housing enabler screening tool: Feasibility and interrater agreement in a real estate company practice context, J. Appl. Gerontol. 31 (2012) 641–660. https://doi.org/10.1177/0733464810397354.

[248] T.S. Gadakari, J. Wang, K. Hadjri, J. Huang, Promoting Ageing-in-Place: Design of residential buildings for older people in China, Environ. Proc. J. 2 (2017) 113. https://doi.org/10.21834/e-bpj.v2i6.965.

[249] P. Mercader-Moyano, M. Flores-García, A. Serrano-Jiménez, Housing and neighbourhood diagnosis for ageing in place: Multidimensional Assessment System of the Built Environment (MASBE), Sustain. Cities Soc. 62 (2020). https://doi.org/10.1016/j.scs.2020.102422.

[250] T. Deng, K. Zhang, Z.J. (Max) Shen, A systematic review of a digital twin city: A new pattern of urban governance toward smart cities, J. Manag. Sci. Eng. 6 (2021) 125–134. https://doi.org/10.1016/j.jmse.2021.03.003.

[251] G. White, A. Zink, L. Codecá, S. Clarke, A digital twin smart city for citizen feedback, Cities. 110 (2021). https://doi.org/10.1016/j.cities.2020.103064.

[252] P. Najafi, M. Mohammadi, P. van Wesemael, P.M. Le Blanc, A user-centred virtual city information model for inclusive community design: State-of-art, Cities. 134 (2023) 104203. https://doi.org/10.1016/j.cities.2023.104203.

[253] E. Geronikolakis, G. Papagiannakis, An XR rapid prototyping framework for interoperability across the reality spectrum, (2021). http://arxiv.org/abs/2101.01771.

[254] J. Tümler, A. Toprak, B. Yan, Multi-user Multi-platform xR Collaboration: System and Evaluation BT - Virtual, Augmented and Mixed Reality: Design and Development, in: J.Y.C. Chen, G. Fragomeni (Eds.), Springer International Publishing, Cham, 2022: pp. 74–93.

[255] L. Appel, E. Appel, O. Bogler, M. Wiseman, L. Cohen, N. Ein, H.B. Abrams, J.L. Campos, Older Adults With Cognitive and/or Physical Impairments Can Benefit From Immersive Virtual Reality Experiences: A Feasibility Study, Front. Med. 6 (2020). https://doi.org/10.3389/fmed.2019.00329.

[256] F.D. Davis, Perceived usefulness, perceived ease of use, and user acceptance of information technology, MIS Q. Manag. Inf. Syst. 13 (1989) 319–339. https://doi.org/10.2307/249008.

[257] M.Q. Patton, Qualitative research & evaluation methods: Integrating theory and practice, Sage publications, 2014.

[258] J. Torrington, Care Homes for Older People: A Briefing and Design Guide, 1997/07/01, Taylor & Francis, London, 1996. https://doi.org/DOI: 10.1017/S0144686X97296558.

[259] Enterprise Green Communities, Aging in Place Design Guidelines, 2016.

[260] S. Judd, P. Phippen, M. 1945 J. 13- Marshall, Design for dementia, Journal of Dementia Care, London SE - 150 pages : illustrations (some color), portraits ; 30 cm, 1998.

[261] S.C. Howell, Designing for aging : patterns of use, MIT Press, Cambridge, Mass. SE - xii, 329 pages : illustrations ; 22 x 29 cm, 1980.

[262] M. Mohammadi, Empathische woonomgeving, 7 (2017). https://research.tue.nl/nl/publications/empathische-woonomgeving.

[263] N. Marangunić, A. Granić, Technology acceptance model: a literature review from 1986 to 2013, Univers. Access Inf. Soc. 14 (2015) 81–95. https://doi.org/10.1007/s10209-014-0348-1.

[264] L. Dogruel, S. Joeckel, N.D. Bowman, The use and acceptance of new media entertainment technology by elderly users: Development of an expanded technology acceptance model, Behav. Inf. Technol. 34 (2015) 1052–1063. https://doi.org/10.1080/0144929X.2015.1077890.

[265] Norman, D.A., Design of Everyday Things, 2002.

[266] J. Zhao, X. Xu, H. Jiang, Y. Ding, The effectiveness of virtual reality-based technology on anatomy teaching: A meta-analysis of randomized controlled studies, BMC Med. Educ. 20 (2020) 1–10. https://doi.org/10.1186/s12909-020-1994-z.

[267] A.L. Morán, C. Ramírez-Fernández, V. Meza-Kubo, F. Orihuela-Espina, E. García-Canseco, A.I. Grimaldo, E. Sucar, On the Effect of Previous Technological Experience on the Usability of a Virtual Rehabilitation Tool for the Physical Activation and Cognitive Stimulation of Elders, J. Med. Syst. 39 (2015). https://doi.org/10.1007/s10916-015-0297-0.

[268] D. Healy, A. Flynn, O. Conlan, J. McSharry, J. Walsh, Older Adults' Experiences and Perceptions of Immersive Virtual Reality: Systematic Review and Thematic Synthesis, JMIR Serious Games. 10 (2022) 1–17. https://doi.org/10.2196/35802.

[269] A.G. Money, A. Atwal, K.L. Young, Y. Day, L. Wilson, K.G. Money, Using the Technology Acceptance Model to explore community dwelling older adults' perceptions of a 3D interior design application to facilitate pre-discharge home

adaptations, BMC Med. Inform. Decis. Mak. 15 (2015) 1–15. https://doi.org/10.1186/s12911-015-0190-2.

[270] W. Zhong, T. Schroeder, J. Bekkering, Designing with nature: Advancing three-dimensional green spaces in architecture through frameworks for biophilic design and sustainability, Front. Archit. Res. 12 (2023) 732–753. https://doi.org/10.1016/j.foar.2023.03.001.

[271] Y. Zhao, P.E.W. van den Berg, I. V. Ossokina, T.A. Arentze, Comparing self-navigation and video mode in a choice experiment to measure public space preferences, Comput. Environ. Urban Syst. 95 (2022) 101828. https://doi.org/10.1016/j.compenvurbsys.2022.101828.

[272] P. Koutsabasis, S. Vosinakis, K. Malisova, N. Paparounas, On the value of Virtual Worlds for collaborative design, Des. Stud. 33 (2012) 357–390. https://doi.org/10.1016/j.destud.2011.11.004.

Appendices

Appendix A: Summary of Studies That Investigated Smart Technology and Home Modification

Article	Country/ region	Contribution category	Technology involved	Specific tools and technologies used/provided	Method (n =participants)	Technology application stage	Focus (ageing)
Ahrentzen and Tural, 2015	United States	Design strategy	AT	N/A	Literature review, qualitative and mixed-methods studies	Living lab	Oder adults' sedentary behaviour and active living
Behr et al., 2010	United States	Design strategy	SH	BlueNode system	Case study	Pilot project	Quality of life
Bishop et al., 2015	United States	User evaluation	AT	Multiple Sclerosis Impact Scale-29 (MSIS-29)	Questionnaire survey and logistic regression analysis (n=5082)	Widespread application	The prevalence of and need for housing modifications and devices among multiple sclerosis (MS) group
Bitterman and Shach-Pinsly, 2015	Israel	Design strategy	SH	N/A	Literature review	Living lab	Design requirements for older people
Braubach and Power, 2011	Europe	Home assessment/ design strategy	AT	N/A	Literature review and data analysis (the Large Analysis and Review of European housing and health Status project)	N/A	Risk of accidents (fall risk)
Carnemolla, 2018	Australia	User evaluation	SH and IoT	Human/Activity/Space/Technology HAST model	Literature review and case study (n=3)	Concept	The IoT application in built environment and caregiving

Article	Country/ region	Contribution category	Technology involved	Specific tools and technologies used/provided	Method (n =participants)	Technology application stage	Focus (ageing)
Chabot et al., 2019	United States	Technology selection	ST	Cognitive and visual assessment tests	Literature review	N/A	Selecting appropriate technology for older people
Chase et al., 2012	United States	Home assessment/user evaluation	AT	N/A	Literature review	Living lab	Fall prevention
Cho and Kim, 2014	Republic of Korea	User evaluation	AT	User interface design principle framework	Literature review and case study	Widespread application	User interface and user experience
De Vries et al., 2012	Netherlands	Design strategy	ST	Smart-BIM	Prototype testing	Prototype	Participatory design
Durick and Linda Leung, 2018	Australia	Design strategy	SH	Interactive architectural components	Literature review	Concept	User-centred design approaches
Emily, 2014	United States	Technology selection	AT	N/A	Literature review	N/A	The use of assistive technology
Engineer et al., 2018	United States	Design strategy	IoT	N/A	Literature review	N/A	Interior design on well-being and longevity of older adults
Gabriel et al., 2014	Australia	Design strategy	AT	N/A	Literature review and interview	N/A	Housing and support needs of people with dementia
Golant, 2017	United States	Technology selection	ST	Technology acceptance models	Literature review	N/A	Technology acceptance
Güttler et al., 2015	Germany	Design strategy	AAL	Robotic architectural components	Living lab experiment	Concept/Prototype/living lab	Activities of daily living
Haak et al., 2015	Europe	Home assessment	ICT	ICT tool, HE instrument, and person-environment fit model	Research circle methodology (n=61)	Concept	Accessibility/housing provision
Horowitz et al., 2013	United States	Home assessment	AT	HSSAT checklist	Case study (n=28)	N/A	Home safety (fall risk)

Article	Country/ region	Contribution category	Technology involved	Specific tools and technologies used/provided	Method (n =participants)	Technology application stage	Focus (ageing)
Jacelon and Hanson, 2013	United States	Design strategy/user evaluation	SH	N/A	Literature review	Prototype/living lab	Oder adults' preference and participatory design
Jännes et al., 2015	Finland	Technology selection	AT	Technology map	Literature review, in-depth and semi-structured interviews (n=27), and a questionnaire survey (n=515)	N/A	Older people's needs and views on technology
Kerbler, 2014	Europe	Design strategy/user evaluation	ST	N/A	Literature review	Pilot project	Living environment
Lien et al., 2015	United States	User evaluation/home assessment	AT	Ecological theory of aging (ETA), HE instrument, and election, optimization, and compensation (SOC) model	Quantitative data collection and qualitative interviews (n=50)	N/A	Accessibility and usability of the home environment, adaptive environmental behaviours
Linner et al., 2015	Germany	Design strategy	AAL	Robotic micro-rooms (RmRs)	Field study	Prototype	Activities of daily living
Lo Bianco et al., 2016	Australia	Home assessment/ design strategy	AT	Augmented reality technology	Semi-structured interviews (n=10)	Prototype	Fall prevention
Lyons et al., 2010	New Zealand	Design strategy	SH	Use Cases	Case study (n=4)	N/A	Activities of daily living and abnormal behaviours
Mackenzie et al., 2015	Australia	User evaluation	AT	N/A	Semi-structured interviews (N=202)	N/A	Housing needs, experiences, and expectations of older people

Article	Country/ region	Contribution category	Technology involved	Specific tools and technologies used/provided	Method (n =participants)	Technology application stage	Focus (ageing)
Moretti et al., 2013	New Zealand	Design strategy	SH	Monnit sensors	Case study (n=1)	Pilot project	Technology application and data integrity
Moussaoui et al., 2012	France	Home assessment	AT	Virtual reality technology	Simulation techniques of mobile and manipulation robotics	Concept	Accessibility
Normie, 2011	United States	Technology selection	ST	N/A	Literature review	Prototype/living lab	Technology interventions and applications
Ocepek et al., 2013	Slovenia	User evaluation	AT	The Canadian Occupational Performance Measure (COPM) and the Functional Independence Measure (FIM)	A quantitative quasi-experimental study (N=59)	Pilot project	The effect of treatments in the Smart Home IRIS
Pynoos et al., 2010	United States	Home assessment	AT	Home assessment checklists and instruments	Literature review	N/A	Fall prevention
Renaut et al., 2015	France	User evaluation	AT	N/A	A thematic analysis of qualitative interviews (n=28)	Widespread application	Adaptations in the home environment
Röcker and Ziefle, 2011	Germany	Design strategy	AAL	An interactive environment with a large-scale interactive wall and a smart floor	Literature review	Concept	Usability and technology acceptance

Appendix B: Questionnaire (for care professionals)

PART 1: basic information

1. What is your position?

2. How long have you been working at the care home?

1) Less than 1 year

2) 1-3 years

3) 3-5 years

4) Over 5 years

3. What is your work area?

1) First floor

2) Second floor

3) The entire building

4. Do you work shifts? If so, when do you work in working days?

1) Day shift

2) Night shift

3) It varies

5. How much time do you approximately spend in the bedrooms with each client every day?

6. How much is the average amount of time the residents spend outdoors one day when the weather suffices in summer?

1) Less than 1 hour

2) 1-2 hours

3) 2-3 hours

4) More than 4 hours

7. How much is the average amount of time the residents spend outdoors one day when the weather suffices in winter?

1) Less than 1 hour

2) 1-2 hours

3) 2-3 hours

4) More than 4 hours

8. Which is the favourite place of the residents in summer?

1) Bedroom

2) Central living room

3) Activity room

4) Garden

5) Terrace

6) Corridor

7) Other

9. Which is the favourite place of the residents in winter?

1) Bedroom

2) Central living room

3) Activity room

4) Garden

5) Terrace

6) Corridor

7) Other

PART 2: self-perception (please fill in questions according to your own opinion)

10. What is your thermal comfort in bedrooms during the summer? (how does the room feel?)

Cold Neutral Hot

1 2 3 4 5 6 7

11. What is your thermal comfort in the central living room during the summer? (how does the room feel?)

Cold Neutral Hot

1 2 3 4 5 6 7

12. What is your thermal comfort in bedrooms during the winter? (how does the room feel?)

Cold Neutral Hot

1 2 3 4 5 6 7

13. What is your thermal comfort in the central living room during the winter? (how does the room feel?)

Cold Neutral Hot

1 2 3 4 5 6 7

14. How is the luminance in bedrooms?

1) Most of the rooms are dark

2) Most of the rooms are moderate

3) Most of the rooms are light

4) Some rooms are dark and some rooms are light

5) Other

15. How is the luminance in the central living room?

Very dark Neutral Very light

1 2 3 4 5 6 7

16. Please mark the following statements if they are true when you stay in bedrooms:

1) I can clearly hear the noise coming from outside

2) I can hear a faint noise coming from outside

3) I cannot hear any noise coming from outside

17. Please mark the following statements if they are true when you stay in bedrooms:

1) I can clearly hear the noise coming from other rooms

2) I can hear a faint noise coming from other rooms

3) I cannot hear any noise coming from other rooms

18. How is the indoor air quality in bedrooms?

Very fresh Neutral Very stale

1 2 3 4 5 6 7

19. How is the indoor air quality in the central living room? (multiple-choice)

1) Fresh

2) Neutral

3) Stale

4) Odours during the cooking time

5) Other odours (e.g. mouldy)

20. How would you rate the humidity level in summer?

Very dry Neutral Very humid

1 2 3 4 5 6 7

21. How would you rate the humidity level in winter?

Very dry Neutral Very humid

1 2 3 4 5 6 7

22. Do you open windows in the bedrooms?

1) No

2) Yes

If yes, when do you open the windows, and how many hours do you schedule the bedroom window open on a summer day?

If yes, when do you open the windows, and how many hours do you schedule the bedroom window open on a winter day?

23. What are the main reasons to open the window? (multiple-choice)

1) I feel the room is too warm

2) I feel the air is stuffy

3) There is a bad odour

4) I feel the room is too humid

5) I feel the room is too dry

6) The resident wants fresh air

7) The resident is too warm

8) I open it as a routine

9) Other

24. When do you close it? (multiple-choice)

1) I feel the room is too cold

2) The resident is too cold

3) In the night

4) When the resident leaves the room

5) When the resident returns to the room

6) The weather changes

7) Other

25. What do you think of the central ventilation systems? (multiple-choice)

1) Very satisfied

2) It is noisy sometimes

3) Turn it down at night

4) Turn it down when I feel cold

5) Turn it up during the cooking/shower

6) Turn it up when I feel hot

7) Other

26. Are you satisfied with the indoor environment of the care home?

Very unsatisfied   Moderate   Very satisfied

1   2   3   4   5   6   7

27. Do you have any suggestions or comments to improve the indoor environment for older people?

Appendix C: Questionnaire (for nursing home residents' guardians)

PART 1: basic information

1. What is the room number of your family?

2. How old is your family?

3. What is the gender of your family?

1) Male

2) Female

3) Other

4. How long is your family living at the care home?

1) Less than 3 months

2) 3-6 months

3) 7-12 months

4) 1-2 years

5) More than 2 years

5. How often do you visit the care home?

1) Every day

2) About twice per week

3) About once per week

4) About once every two weeks

5) About once per month

6. How long are your visits?

1) Less than 1 hour

2) 1 hour

3) 2 hours

4) More than 2 hours

7. Have your visiting routine changed due to Covid-19? How?

1) Yes, I visited less

2) Yes, I visited more

3) No

PART 2: self-perception (please fill in questions according to your own opinion)

8. What is your thermal comfort in the bedroom during the summer? (how does the room feel?)

Cold Neutral Hot

1 2 3 4 5 6 7

9. What is your thermal comfort in the bedroom during the winter? (how does the room feel?)

Cold Neutral Hot

1 2 3 4 5 6 7

10. How would you rate the indoor luminance in the bedroom?

Very dark Neutral Very light

1 2 3 4 5 6 7

11. Please mark the following statements if they are true:

1) I can clearly hear the noise coming from outside

2) I can hear a faint noise coming from outside

3) I cannot hear any noise coming from outside

12. Please mark the following statements if they are true:

1) I can clearly hear the noise coming from other rooms

2) I can hear a faint noise coming from other rooms

3) I cannot hear any noise coming from other rooms

13. How is the indoor air quality in the bedroom? (multiple-choice)

1) Fresh

2) Neutral

3) Stale

4) Odours during the cooking time

5) Other doors (e.g., mouldy)

14. How would you rate the humidity level in the summer?

Very dry   Neutral   Very humid

1   2   3   4   5   6   7

15. How would you rate the humidity level in the winter?

Very dry   Neutral   Very humid

1   2   3   4   5   6   7

16. Are you satisfied with the indoor environment of the care home?

Very unsatisfied   Neutral   Very satisfied

1   2   3   4   5   6   7

17. Do you adjust the indoor environment when you enter the bedroom (e.g., open the window/curtain, turn on the light, turn up the heating, etc.)?

1) No

2) Yes

If yes, what do you usually do?

PART 3: your family's perception (please fill in the questions about your family's comfort, we know you probably are not sure of these answers, but try to fill them in according to your knowledge)

18. In your opinion, what is the thermal comfort of your family in the bedroom during the summer? (how does the room feel to them?)

Cold   Neutral   Hot

1   2   3   4   5   6   7

19. In your opinion, what is the thermal comfort of your family in the bedroom during the winter? (how does the room feel to them?)

Cold   Neutral   Hot

1   2   3   4   5   6   7

20. In your opinion, what is the preference of your family for indoor luminance?

Very dark   Neutral   Very light

1   2   3   4   5   6   7

21. Please mark the following statements if you heard from your family:

1) He or she can clearly hear the noise coming from outside

2) He or she can hear a faint noise coming from outside

3) He or she cannot hear any noise coming from outside

22. Please mark the following statements if you heard from your family:

1) He or she can clearly hear the noise coming from other rooms

2) He or she can hear a faint noise coming from other rooms

3) He or she cannot hear any noise coming from other rooms

23. In your opinion, how does your family rate the indoor air quality in the bedroom? (multiple-choice)

1) Fresh

2) Neutral

3) Stale

4) Odours during the cooking time

5) Other doors (e.g., mouldy)

24. In your opinion, how does your family rate the humidity level in the summer?

Very dry   Neutral   Very humid

1   2   3   4   5   6   7

25. In your opinion, how does your family rate the humidity level in the winter?

Very dry   Neutral   Very humid

1   2   3   4   5   6   7

26. Which is the favourite space of your family in the building in summer?

1) Their bedrooms

2) Central living room

3) Activity room

4) Corridor

5) Garden

6) Terrace

7) Other

27. Which is the favourite space of your family in the building in winter?

1) Their bedrooms

2) Central living room

3) Activity room

4) Corridor

5) Garden

6) Terrace

7) Other

Appendix D: Interview Questions (for social housing residents)

1. May I know your age (and your partner's)?
2. When did you move to this residential compound?
3. How long do you normally stay at home every day?
4. What do you think about the building facilities (e.g. elevator, heating system, extractor, boiler, etc.)? Could you elaborate on your daily experiences using these systems?
5. How would you rate the temperature in your home? (e.g. too hot during summer or too cold during winter)
6. How would you rate the air quality in your home? (e.g. Is the air too dry or humid at times? Do you have trouble with mould in the bathroom or kitchen?
7. How often and when do you open windows? Do you often smell odours coming from inside or outside your home?
8. How would you rate the natural light during the daytime? Do you think the natural light is enough for your daily activities?
9. Do you experience disturbance due to noise coming from outside or your neighbours? Can you elaborate when and how does it affect you?
10. Do you experience any inconvenience when you move around your home or the community (e.g., common areas or corridors)? Could you elaborate on your experiences? (what and where)
11. From your perspective, what improvements could be made to your home?
12. Could you tell us what your daily schedule looks like? (when you get up in the morning, have dinner, go shopping, etc.)
13. Do you exercise every day? What activities do you like (e.g. walking, biking)?
14. Do you need assistance with your daily activities (e.g. housework, room cleaning)? Who provides this assistance?
15. Which room do you spend most of the day in? What type of activities do you carry out there?
16. What is your opinion about your home layout? (e.g. walking around or getting something) Could you show me some of the issues you have with the layout?
17. Could you show me how to prepare for a shower/bath?
18. Could you show me how you prepare dinner?
19. Do you think the floor is slippery with water on it? Have you ever slipped?
20. How do you use the balcony?
21. Do you have any complaints about the rooms? (e.g. the summer sunshine is so early and intense that I cannot sleep well)

22. What is your favourite space in your home? And in the residential compound?
23. Do you do any activities in outdoor spaces near the building? Can you elaborate?
24. How often do you communicate with your family or friends? By which method?
25. What would you do if you felt sick or had a health emergency? Do you have a plan?
26. Are you concerned about energy savings? If yes, do you do something to save energy at home?
27. Have you noticed any potential hazards in your home and neighbourhood?

Appendix E: The Program Code of the Smart System Animation for People with Dementia

```
using UnityEngine;

public class GuidingEnvironment : MonoBehaviour
{
    public GameObject objectToTurnOn;
    public GameObject objectToTurnOff;
    public KeyCode toggleKey = KeyCode.Space;

    private bool isObjectOn = true; // Track the state of objectToTurnOn

    private void Update()
    {
        if (Input.GetKeyDown(toggleKey))
        {
            ToggleObjects();
        }
    }
    public void ToggleObjects()
    {
        if (isObjectOn)
        {
            if (objectToTurnOn != null)
            {
                objectToTurnOn.SetActive(false);
            }

            if (objectToTurnOff != null)
            {
                objectToTurnOff.SetActive(true);
```

```
            }
        }
        else
        {
            if (objectToTurnOn != null)
            {
                objectToTurnOn.SetActive(true);
            }

            if (objectToTurnOff != null)
            {
                objectToTurnOff.SetActive(false);
            }
        }
        isObjectOn = !isObjectOn;
    }
}
```

List of Publications

Journal articles

Ma, C., Guerra-Santin, O., and Mohammadi, M. (2024). Exploring the influence of indoor environment and spatial layout on changed behaviours of people with dementia in a nursing home. Building and Environment, 256, 111452.

Ma, C., Guerra-Santin, O., Grave, A., and Mohammadi, M. (2023). Supporting dementia care by monitoring indoor environmental quality in a nursing home. Indoor and Built Environment, 32(9), 1843-1861.

Ma, C., Guerra-Santin, O., and Mohammadi, M. (2022). Smart home modification design strategies for ageing in place: a systematic review. *Journal of Housing and the Built Environment*, 37(2), 625-651.

Ma, C., Najafi, P., Guerra-Santin, O., and Mohammadi, M. Social housing renovation for healthy ageing: An empathic design approach for creating immersive environments through virtual reality (submitted)

Conference papers

Ma, C., Najafi, P., Guerra-Santin, O., and Mohammadi, M. (2024). Implement Virtual Reality, Digital Twin, and Artificial Intelligence in the Social Housing Renovation Project Based on the Blue Zones Concept. *SHE2024 International Scientific Conference*.

Ma, C., Guerra-Santin, O., Grave, A., and Mohammadi, M. (2022). Monitoring the indoor environment for older people with dementia. a lesson learned. *CLIMA 2022 Conference, 1-7*.

Curriculum Vitae

Chuan Ma was born on June 21st, 1989, in Zhengzhou, Henan, China. He studied Architecture and obtained his B.Sc. from Zhengzhou University in 2012. Then, he worked as an architect designer in Shanghai, China and was responsible for or participated in the design and construction of several large-scale public building projects. In 2015, he started his master's studies at Politecnico di Milano, Italy, obtaining his master's degree in Architecture and Architectural Design in 2017. Between 2017 and 2018, he worked as a design consultant for companies in Milan, Shanghai, and Zhengzhou. In September 2018, he started as a doctoral candidate at Eindhoven University of Technology (Eindhoven, the Netherlands), the chair of Smart Architectural Technologies. His main research proposal is 'Crafting Smart Homes: Innovative Design Strategies to Enhance Housing Quality for Ageing Well', and the research results are presented in this dissertation. His research interests focus on smart home design and renovation, indoor environmental quality, digital twin, virtual reality (VR)-based scenario design, and living qualities of older adults.

Bouwstenen is een publicatiereeks
van de Faculteit Bouwkunde,
Technische Universiteit Eindhoven.
Zij presenteert resultaten van
onderzoek en andere activiteiten op
het vakgebied der Bouwkunde,
uitgevoerd in het kader van deze
Faculteit.

Bouwstenen en andere proefschriften van de
TU/e zijn online beschikbaar via:
https://research.tue.nl/

Reeds verschenen in de serie
Bouwstenen

nr 1
Elan: A Computer Model for Building Energy Design: Theory and Validation
Martin H. de Wit
H.H. Driessen
R.M.M. van der Velden

nr 2
Kwaliteit, Keuzevrijheid en Kosten: Evaluatie van Experiment Klarendal, Arnhem
J. Smeets
C. le Nobel
M. Broos
J. Frenken
A. v.d. Sanden

nr 3
Crooswijk: Van 'Bijzonder' naar 'Gewoon'
Vincent Smit
Kees Noort

nr 4
Staal in de Woningbouw
Edwin J.F. Delsing

nr 5
Mathematical Theory of Stressed Skin Action in Profiled Sheeting with Various Edge Conditions
Andre W.A.M.J. van den Bogaard

nr 6
Hoe Berekenbaar en Betrouwbaar is de Coëfficiënt k in x-ksigma en x-ks?
K.B. Lub
A.J. Bosch

nr 7
Het Typologisch Gereedschap: Een Verkennende Studie Omtrent Typologie en Omtrent de Aanpak van Typologisch Onderzoek
J.H. Luiten

nr 8
Informatievoorziening en Beheerprocessen
A. Nauta
Jos Smeets (red.)
Helga Fassbinder (projectleider)
Adrie Proveniers
J. v.d. Moosdijk

nr 9
Strukturering en Verwerking van Tijdgegevens voor de Uitvoering van Bouwwerken
ir. W.F. Schaefer
P.A. Erkelens

nr 10
Stedebouw en de Vorming van een Speciale Wetenschap
K. Doevendans

nr 11
Informatica en Ondersteuning van Ruimtelijke Besluitvorming
G.G. van der Meulen

nr 12
Staal in de Woningbouw, Korrosie-Bescherming van de Begane Grondvloer
Edwin J.F. Delsing

nr 13
Een Thermisch Model voor de Berekening van Staalplaatbetonvloeren onder Brandomstandigheden
A.F. Hamerlinck

nr 14
De Wijkgedachte in Nederland: Gemeenschapsstreven in een Stedebouwkundige Context
K. Doevendans
R. Stolzenburg

nr 15
Diaphragm Effect of Trapezoidally Profiled Steel Sheets: Experimental Research into the Influence of Force Application
Andre W.A.M.J. van den Bogaard

nr 16
Versterken met Spuit-Ferrocement: Het Mechanische Gedrag van met Spuit-Ferrocement Versterkte Gewapend Betonbalken
K.B. Lubir
M.C.G. van Wanroy

nr 17
De Tractaten van Jean Nicolas Louis Durand
G. van Zeyl

nr 18
Wonen onder een Plat Dak: Drie Opstellen over Enkele Vooronderstellingen van de Stedebouw
K. Doevendans

nr 19
Supporting Decision Making Processes: A Graphical and Interactive Analysis of Multivariate Data
W. Adams

nr 20
Self-Help Building Productivity: A Method for Improving House Building by Low-Income Groups Applied to Kenya 1990-2000
P. A. Erkelens

nr 21
De Verdeling van Woningen: Een Kwestie van Onderhandelen
Vincent Smit

nr 22
Flexibiliteit en Kosten in het Ontwerpproces: Een Besluitvormingondersteunend Model
M. Prins

nr 23
Spontane Nederzettingen Begeleid: Voorwaarden en Criteria in Sri Lanka
Po Hin Thung

nr 24
Fundamentals of the Design of Bamboo Structures
Oscar Arce-Villalobos

nr 25
Concepten van de Bouwkunde
M.F.Th. Bax (red.)
H.M.G.J. Trum (red.)

nr 26
Meaning of the Site
Xiaodong Li

nr 27
Het Woonmilieu op Begrip Gebracht: Een Speurtocht naar de Betekenis van het Begrip 'Woonmilieu'
Jaap Ketelaar

nr 28
Urban Environment in Developing Countries
editors: Peter A. Erkelens
George G. van der Meulen (red.)

nr 29
Stategische Plannen voor de Stad: Onderzoek en Planning in Drie Steden
prof.dr. H. Fassbinder (red.)
H. Rikhof (red.)

nr 30
Stedebouwkunde en Stadsbestuur
Piet Beekman

nr 31
De Architectuur van Djenné: Een Onderzoek naar de Historische Stad
P.C.M. Maas

nr 32
Conjoint Experiments and Retail Planning
Harmen Oppewal

nr 33
Strukturformen Indonesischer Bautechnik: Entwicklung Methodischer Grundlagen für eine 'Konstruktive Pattern Language' in Indonesien
Heinz Frick arch. SIA

nr 34
Styles of Architectural Designing: Empirical Research on Working Styles and Personality Dispositions
Anton P.M. van Bakel

nr 35
Conjoint Choice Models for Urban Tourism Planning and Marketing
Benedict Dellaert

nr 36
Stedelijke Planvorming als Co-Produktie
Helga Fassbinder (red.)

nr 37
Design Research in the Netherlands
editors: R.M. Oxman
M.F.Th. Bax
H.H. Achten

nr 38
Communication in the Building Industry
Bauke de Vries

nr 39
Optimaal Dimensioneren van Gelaste Plaatliggers
J.B.W. Stark
F. van Pelt
L.F.M. van Gorp
B.W.E.M. van Hove

nr 40
Huisvesting en Overwinning van Armoede
P.H. Thung
P. Beekman (red.)

nr 41
Urban Habitat: The Environment of Tomorrow
George G. van der Meulen
Peter A. Erkelens

nr 42
A Typology of Joints
John C.M. Olie

nr 43
Modeling Constraints-Based Choices for Leisure Mobility Planning
Marcus P. Stemerding

nr 44
Activity-Based Travel Demand Modeling
Dick Ettema

nr 45
Wind-Induced Pressure Fluctuations on Building Facades
Chris Geurts

nr 46
Generic Representations
Henri Achten

nr 47
Johann Santini Aichel: Architectuur en Ambiguiteit
Dirk De Meyer

nr 48
Concrete Behaviour in Multiaxial Compression
Erik van Geel

nr 49
Modelling Site Selection
Frank Witlox

nr 50
Ecolemma Model
Ferdinand Beetstra

nr 51
Conjoint Approaches to Developing Activity-Based Models
Donggen Wang

nr 52
On the Effectiveness of Ventilation
Ad Roos

nr 53
Conjoint Modeling Approaches for Residential Group preferences
Eric Molin

nr 54
Modelling Architectural Design Information by Features
Jos van Leeuwen

nr 55
A Spatial Decision Support System for the Planning of Retail and Service Facilities
Theo Arentze

nr 56
Integrated Lighting System Assistant
Ellie de Groot

nr 57
Ontwerpend Leren, Leren Ontwerpen
J.T. Boekholt

nr 58
Temporal Aspects of Theme Park Choice Behavior
Astrid Kemperman

nr 59
Ontwerp van een Geïndustrialiseerde Funderingswijze
Faas Moonen

nr 60
Merlin: A Decision Support System for Outdoor Leisure Planning
Manon van Middelkoop

nr 61
The Aura of Modernity
Jos Bosman

nr 62
Urban Form and Activity-Travel Patterns
Daniëlle Snellen

nr 63
Design Research in the Netherlands 2000
Henri Achten

nr 64
Computer Aided Dimensional Control in Building Construction
Rui Wu

nr 65
Beyond Sustainable Building
editors: Peter A. Erkelens
Sander de Jonge
August A.M. van Vliet
co-editor: Ruth J.G. Verhagen

nr 66
Das Globalrecyclingfähige Haus
Hans Löfflad

nr 67
Cool Schools for Hot Suburbs
René J. Dierkx

nr 68
A Bamboo Building Design Decision Support Tool
Fitri Mardjono

nr 69
Driving Rain on Building Envelopes
Fabien van Mook

nr 70
Heating Monumental Churches
Henk Schellen

nr 71
Van Woningverhuurder naar Aanbieder van Woongenot
Patrick Dogge

nr 72
Moisture Transfer Properties of Coated Gypsum
Emile Goossens

nr 73
Plybamboo Wall-Panels for Housing
Guillermo E. González-Beltrán

nr 74
The Future Site-Proceedings
Ger Maas
Frans van Gassel

nr 75
Radon transport in Autoclaved Aerated Concrete
Michel van der Pal

nr 76
The Reliability and Validity of Interactive Virtual Reality Computer Experiments
Amy Tan

nr 77
Measuring Housing Preferences Using Virtual Reality and Belief Networks
Maciej A. Orzechowski

nr 78
Computational Representations of Words and Associations in Architectural Design
Nicole Segers

nr 79
Measuring and Predicting Adaptation in Multidimensional Activity-Travel Patterns
Chang-Hyeon Joh

nr 80
Strategic Briefing
Fayez Al Hassan

nr 81
Well Being in Hospitals
Simona Di Cicco

nr 82
Solares Bauen: Implementierungs- und Umsetzungs-Aspekte in der Hochschulausbildung in Österreich
Gerhard Schuster

nr 83
Supporting Strategic Design of Workplace Environments with Case-Based Reasoning
Shauna Mallory-Hill

nr 84
ACCEL: A Tool for Supporting Concept Generation in the Early Design Phase
Maxim Ivashkov

nr 85
Brick-Mortar Interaction in Masonry under Compression
Ad Vermeltfoort

nr 86
Zelfredzaam Wonen
Guus van Vliet

nr 87
Een Ensemble met Grootstedelijke Allure
Jos Bosman
Hans Schippers

nr 88
On the Computation of Well-Structured Graphic Representations in Architectural Design
Henri Achten

nr 89
De Evolutie van een West-Afrikaanse Vernaculaire Architectuur
Wolf Schijns

nr 90
ROMBO Tactiek
Christoph Maria Ravesloot

nr 91
External Coupling between Building Energy Simulation and Computational Fluid Dynamics
Ery Djunaedy

nr 92
Design Research in the Netherlands 2005
editors: Henri Achten
Kees Dorst
Pieter Jan Stappers
Bauke de Vries

nr 93
Ein Modell zur Baulichen Transformation
Jalil H. Saber Zaimian

nr 94
Human Lighting Demands: Healthy Lighting in an Office Environment
Myriam Aries

nr 95
A Spatial Decision Support System for the Provision and Monitoring of Urban Greenspace
Claudia Pelizaro

nr 96
Leren Creëren
Adri Proveniers

nr 97
Simlandscape
Rob de Waard

nr 98
Design Team Communication
Ad den Otter

nr 99
Humaan-Ecologisch Georiënteerde Woningbouw
Juri Czabanowski

nr 100
Hambase
Martin de Wit

nr 101
Sound Transmission through Pipe Systems and into Building Structures
Susanne Bron-van der Jagt

nr 102
Het Bouwkundig Contrapunt
Jan Francis Boelen

nr 103
A Framework for a Multi-Agent Planning Support System
Dick Saarloos

nr 104
Bracing Steel Frames with Calcium Silicate Element Walls
Bright Mweene Ng'andu

nr 105
Naar een Nieuwe Houtskeletbouw
F.N.G. De Medts

nr 106 and 107
Niet gepubliceerd

nr 108
Geborgenheid
T.E.L. van Pinxteren

nr 109
Modelling Strategic Behaviour in Anticipation of Congestion
Qi Han

nr 110
Reflecties op het Woondomein
Fred Sanders

nr 111
On Assessment of Wind Comfort by Sand Erosion
Gábor Dezsö

nr 112
Bench Heating in Monumental Churches
Dionne Limpens-Neilen

nr 113
RE. Architecture
Ana Pereira Roders

nr 114
Toward Applicable Green Architecture
Usama El Fiky

nr 115
Knowledge Representation under Inherent Uncertainty in a Multi-Agent System for Land Use Planning
Liying Ma

nr 116
Integrated Heat Air and Moisture Modeling and Simulation
Jos van Schijndel

nr 117
Concrete Behaviour in Multiaxial Compression
J.P.W. Bongers

nr 118
The Image of the Urban Landscape
Ana Moya Pellitero

nr 119
The Self-Organizing City in Vietnam
Stephanie Geertman

nr 120
A Multi-Agent Planning Support System for Assessing Externalities of Urban Form Scenarios
Rachel Katoshevski-Cavari

nr 121
Den Schulbau Neu Denken, Fühlen und Wollen
Urs Christian Maurer-Dietrich

nr 122
Peter Eisenman Theories and Practices
Bernhard Kormoss

nr 123
User Simulation of Space Utilisation
Vincent Tabak

nr 125
In Search of a Complex System Model
Oswald Devisch

nr 126
Lighting at Work:
Environmental Study of Direct Effects of Lighting Level and Spectrum on Psycho-Physiological Variables
Grazyna Górnicka

nr 127
Flanking Sound Transmission through Lightweight Framed Double Leaf Walls
Stefan Schoenwald

nr 128
Bounded Rationality and Spatio-Temporal Pedestrian Shopping Behavior
Wei Zhu

nr 129
Travel Information:
Impact on Activity Travel Pattern
Zhongwei Sun

nr 130
Co-Simulation for Performance Prediction of Innovative Integrated Mechanical Energy Systems in Buildings
Marija Trčka

nr 131
Niet gepubliceerd

nr 132
Architectural Cue Model in Evacuation Simulation for Underground Space Design
Chengyu Sun

nr 133
Uncertainty and Sensitivity Analysis in Building Performance Simulation for Decision Support and Design Optimization
Christina Hopfe

nr 134
Facilitating Distributed Collaboration in the AEC/FM Sector Using Semantic Web Technologies
Jacob Beetz

nr 135
Circumferentially Adhesive Bonded Glass Panes for Bracing Steel Frame in Façades
Edwin Huveners

nr 136
Influence of Temperature on Concrete Beams Strengthened in Flexure with CFRP
Ernst-Lucas Klamer

nr 137
Sturen op Klantwaarde
Jos Smeets

nr 139
Lateral Behavior of Steel Frames with Discretely Connected Precast Concrete Infill Panels
Paul Teewen

nr 140
Integral Design Method in the Context of Sustainable Building Design
Perica Savanović

nr 141
Household Activity-Travel Behavior: Implementation of Within-Household Interactions
Renni Anggraini

nr 142
Design Research in the Netherlands 2010
Henri Achten

nr 143
Modelling Life Trajectories and Transport Mode Choice Using Bayesian Belief Networks
Marloes Verhoeven

nr 144
Assessing Construction Project Performance in Ghana
William Gyadu-Asiedu

nr 145
Empowering Seniors through Domotic Homes
Masi Mohammadi

nr 146
An Integral Design Concept for Ecological Self-Compacting Concrete
Martin Hunger

nr 147
Governing Multi-Actor Decision Processes in Dutch Industrial Area Redevelopment
Erik Blokhuis

nr 148
A Multifunctional Design Approach for Sustainable Concrete
Götz Hüsken

nr 149
Quality Monitoring in Infrastructural Design-Build Projects
Ruben Favié

nr 150
Assessment Matrix for Conservation of Valuable Timber Structures
Michael Abels

nr 151
Co-simulation of Building Energy Simulation and Computational Fluid Dynamics for Whole-Building Heat, Air and Moisture Engineering
Mohammad Mirsadeghi

nr 152
External Coupling of Building Energy Simulation and Building Element Heat, Air and Moisture Simulation
Daniel Cóstola

nr 153
Adaptive Decision Making In Multi-Stakeholder Retail Planning
Ingrid Janssen

nr 154
Landscape Generator
Kymo Slager

nr 155
Constraint Specification in Architecture
Remco Niemeijer

nr 156
A Need-Based Approach to Dynamic Activity Generation
Linda Nijland

nr 157
Modeling Office Firm Dynamics in an Agent-Based Micro Simulation Framework
Gustavo Garcia Manzato

nr 158
Lightweight Floor System for Vibration Comfort
Sander Zegers

nr 159
Aanpasbaarheid van de Draagstructuur
Roel Gijsbers

nr 160
'Village in the City' in Guangzhou, China
Yanliu Lin

nr 161
Climate Risk Assessment in Museums
Marco Martens

nr 162
Social Activity-Travel Patterns
Pauline van den Berg

nr 163
Sound Concentration Caused by Curved Surfaces
Martijn Vercammen

nr 164
Design of Environmentally Friendly Calcium Sulfate-Based Building Materials: Towards an Improved Indoor Air Quality
Qingliang Yu

nr 165
Beyond Uniform Thermal Comfort on the Effects of Non-Uniformity and Individual Physiology
Lisje Schellen

nr 166
Sustainable Residential Districts
Gaby Abdalla

nr 167
Towards a Performance Assessment Methodology using Computational Simulation for Air Distribution System Designs in Operating Rooms
Mônica do Amaral Melhado

nr 168
Strategic Decision Modeling in Brownfield Redevelopment
Brano Glumac

nr 169
Pamela: A Parking Analysis Model for Predicting Effects in Local Areas
Peter van der Waerden

nr 170
A Vision Driven Wayfinding Simulation-System Based on the Architectural Features Perceived in the Office Environment
Qunli Chen

nr 171
Measuring Mental Representations Underlying Activity-Travel Choices
Oliver Horeni

nr 172
Modelling the Effects of Social Networks on Activity and Travel Behaviour
Nicole Ronald

nr 173
Uncertainty Propagation and Sensitivity Analysis Techniques in Building Performance Simulation to Support Conceptual Building and System Design
Christian Struck

nr 174
Numerical Modeling of Micro-Scale Wind-Induced Pollutant Dispersion in the Built Environment
Pierre Gousseau

nr 175
Modeling Recreation Choices over the Family Lifecycle
Anna Beatriz Grigolon

nr 176
Experimental and Numerical Analysis of Mixing Ventilation at Laminar, Transitional and Turbulent Slot Reynolds Numbers
Twan van Hooff

nr 177
Collaborative Design Support: Workshops to Stimulate Interaction and Knowledge Exchange Between Practitioners
Emile M.C.J. Quanjel

nr 178
Future-Proof Platforms for Aging-in-Place
Michiel Brink

nr 179
Motivate: A Context-Aware Mobile Application for Physical Activity Promotion
Yuzhong Lin

nr 180
Experience the City: Analysis of Space-Time Behaviour and Spatial Learning
Anastasia Moiseeva

nr 181
Unbonded Post-Tensioned Shear Walls of Calcium Silicate Element Masonry
Lex van der Meer

nr 182
Construction and Demolition Waste Recycling into Innovative Building Materials for Sustainable Construction in Tanzania
Mwita M. Sabai

nr 183
Durability of Concrete with Emphasis on Chloride Migration
Przemysław Spiesz

nr 184
Computational Modeling of Urban Wind Flow and Natural Ventilation Potential of Buildings
Rubina Ramponi

nr 185
A Distributed Dynamic Simulation Mechanism for Buildings Automation and Control Systems
Azzedine Yahiaoui

nr 186
Modeling Cognitive Learning of Urban Networks in Daily Activity-Travel Behavior
Şehnaz Cenani Durmazoğlu

nr 187
Functionality and Adaptability of Design Solutions for Public Apartment Buildings in Ghana
Stephen Agyefi-Mensah

nr 188
A Construction Waste Generation Model for Developing Countries
Lilliana Abarca-Guerrero

nr 189
Synchronizing Networks: The Modeling of Supernetworks for Activity-Travel Behavior
Feixiong Liao

nr 190
Time and Money Allocation Decisions in Out-of-Home Leisure Activity Choices
Gamze Zeynep Dane

nr 191
How to Measure Added Value of CRE and Building Design
Rianne Appel-Meulenbroek

nr 192
Secondary Materials in Cement-Based Products: Treatment, Modeling and Environmental Interaction
Miruna Florea

nr 193
Concepts for the Robustness Improvement of Self-Compacting Concrete: Effects of Admixtures and Mixture Components on the Rheology and Early Hydration at Varying Temperatures
Wolfram Schmidt

nr 194
Modelling and Simulation of Virtual Natural Lighting Solutions in Buildings
Rizki A. Mangkuto

nr 195
Nano-Silica Production at Low Temperatures from the Dissolution of Olivine - Synthesis, Tailoring and Modelling
Alberto Lazaro Garcia

nr 196
Building Energy Simulation Based Assessment of Industrial Halls for Design Support
Bruno Lee

nr 197
Computational Performance Prediction of the Potential of Hybrid Adaptable Thermal Storage Concepts for Lightweight Low-Energy Houses
Pieter-Jan Hoes

nr 198
Application of Nano-Silica in Concrete
George Quercia Bianchi

nr 199
Dynamics of Social Networks and Activity Travel Behaviour
Fariya Sharmeen

nr 200
Building Structural Design Generation and Optimisation including Spatial Modification
Juan Manuel Davila Delgado

nr 201
Hydration and Thermal Decomposition of Cement/Calcium-Sulphate Based Materials
Ariën de Korte

nr 202
Republiek van Beelden: De Politieke Werkingen van het Ontwerp in Regionale Planvorming
Bart de Zwart

nr 203
Effects of Energy Price Increases on Individual Activity-Travel Repertoires and Energy Consumption
Dujuan Yang

nr 204
Geometry and Ventilation: Evaluation of the Leeward Sawtooth Roof Potential in the Natural Ventilation of Buildings
Jorge Isaac Perén Montero

nr 205
Computational Modelling of Evaporative Cooling as a Climate Change Adaptation Measure at the Spatial Scale of Buildings and Streets
Hamid Montazeri

nr 206
Local Buckling of Aluminium Beams in Fire Conditions
Ronald van der Meulen

nr 207
Historic Urban Landscapes: Framing the Integration of Urban and Heritage Planning in Multilevel Governance
Loes Veldpaus

nr 208
Sustainable Transformation of the Cities: Urban Design Pragmatics to Achieve a Sustainable City
Ernesto Antonio Zumelzu Scheel

nr 209
Development of Sustainable Protective Ultra-High Performance Fibre Reinforced Concrete (UHPFRC): Design, Assessment and Modeling
Rui Yu

nr 210
Uncertainty in Modeling Activity-Travel Demand in Complex Uban Systems
Soora Rasouli

nr 211
Simulation-based Performance Assessment of Climate Adaptive Greenhouse Shells
Chul-sung Lee

nr 212
Green Cities: Modelling the Spatial Transformation of the Urban Environment using Renewable Energy Technologies
Saleh Mohammadi

nr 213
A Bounded Rationality Model of Short and Long-Term Dynamics of Activity-Travel Behavior
Ifigeneia Psarra

nr 214
Effects of Pricing Strategies on Dynamic Repertoires of Activity-Travel Behaviour
Elaheh Khademi

nr 215
Handstorm Principles for Creative and Collaborative Working
Frans van Gassel

nr 216
Light Conditions in Nursing Homes: Visual Comfort and Visual Functioning of Residents
Marianne M. Sinoo

nr 217
Woonsporen: De Sociale en Ruimtelijke Biografie van een Stedelijk Bouwblok in de Amsterdamse Transvaalbuurt
Hüseyin Hüsnü Yegenoglu

nr 218
Studies on User Control in Ambient Intelligent Systems
Berent Willem Meerbeek

nr 219
Daily Livings in a Smart Home: Users' Living Preference Modeling of Smart Homes
Erfaneh Allameh

nr 220
Smart Home Design: Spatial Preference Modeling of Smart Homes
Mohammadali Heidari Jozam

nr 221
Wonen: Discoursen, Praktijken, Perspectieven
Jos Smeets

nr 222
Personal Control over Indoor Climate in Offices: Impact on Comfort, Health and Productivity
Atze Christiaan Boerstra

nr 223
Personalized Route Finding in Multimodal Transportation Networks
Jianwe Zhang

nr 224
The Design of an Adaptive Healing Room for Stroke Patients
Elke Daemen

nr 225
Experimental and Numerical Analysis of Climate Change Induced Risks to Historic Buildings and Collections
Zara Huijbregts

nr 226
Wind Flow Modeling in Urban Areas Through Experimental and Numerical Techniques
Alessio Ricci

nr 227
Clever Climate Control for Culture: Energy Efficient Indoor Climate Control Strategies for Museums Respecting Collection Preservation and Thermal Comfort of Visitors
Rick Kramer

nr 228
Fatigue Life Estimation of Metal Structures Based on Damage Modeling
Sarmediran Silitonga

nr 229
A multi-agents and occupancy based strategy for energy management and process control on the room-level
Timilehin Moses Labeodan

nr 230
Environmental assessment of Building Integrated Photovoltaics: Numerical and Experimental Carrying Capacity Based Approach
Michiel Ritzen

nr 231
Performance of Admixture and Secondary Minerals in Alkali Activated Concrete: Sustaining a Concrete Future
Arno Keulen

nr 250
Effects of the built environment on dynamic repertoires of activity-travel behaviour
Aida Pontes de Aquino

nr 251
Modeling for auralization of urban environments: Incorporation of directivity in sound propagation and analysis of a framework for auralizing a car pass-by
Fotis Georgiou

nr 252
Wind Loads on Heliostats and Photovoltaic Trackers
Andreas Pfahl

nr 253
Approaches for computational performance optimization of innovative adaptive façade concepts
Roel Loonen

nr 254
Multi-scale FEM-DEM Model for Granular Materials: Micro-scale boundary conditions, Statics, and Dynamics
Jiadun Liu

nr 255
Bending Moment - Shear Force Interaction of Rolled I-Shaped Steel Sections
Rianne Willie Adriana Dekker

nr 256
Paralympic tandem cycling and hand-cycling: Computational and wind tunnel analysis of aerodynamic performance
Paul Fionn Mannion

nr 257
Experimental characterization and numerical modelling of 3D printed concrete: Controlling structural behaviour in the fresh and hardened state
Robert Johannes Maria Wolfs

nr 258
Requirement checking in the building industry: Enabling modularized and extensible requirement checking systems based on semantic web technologies
Chi Zhang

nr 259
A Sustainable Industrial Site Redevelopment Planning Support System
Tong Wang

nr 260
Efficient storage and retrieval of detailed building models: Multi-disciplinary and long-term use of geometric and semantic construction information
Thomas Ferdinand Krijnen

nr 261
The users' value of business center concepts for knowledge sharing and networking behavior within and between organizations
Minou Weijs-Perrée

nr 262
Characterization and improvement of aerodynamic performance of vertical axis wind turbines using computational fluid dynamics (CFD)
Abdolrahim Rezaeiha

nr 263
In-situ characterization of the acoustic impedance of vegetated roofs
Chang Liu

nr 264
Occupancy-based lighting control: Developing an energy saving strategy that ensures office workers' comfort
Christel de Bakker

nr 265
Stakeholders-Oriented Spatial Decision Support System
Cahyono Susetyo

nr 266
Climate-induced damage in oak museum objects
Rianne Aleida Luimes

nr 267
Towards individual thermal comfort: Model predictive personalized control of heating systems
Katarina Katic

nr 268
Modelling and Measuring Quality of Urban Life: Housing, Neighborhood, Transport and Job
Lida Aminian

nr 269
Optimization of an aquifer thermal energy storage system through integrated modelling of aquifer, HVAC systems and building
Basar Bozkaya

nr 270
Numerical modeling for urban sound propagation: developments in wave-based and energy-based methods
Raúl Pagán Muñoz

nr 271
Lighting in multi-user office environments: improving employee wellbeing through personal control
Sanae van der Vleuten-Chraibi

nr 272
A strategy for fit-for-purpose occupant behavior modelling in building energy and comfort performance simulation
Isabella I. Gaetani dell'Aquila d'Aragona

nr 273
Een architectuurhistorische waardestelling van naoorlogse woonwijken in Nederland: Het voorbeeld van de Westelijke Tuinsteden in Amsterdam
Eleonore Henriette Marie Mens

nr 274
Job-Housing Co-Dependent Mobility Decisions in Life Trajectories
Jia Guo

nr 275
A user-oriented focus to create healthcare facilities: decision making on strategic values
Emilia Rosalia Catharina Maria Huisman

nr 276
Dynamics of plane impinging jets at moderate Reynolds numbers – with applications to air curtains
Adelya Khayrullina

nr 277
Valorization of Municipal Solid Waste Incineration Bottom Ash - Chemical Nature, Leachability and Treatments of Hazardous Elements
Qadeer Alam

nr 278
Treatments and valorization of MSWI bottom ash - application in cement-based materials
Veronica Caprai

nr 279
Personal lighting conditions of office workers - input for intelligent systems to optimize subjective alertness
Juliëtte van Duijnhoven

nr 280
Social influence effects in tourism travel: air trip itinerary and destination choices
Xiaofeng Pan

nr 281
Advancing Post-War Housing: Integrating Heritage Impact, Environmental Impact, Hygrothermal Risk and Costs in Renovation Design Decisions
Lisanne Claartje Havinga

nr 282
Impact resistant ultra-high performance fibre reinforced concrete: materials, components and properties
Peipeng Li

nr 283
Demand-driven Science Parks: The Perceived Benefits and Trade-offs of Tenant Firms with regard to Science Park Attributes
Wei Keat Benny Ng

nr 284
Raise the lantern; how light can help to maintain a healthy and safe hospital environment focusing on nurses
Maria Petronella Johanna Aarts

nr 285
Modelling Learning and Dynamic Route and Parking Choice Behaviour under Uncertainty
Elaine Cristina Schneider de Carvalho

nr 286
Identifying indoor local microclimates for safekeeping of cultural heritage
Karin Kompatscher

nr 287
Probabilistic modeling of fatigue resistance for welded and riveted bridge details. Resistance models and estimation of uncertainty.
Davide Leonetti

nr 288
Performance of Layered UHPFRC under Static and Dynamic Loads: Effects of steel fibers, coarse aggregates and layered structures
Yangyueye Cao

nr 289
Photocatalytic abatement of the nitrogen oxide pollution: synthesis, application and long-term evaluation of titania-silica composites
Yuri Hendrix

nr 290
Assessing knowledge adoption in post-disaster reconstruction: Understanding the impact of hazard-resistant construction knowledge on reconstruction processes of self-recovering communities in Nepal and the Philippines
Eefje Hendriks

nr 291
Locating electric vehicle charging stations: A multi-agent based dynamic simulation
Seheon Kim

nr 292
De invloed van Lean Management op de beheersing van het bouwproces
Wim van den Bouwhuijsen

nr 293
Neighborhood Environment and Physical Activity of Older Adults
Zhengying Liu

nr 294
Practical and continuous luminance distribution measurements for lighting quality
Thijs Willem Kruisselbrink

nr 295
Auditory Distraction in Open-Plan Study Environments in Higher Education
Pieternella Elizabeth Braat-Eggen

nr 296
Exploring the effect of the sound environment on nurses' task performance: an applied approach focusing on prospective memory
Jikke Reinten

nr 297
Design and performance of water resistant cementitious materials– Mechanisms, evaluation and applications
Zhengyao Qu

nr 298
Design Optimization of Seasonal Thermal Energy Storage Integrated District Heating and Cooling System: A Modeling and Simulation Approach
Luyi Xu

nr 299
Land use and transport: Integrated approaches for planning and management
Zhongqi Wang

nr 300
Multi-disciplinary optimization of building spatial designs: co-evolutionary design process simulations, evolutionary algorithms, hybrid approaches
Sjonnie Boonstra

nr 301
Modeling the spatial and temporal relation between urban land use, temperature, and energy demand
Hung-Chu Chen

nr 302
Seismic retrofitting of masonry walls with flexible deep mounted CFRP strips
Ömer Serhat Türkmen

nr 303
Coupled Aerostructural Shape and Topology Optimization of Horizontal-Axis Wind Turbine Rotor Blades
Zhijun Wang

nr 304
Valorization of Recycled Waste Glass and Converter Steel Slag as Ingredients for Building Materials: Hydration and Carbonation Studies
Gang Liu

nr 305
Low-Carbon City Development based on Land Use Planning
Gengzhe Wang

nr 306
Sustainable energy transition scenario analysis for buildings and neighborhoods - Data driven optimization
Shalika Saubhagya Wickramarachchi Walker

nr 307
In-between living and manufactured: an exploratory study on biobuilding components for building design
Berrak Kirbas Akyurek

nr 308
Development of alternative cementitious binders and functionalized materials: design, performance and durability
Anna Monika Kaja

nr 309
Development a morphological approach for interactive kinetic façade design: Improving multiple occupants' visual comfort
Seyed Morteza Hosseini

nr 310
PV in urban context: modeling and simulation strategies for analyzing the performance of shaded PV systems
Ádám Bognár

nr 311
Life Trajectory, Household Car Ownership Dynamics and Home Renewable Energy Equipment Adoption
Gaofeng Gu

nr 312
Impact of Street-Scale Built Environment on Walking/Cycling around Metro Stations
Yanan Liu

nr 313
Advances in Urban Traffic Network Equilibrium Models and Algorithms
Dong Wang

nr 314
Development of an uncertainty analysis framework for model-based consequential life cycle assessment: application to activity-based modelling and life cycle assessment of multimodal mobility
Paul Martin Baustert

nr 315
Variable stiffness and damping structural joints for semi-active vibration control
Qinyu Wang

nr 316
Understanding Carsharing-Facilitating Neighborhood Preferences
Juan Wang

nr 317
Dynamic alignment of Corporate Real Estate to business strategies: An empirical analysis using historical data and in-depth modelling of decision making
Howard Cooke

nr 318
Local People Matter: Towards participatory governance of cultural heritage in China
Ji Li

nr 319
Walkability and Walkable Healthy Neighborhoods
Bojing Liao

nr 320
Light directionality in design of healthy offices: exploration of two methods
Parisa Khademagha

nr 321
Room acoustic modeling with the time-domain discontinuous Galerkin method
Huiqing Wang

nr 322
Sustainable insulating lightweight materials for enhancing indoor building performance: miscanthus, aerogel and nano-silica
Yuxuan Chen

nr 323
Computational analysis of the impact of façade geometrical details on wind flow and pollutant dispersion
Xing Zheng

nr 324
Analysis of urban wind energy potential around high-rise buildings in close proximity using computational fluid dynamics
Yu-Hsuan Jang

nr 325
A new approach to automated energy performance and fault detection and diagnosis of HVAC systems: Development of the 4S3F method
Arie Taal

nr 326
Innovative Admixtures for Modifying Viscosity and Volume Change of Cement Composites
Hossein Karimi

nr 327
Towards houses with low grid dependency: A simulation-based design optimization approach
Zahra Mohammadi

nr 328
Activation of demand flexibility for heating systems in buildings: Real-life demonstration of optimal control for power-to-heat and thermal energy storage
Christian Finck

nr 329
A computational framework for analysis and optimisation of automated solar shading systems
Samuel B. de Vries

nr 330
Challenges and potential solutions for cultural heritage adaptive reuse: a comparative study employing the Historic Urban Landscape approach
Nadia Pintossi

nr 331
Shared control in office lighting systems
Tatiana Aleksandrovna Lashina

nr 332
Comfort in Urban Public Spaces
You Peng

nr 333
Numerical modelling of metal soap formation in historical oil paintings
Gerardus Johannes Anna Maria Eumelen

nr 334
A transdisciplinary decision-making approach to food-water-energy nexus: A guide towards sustainable development
Maryam Ghodsvali

nr 335
Numerical modelling of transient low-frequency sound propagation and vibration in buildings
Indra Sihar

nr 336
Characterization of impact sound from lightweight joist floors
Yi Qin

nr 337
Cities for Children: Supporting Children and Caregivers in Participatory Urban Planning
Özlemnur Ataol

nr 338
Engaging the unengaged: Exploring citizen participation in nature-based solutions in China
Li Dai

nr 339
Municipal Solid Waste Incineration Residues: analysis, treatments, and applications
Ekaterina Loginova

nr 340
Enhancing the Uptake of Nature-Based Solutions in Urban Settings: An Information Systems Approach
Shahryar Ershad Sarabi

nr 341
Work Schedule Arrangements in Two-Adult Households with Children
Bilin Han

nr 342
Increasing awareness of urban cultural heritage using digital technologies: empirical design and analysis of a new multi-media web platform
Benshuo Wang

nr 343
Mechanical and physical properties of fibre-cement composites using alternative natural fibres
Katerina Kochova

nr 344
Numerical and experimental investigation of urban microclimate in a real compact heterogeneous urban area
Nestoras Antoniou

nr 345
Examining in-class activities to facilitate academic achievement in higher education: A framework for optimal indoor environmental conditions
Henk W. Brink

nr 346
High-temperature resistant geopolymers: composition, microstructure and performance
Kinga Malgorzata Klima

nr 347
Individual and household decision-making in shared parking
Qianqian Yan

nr 348
In-situ formation of LDHs in Alkali activated binders
Tao Liu

nr 349
Condition assessment of concrete sewer pipes through an integrated experimental-numerical approach
Irene C. Scheperboer

nr 350
In situ PU-based characterization of sound absorbing materials for room acoustic modeling purposes
Baltazar Briere de La Hosseraye

nr 351
Uncertainty analysis and management in building energy data mining: A bottom-up approach considering the temporal and spatial aspect of data
Waqas Khan

nr 352
Personalized Heating Control Systems to improve thermal comfort and reduce energy consumption
Michal Veselý

nr 353
Restorative value of the urban greenscape: Urban residential streets as restorative environments
Robert P. van Dongen

nr 354
Urban ventilation and the compact Mediterranean city: numerical investigations of the dynamic relationships between density, morphology and wind flow
Olga Palusci

nr 355
Data science for buildings: a multi-scale approach bridging occupants to smart-city energy planning
Julien Leprince

nr 356
Class Association Rule Models for Predicting Transportation Mode Choice
Jiajia Zhang

nr 357
Acceptance and use of autonomous vehicles
Zhihui Tian

nr 358
Consumer Acceptance of Crowdshipping Services
Chenyu Wang

nr 359
Determinants of habitual participation in leisure-time physical activity and active travel in life trajectories
Xiaoyue Chen

nr 360
Analysis of Citizens' Motivation and Intention Using Modern Information Technology in Urban Planning Public Participation
Wenshu Li

nr 361
Linking smart and physical port cities. Port-city interface areas: from obsolete/isolated to smart environments.
Mercè de Miguel Capdevila

nr 362
Assessment and improvement of indoor thermal comfort and energy demand of Chinese heritage apartment buildings under climate change
Muxi Lei

nr 363
Indoor airflow and heat transfer in a cross-ventilated generic building: wind tunnel experiments and computational fluid dynamics analyses
Katarina Kosutova

nr 364
A Robotic Construction Simulation Platform for Light-weight Prefabricated Structures.
Aiyu Zhu

nr 365
Lifetime prediction of vertical-axis wind turbines based on CFD simulations and high-cycle fatigue modeling
Feiyu Geng

nr 366
Computational modeling of convective heat transfer at building surfaces
Samy Iousef

nr 367
Numerical simulation of the atmospheric boundary layer with application to natural ventilation
Raffaele Vasaturo

nr 368
Bouwen zonder scrupules. De Nederlandse bouwnijverheid tijdens de bezetting en de eerste jaren van wederopbouw (1940-1950)
Geert-Jan Mellink

nr 369
Factors Promoting a Positive Experienced Neighborhood Public Space--A Virtual Environment-based analysis.
Yuwen Zhao

nr 370
Place quality making in high-speed railway station areas: Devising place quality indicators for urban design, beyond the transport-land use divide
Jinglun Du

nr 371
Sustainable Bio-based Adsorptive Concrete for Phosphorus Removal
Fan Wu

nr 372
The physical workplace as a resource for mental health: A salutogenic approach to a mentally healthy workplace design at home and at the office
Lisanne Bergefurt

nr 373
High-end application of basic oxygen furnace steel slag as sustainable building materials
Muhammad Jawad Ahmed

nr 374
Energy-Efficient Urban Rail Transit Operations: Models, Algorithms, and Applications
Kang Huang

nr 375
Household Energy Efficiency Adoption: Influencing Factors and Diffusion Interventions
Hua Du

nr 376
High-temperature resistant geopolymer-based materials out of industrial residuals.
Yan Luo

nr 377
A Simulation Approach Exploring the Impacts of Land Use Variables on Travel Behavior.
Xiaoming Lyu

nr 378
Understanding and modelling individual preferences for Mobility as a Service
Valeria Caiati

nr 379
Linking the physical and digital built environment - Enabling occupant-centric decision-making using cross-domain semantic digital twins
Alex Donkers

nr 380
Indoor Air Quality in Daycare Centers: Assessing and Mitigating Indoor Exposure on Young Children
Hailin Zheng

nr 381
A Data-Driven Approach to Understanding Visitors' Behavior to Reduce the Negative Effects of Tourism in Historical Cities
Sezi Karayazi

nr 382
Wind effects on internal depressurization for asbestos abatement
Anjali Radhakrishnan Jayakumari

nr 383
Spatiotemporal Graph Convolutional Neural Network for Robust and Accurate Traffic Flow Prediction
Yutian Liu

nr 384
Photo-responsive functional aluminosilicate cementitious materials - Design, Performance and Durability
Daoru Liu

nr 385
High-end applications of basic oxygen furnace slag as a cementitious binder. Phase Assemblage, Mechanical & Chemical Activation, Composites Application
Winnie Franco Santos

nr 386
Towards improved performance modelling of distributed PV systems in the built environment
Bin Meng

nr 387
Development of sustainable insulation materials. Design, performance and applications
Alex Koh Chuen Hon

nr 388
Simulations of Sandwich Panel Systems under Fire: Two-Scale Methods for Connections, Pyrolysis for Insulation, Experimental Validations
Qingfeng Xu

nr 389
Long-term Mechanical Performance of the Flax Fiber Reinforced Polymer Composites Considering the Environmental Effects
Bowen Xu

nr 390
Quality engineering and control for digital fabrication with concrete
Derk Bos

nr 391
Structural Engineering of 3D Printed Strain Hardening Cementitious Composites. From micro-scale analysis to application
Karsten Nefs

nr 392
Children's Outdoor Play in the Digital Age; The Role of Digital Interventions in Stimulating Children's Outdoor Play Behavior
Avin Khalilollahi

nr 393
Biophilic design and integrating nature in architecture: Guidelines for three-dimensional green spaces to innovate architectural typologies and create impact for sustainability
Weijie Zhong