CONTEMPORARY USE OF CO-DESIGN AND COMPUTATIONAL DESIGN METHODS FOR INCLUSIVE BUILT ENVIRONMENTS: A CASE STUDY OF PLATFORM-TRAIN INTERFACES

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To dad

Acknowledgements

Completing this thesis has been a monumental journey, one that would not have been possible without the support, patience, and encouragement of several individuals.

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Summary

Accessibility of the built environment has a huge impact on the experience and extent of disability. This is particularly true for public spaces – for example, train stations – both indoors and outdoors. Mobility-related impairments are amongst the most common types of impairments, according to international disability indexes. There is an emerging need for researchers and practitioners to investigate the built environment through the lens of users of *mobility assistive devices* (MobAD) – such as wheelchairs or canes. The profound implications of design decisions on societal equality and individual wellbeing underscore the significance of this research.

Universal Design is a late twentieth-century design philosophy aimed at creating built environments that are accessible for both disabled and non-disabled people. So far, very little attention has been paid to the role of contemporary approaches, such as computational design or structural adaptation, as agents of universal design. The disregard for the functional capabilities of a diverse population as well as the technological stagnation of the spatial design profession are two major factors for built environments of substandard quality insofar as disability access is concerned.

The central aim of this research is to investigate the impact of ill-designed spaces on MobAD users and explore how designers can create accessible environments for all. Adopting a research-by-design approach, the research problem emerges from a real-world context and is continuously shaped by MobAD users' needs and interests. The research-by-design strategy fosters a seamless interplay between theory and application, encouraging interdisciplinary collaboration and stakeholder participation to create a usable and accessible solution.

The research design is realised in two parts: Part A focuses on understanding the problem through theoretical background investigation, literature review, and accessibility assessment. Part B centres on designing a suitable solution through a series of design ideation, inspiration, formation, and evaluation processes. The research employs various strategies to identify challenges and arrive at an appropriate solution, such as a systematic literature review, accessibility audits, online surveys, co-design workshops, computation-enabled design development, and usability evaluation.

The research revealed substantial disparities in the built environment in terms of MobAD-accessibility. Ill-designed spaces significantly impeded the mobility and independence of these individuals, while well-designed spaces facilitated inclusivity and enhanced user wellbeing. The study identified key areas of concern regarding physical inaccessibility and outlined specific requirements for designing accessible spaces. For the identified research problem, a human-centred design solution was proposed, developed through stakeholder participation and extensive use of state-of-the-art computational tools as well as structural adaptation. Upon evaluation, this solution demonstrated potential to improve accessibility for MobAD users at critical points within the built environment.

The contribution of this research has been to introduce new techniques, such applications of deep neural networks and evolutionary algorithms, which can highlight the potential usefulness of computational methods for the design practice. Moreover, this effort foregrounds structural adaptation as an enabler of physical accessibility and, thereby, augments the ambit of adaptive architecture beyond previously investigated domains. Most importantly, this research describes a practical application of an integrative design effort – i.e., one that adopts inclusive, collaborative, computational, and structurally-adaptive approaches – to alleviate social exclusion in the built environment.

Keywords: inclusive design, co-design, computational design, adaptive architecture, mobility assistive devices, disability

Contents

List of Figures

Glossary of terms and concepts

Analogy: Analogy is the process of association between situations from one domain (source) to another (target) made possible through the establishment of relations or representations.

Artificial intelligence (AI): AI refers to the simulation of human intelligence in machines that are programmed to think like humans and mimic their actions. AI can perform tasks that typically require human intelligence, such as visual perception, speech recognition, decision-making, and language understanding.

Building Information Modelling (BIM): BIM is a process involving the generation and management of digital representations of physical and functional characteristics of places using digital software. BIM is used to design, construct, operate, and maintain diverse physical infrastructures, such as buildings and road systems.

Cane user: an individual who uses a cane as a mobility aid. Canes are typically employed to improve balance, increase stability, or assist with walking, especially for those with visual impairments or disabilities that affect mobility.

Computer-Aided Design (CAD): CAD refers to the use of computer systems to aid in the creation, modification, analysis, or optimisation of a design. CAD software is used to increase the productivity of the designer, improve the quality of design, improve communications through documentation, and to create a database for manufacturing.

Design by analogy: Design-by-analogy is a creative problem-solving approach in the field of design and engineering, where a solution to a new problem or a design challenge is developed by drawing parallels or analogies from a different but structurally similar context.

Design optimisation: In a built-environment context, design optimisation refers to the process of adjusting a building's design to improve its efficiency, functionality, and/or sustainability, ensuring the best use of resources and space. This involves iterative testing and tweaking of design parameters – usually using computational tools – to enhance aspects such as energy efficiency, material use, spatial dynamics, and user comfort.

Evolutionary computation and algorithms: Evolutionary computation is a sub-field of AI that uses algorithms inspired by Darwinian evolution to solve complex problems, including optimisation issues with numerous variables. Evolutionary algorithms adapt and improve with more data and experience, mimicking biological evolution and breeding processes.

Machine learning: Machine learning is a popular AI technique, in which algorithms build data models to teach computers how to make predictions or take decisions so as to improve performance on some sets of tasks, such as speech or image recognition.

Neural networks: Neural networks, a machine learning method, are computational models inspired by the structure of biological brains. They consist of connected units or nodes called artificial neurons, which are organised in layers: an input layer, multiple hidden layers, and an output layer. Information is processed starting from the input layer, which receives data from the external environment, and is then passed through the hidden layers where it is further analyzed and processed. The output layer provides the final result of the data processing. Deep neural networks, a subtype of neural networks, feature several hidden layers with potentially millions of neurons, enabling them to independently learn and derive features from data for complex analysis.

Pattern recognition: Pattern recognition is a method that identifies and categorises patterns in data, where a pattern is defined as a group of similar items, objects, or features. Deep neural networks are employed within this field to recognise and classify objects and shapes – with visual imagery analysis being the most researched domain – even when obscured.

Quality of Life: Quality of life (QoL) expresses life aspects that contribute to a sense of security, physical and emotional well-being, engagement, freedom, control, and choice. There are many factors, facets, frameworks, and concepts to clarify its meaning. The World Health Organisation (WHO) distinguishes six main domains in measuring QoL of individuals: physical health, psychological state, level of independence, social relations, interaction with the environment, and spirituality/religion/personal beliefs as the domains of quality of life of individuals.

Stakeholders: this term refers to individuals or groups who have an interest or concern in a design project, such as the community, design professionals, and regulatory bodies.

Universal accessibility: Universal accessibility refers to the conditions for easy access that would allow any individual – regardless of their functioning capacity and disability status – to access and enjoy a place, product, or service, and to do so freely and independently.

Universal MobAD user: The concept of a “Universal MobAD user" refers to creating environments that are universally accessible to anyone using a mobility assistive device (MobAD), focusing on inclusivity regardless of a specific type or severity of mobility impairment. This approach aims to ensure that all aspects of the built environment are usable for everyone, enhancing accessibility and enabling independence for users with diverse functioning needs.

Videoconferencing: Videoconferencing is a technology that allows users in different locations to hold face-to-face meetings, through an internet-connected digital device (e.g., a laptop), a camera, and audio systems, without having to move to a single location. This technology is particularly convenient for business users in different cities or countries, as it saves time, expenses, and the need for travel.

Whiteboarding tools: Whiteboarding tools are digital applications or software that recreate the experience of using a physical whiteboard in a virtual environment. These tools provide a collaborative platform where multiple users can draw, write, and place digital sticky notes or images simultaneously, regardless of their location.

1. Introduction

According to the International Human Rights Law (UN, 1948), human rights are “rights inherent to all human beings, regardless of race, gender, nationality, ethnicity, language, religion, or any other status. Human rights include the right to life and liberty, freedom from slavery and torture, freedom of opinion and expression, the right to work and education, and many more. Everyone is entitled to these rights, without discrimination”. Despite these fundamental principles, disabled individuals often face challenges and barriers in fully exercising their human rights. These challenges include, but are not limited to, physical accessibility, communication barriers, discriminatory attitudes, and lack of equal opportunities in education and employment.

The current thesis focuses on the reciprocal relations that develop between the built environment and disabled people as well as the potential role of technology as a facilitator in this context. The thesis is mainly directed to design researchers and professionals, as it scrutinises cases where design has aggravated the disabled people-built environment relationship as well as ways in which design can ameliorate this relationship. Figure 1.1 illustrates the primary components of this thesis. The following sections of this chapter provide further information on thesis components before elucidating the research purpose.

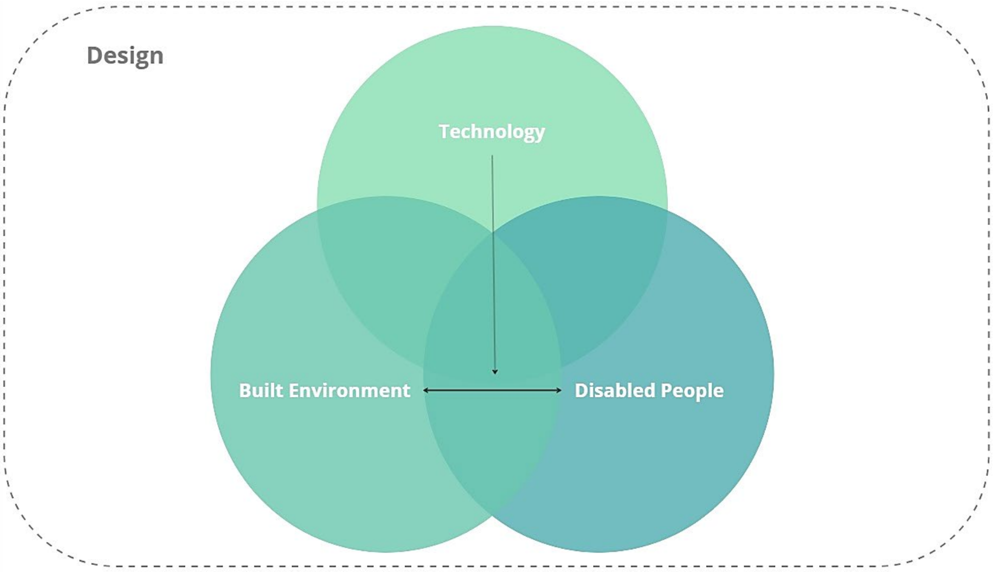


Figure 1.1: Primary components of this thesis

1.1. Research context

Understanding the interplay between disabled individuals and the built environment is pivotal for enhancing their access to fundamental human rights. This section delineates the critical aspects of disability, its interaction with physical spaces, and the overarching importance of the present research. The following subsections will explore the nature and implications of disability, analyse how the built environment can impact disabled people, and underscore the significance of this research in contributing to more inclusive design practices and outputs, with a long-term vision to support a more equitable and inclusive society.

1.1.1. Disability

For this thesis, *disabled people* are the main subject of interrogation. Disability is part of the human condition. It is a condition that can significantly affect the quality of life of individuals, namely their health and well-being, functioning capabilities, and participation in society (Drum, 2009; Nagi, 1991). Almost everyone will be temporarily or permanently impaired at some point in life, and those who survive to old age will experience increasing difficulties in functioning (Davis, 2013). Most extended families have at least one disabled member, and many non-disabled people take responsibility for supporting and caring for their relatives and friends with disabilities. This issue will become more acute as the demographics of societies change and more people live to an old age (Lee, 2003).

Regarding disability statistics, an estimated 1 billion people worldwide have some type of disability, which is approximately 15% of the global population (UN, 2019). Disability is more common among older adults; with 20% of people aged 60 and over having a disability, compared to 10% of people aged 15 to 59 (UN, 2019). In a UK context, recent data has shown that an estimated 14.1 million people reported having a disability, which is 21% of the country's population (GOV UK, 2022). It is worth noting that the employment rate for disabled people aged 16 to 64 was 53.6% in 2020, compared to 82.4% for non-disabled people

(GOV UK, 2022). Additionally, disabled people are less likely to have a degree-level qualification (29.7%) than non-disabled people (43.8%) (GOV UK, 2022). According to the latest statistics from the Family Resources Survey 2020-21, the most common type of disability in the UK is mobility related (GOV UK, 2022). An estimated 7.6 million people, which corresponds to 11% of the country's population, reported having a mobility-related disability due to multiple conditions, including, but not limited to, arthritis, multiple sclerosis, cerebral palsy, and leg fractures (GOV UK, 2022).

On many occasions, *assistive technologies* have been implemented to support disabled people to maintain or improve their everyday activities (Hamraie, 2017). The term refers to any technology that is designed to help people with disabilities. *Assistive devices* are the by-products of the eponymous technologies, such as screen readers, speech recognition software, wheelchairs, and voice-activated assistants (Cowan et al., 2012). Approximately 650 million people worldwide use at least one assistive device, which is just under 10% of the global population (UN, 2019). In a UK context, hearing aids are the most common assistive device, with an estimated 3.8 million people (5.5% of the total population) reported using one (GOV UK, 2022). This is followed by mobility aids, such as walking sticks, crutches, and wheelchairs, which were used by an estimated 2.2 million people (3.2% of the population) (GOV UK, 2022). Notwithstanding the contribution of assistive devices, existing societal barriers (e.g., stereotyping and prejudice) or physical obstacles in the built environment can be insurmountable challenges for disabled people.

Over the years, different approaches have been developed regarding how disability is understood and experienced by researchers in the field. According to Drum (2009), the medical, functional, and social model of disability comprise three primary conceptualisations of disability.

- The *Medical Model* of disability views disability as an individual's underlying condition or impairment that can be cured or ameliorated through treatment or intervention (Nagi, 1991). It focuses on the individual's physical and mental impairments (e.g., mobility, sensory, intellectual, communication, and developmental impairments) and their ability to engage in substantial gainful work (Drum, 2009). Despite that many researchers have adopted it, the Medical Model has certain limitations, such as treating disabilities as a single category rather than recognising the diversity and complexity of disability experiences (Iezzoni & Freedman, 2008). This can lead to a “one-size-fits-all” approach to disability, which may not adequately address the needs of all disabled individuals. Additionally, it relies heavily on medical interventions to address disabilities through surgery, medication, and therapy (Drum, 2009).
- The *Functional Model* of disability focuses on the individual's ability to carry out activities. It supports the belief that there are two types of people: those with functional limitations (the "disabled") and those without functional limitations (the "able-bodied") (Drum, 2009). This model emphasises individual performance and can overlook the important role external factors (i.e., medical, physical, cultural, environmental, or political) play in creating disability status (Nagi, 1991). The functional model can have some advantages, such as providing a more objective and standardised way of evaluating disability and ensuring that benefits and accommodations are provided to those who need them. However, it also has some limitations, such as possible stigmatisation of disabled individuals by defining them solely in terms of their limitations and by implying that they are unable to contribute fully to society (Liachowitz, 2010). This can perpetuate negative stereotypes and lead to discrimination.

- The Social Model of Disability shifts the concept of disability from counting or categorising deficits or impairments within an individual to focus on barriers people face interacting with the environment (Drum, 2009). It suggests that disability is socially created and lies in an individual's inability to access the environment. This model emphasises the importance of legal rights and protection and seeks to eliminate discriminatory attitudes, organisational failures, and physical barriers in the built environment (Wendell, 1996). It also promotes disability as a positive individual and collective identity, rather than a personal misfortune, and rejects characterisations of disability as negative (Edwards & Imrie, 2003). However, some critics argue that the Social Model understates or ignores the impact of individual impairments or conditions (Tregaskis, 2003). A common belief among opponents of this model is that some disabilities may have a significant impact on an individual's ability to perform certain tasks regardless of social or environmental factors (Humphrey, 2000).

In theory and practice, components of these models may be mixed. The significance of the three models is that they offer different perspectives on disability, and each model has implications for how society views and treats individuals with disabilities. Mostly aligning with the Social Model of disability, this thesis understands that environmental barriers are predominantly culpable of individuals' inability to fully perform activities of daily living, such as transferring, transporting, and shopping.

There is a significant need for researchers and practitioners in the field of disability studies to investigate physical, organisational, and attitudinal barriers through the lens of users of *mobility assistive devices* (MobAD) – such as wheelchairs, mobility scooters, and canes. This is mainly because this particular group is heterogeneous in terms of (a) medical backgrounds and severity/progression of impairments, (b) functioning capabilities, and (c) device characteristics. For example, some individuals may require a MobAD only for temporary periods, such as during recovery from surgery, while others may rely on a device for their entire lives. Some may have conditions that affect their ability to use certain types of devices or that require specialised features. For instance, a person with a spinal cord injury may use a manual wheelchair, which requires upper body strength and may not be suitable for certain terrains or long distances. Alternatively, the person may use a power wheelchair, which is easier to operate but may require more maintenance and is generally more expensive. Additionally, individuals may experience different types of barriers and discrimination based on the type of mobility device they use. For instance, wheelchair users being denied access to buildings that are not wheelchair accessible while cane users can use those same buildings.

Further to the heterogeneity of MobAD users, the demographic prevalence of this particular group is another crucial factor that warrants attention in research. As indicated above, MobAD users represent a significant portion of the population; understanding their needs and experiences is critical for developing effective policies and support services that meet the diverse and evolving needs of this group. Additionally, as the population ages, and the prevalence of chronic health conditions increases, the number of people requiring mobility assistance is likely to increase. This highlights the importance of research that focuses on the unique needs and experiences of MobAD users in order to promote their social inclusion, maximise their independence, and ensure their full participation in all aspects of society. Therefore, MobAD users comprise the study population of the current research.

1.1.2. Built environment and physical barriers for the Disabled

The built environment is the human-made physical surroundings where people live, work, and interact with one another (CIC, 2017). It includes buildings, streets, parks, transport systems, and other infrastructure or man-made product that make up the physical fabric of human communities (Digital Built Britain, 2022). The built environment can shape human behaviour, health, and quality of life, and plays a critical role in sustainable development (UNESCO, 2018).

Public spaces provide the spatial context for community activities such as transport, recreation, and retail in the built environment (Design Council UK, 2003). Carmona (2019) describes public spaces “as the focus for public life, activities, and events”, which can “range in form from informal street corners to grand civic set pieces”. Urban public spaces can be open, such as parks, squares, or sidewalks, or built-up areas, such as libraries or other public service buildings, used by people in cities. The division between public and private uses is not always discernible in the public realm, especially across dense urban environments (Cho et al., 2015). For instance, several urban thinkers regard sidewalk cafés or restaurant courtyards as indispensable parts of vibrant public spaces (Gehl, 2011; Jacobs, 1993). Oldenburg coined the term “third places” to interpret “a great variety of public places that host the regular, voluntary, informal and happily anticipated gatherings of individuals beyond the realms of home and work” (Oldenburg, 1999). This definition encapsulates privately-owned areas that attract the public interest, such as shopping malls, fitness centres, and art galleries, and are eventually utilised and perceived as parts of the public realm.

Despite their typological or structural variations, a central norm of all public spaces should be that all members of the community have access to them by right or invitation (Fraser, 1990; Harvey, 2006; Lefebvre, 1968). Figure 1.2 provides an example from a public space in Vancouver where designers have integrated ramped pathways into stairs to maximise accessibility for the Disabled.

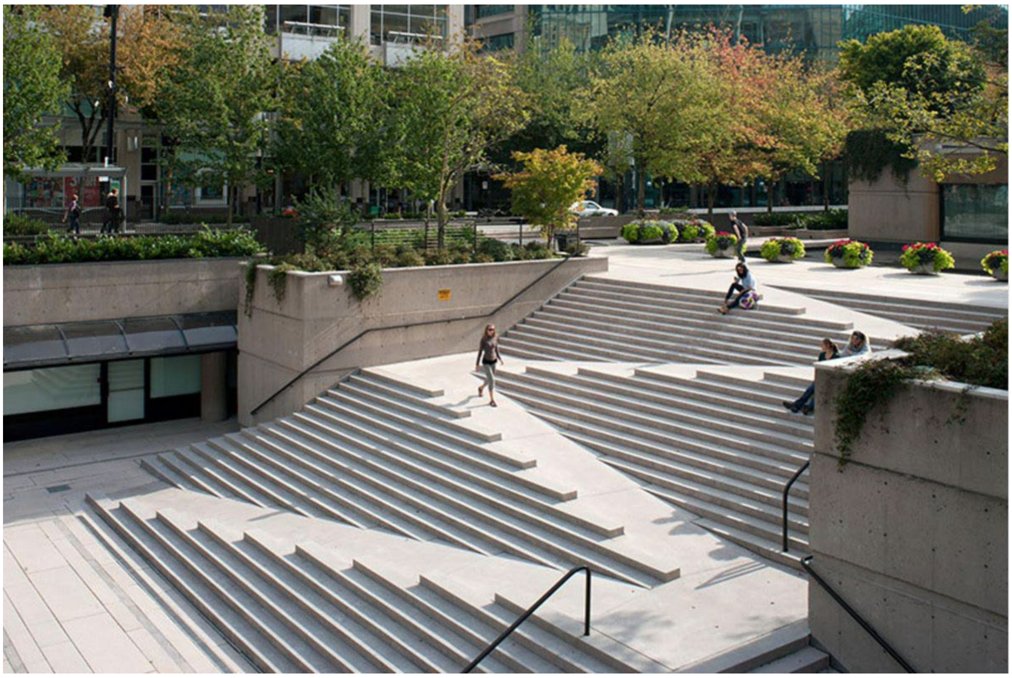


Figure 1.2: Ramps blended into public stairs in Vancouver. Source: Twitter.

Testing the vision of universal access, this thesis focuses on how physical barriers can render public spaces inaccessible to disabled people, thus influencing their quality of life. Specifically, the thesis explores how physical barriers in the built environment significantly affect health and safety, independence, and social participation, which are crucial aspects of quality of life for disabled individuals. Physical and emotional health and safety are primary indicators of QoL (WHO, 1997). Within the field of public health, there is a mounting accusation that the built environment has substantial impacts on personal health and safety (Pineo et al., 2018; Grant et al., 2017). Examples of health and safety issues of disabled people related to urban design include physical factors in tips-and-falls as well as contributors to obesity such as neighbourhoods with limited healthy food retail.

Independence is the ability of people to perform activities and tasks autonomously (WHO, 1997). Research from the fields of human factors and ergonomics has proven that the way an artefact is designed has a strong influence on the independence of its users (Pheasant, 2014; Roger et al., 2015). Similarly, the design of public spaces can increase or diminish the independence of the urban population. For instance, the absence of handrails in public restrooms may limit the functional performance of mobility-impaired people.

Participation in society and everyday activities – including transport, education, employment, political and public life, and healthcare – is a fundamental human right (United Nations, 1948). This is also true for facilitators of social participation, such as transport infrastructure. The Convention on the Rights of People with Disabilities supports the right of all individuals to “full and effective participation and inclusion in society” (United Nations, 2006). Physical accessibility of public spaces can accommodate disabled people with participating in society and performing everyday activities (Hamraie, 2017; Null, 2013). For instance, the provision of automatic doors in transport hubs can allow wheelchair users to experience fewer physical barriers when using public transport.

The above underscores the imperative to redesign and adapt public spaces to be universally accessible, thereby ensuring that all individuals, regardless of functioning capabilities, can engage fully and safely in community life. As this thesis progresses, it will further investigate specific interventions that can remove physical barriers, highlighting how these changes contribute to an inclusive and equitable urban environment. Thus, the drive towards accessibility enhances individual quality of life and fosters a more cohesive and supportive society.

1.2. Research significance

There is a significant need for researchers and practitioners in the field of disability studies to investigate physical barriers in the built environment through the lens of users of mobility assistive devices (MobAD) – such as wheelchairs, mobility scooters, and canes. This is mainly because this particular group is heterogeneous in terms of (a) medical backgrounds and severity/progression of impairments, (b) functioning capabilities, and (c) device characteristics.

The research recognises the various medical backgrounds and the different stages of impairments among MobAD users, which directly influence their interaction with built environments. For example, some individuals may require a MobAD only for temporary periods, such as during recovery from surgery, while others may rely on a device for their entire lives. A deeper understanding of these factors is crucial for designing inclusive spaces that accommodate not only the current needs of individuals but also anticipate potential future requirements as impairments progress. This approach ensures that built environments remain accessible and functional for users over time, regardless of changes in their medical condition.

By taking into account the diverse functioning capabilities of MobAD users, this research aims to address the broad spectrum of accessibility needs in built environments. A considerable portion of MobAD users may have conditions that affect their ability to access certain types of spaces. For instance, a person with a spinal cord injury may use a manual wheelchair, which requires upper body strength and may not be suitable for certain terrains or long distances. This is particularly important in creating spaces that do not just comply with basic legal accessibility standards but truly enhance user experience and interaction. The thesis focuses on developing design principles that are adaptable to different levels of mobility and independence, thereby fostering an environment where all individuals can participate fully and comfortably in community and public life.

The variability in the characteristics of mobility assistive devices, such as size, turning radius, and control mechanisms, presents unique challenges in environmental design. This research aims to optimise the physical layout and features of built environments to accommodate these diverse characteristics. Additionally, individuals may experience different types of barriers and discrimination based on the type of mobility device they use. For instance, wheelchair users being denied access to buildings that are not wheelchair accessible while cane users can use those same buildings. By integrating insights from real-world device usage into environmental planning and design, the study seeks to produce more practical and contextually relevant solutions that enhance navigability and safety for all MobAD users, thus promoting greater inclusion.

Further to the heterogeneity of MobAD users, the demographic prevalence of this particular group is another crucial factor that warrants attention in research. As indicated in Chapter 1.1.1, MobAD users represent a significant portion of the population; understanding their needs and experiences is critical for developing effective policies and support services that meet the diverse and evolving needs of this group. Additionally, as the population ages, and the prevalence of chronic health conditions increases, the number of people requiring mobility assistance is likely to increase. This highlights the importance of research that focuses on the unique needs and experiences of MobAD users, in order to promote their social inclusion, maximise their independence, and ensure their full participation in all aspects of society.

To achieve a vital improvement in accessibility within built environments, a shift towards more human-centred, adaptive, and technologically integrated design approaches is imperative compared to existing conditions. This transition is essential for fostering spaces that are not only compliant with accessibility standards but truly inclusive and responsive to the varied needs of MobAD users.

Currently, many built environments adhere to basic accessibility standards, which do not necessarily account for the diverse and specific needs of MobAD users. For a transformational change, design processes must become more human-centred than they are now, involving MobAD users directly in the design process to capture a broader spectrum of requirements (Escobar, 2018). This approach contrasts sharply with the often generic and minimal compliance-driven approaches observed today. By integrating direct user feedback and participatory design practices, designers can create environments that are intuitively navigable and genuinely suited to the users' day-to-day experiences and challenges (Razzouk & Shute, 2012).

Unlike many designs that are static and inflexible, structural adaptation advocates for environments that can adjust to changing user needs and technological advancements (Fox & Kemp, 2009). The typical fixed layouts and rigid structures prevalent in today's buildings often fail to accommodate the evolving nature of mobility impairments and the diverse functionalities of different MobAD. Emphasising structural adaptation would mean that spaces are built with the flexibility to reconfigure settings and infrastructure – such as adjustable access, modular furniture, and repositionable fixtures – to maintain continual accessibility and relevance.

While some contemporary environments have begun to integrate technology for accessibility, the scope and effectiveness of these integrations are often limited. A future where design is significantly informed by digital technological innovations would involve more extensive use of real-time data, AI, and IoT technologies to enhance user interaction with the environment (Koch, 2019; Zhang, 2020). This contrasts with the current sporadic and often superficial use of technology, moving towards a more comprehensive implementation that includes real-time navigation assistance, environmental personalisation, and obstacle detection systems that actively contribute to the autonomy and safety of MobAD users.

This thesis harnesses human-centred design, structural adaptation, and digital technological innovation as the three pivotal factors to transform the design of the built environment and ameliorate physical barriers, thereby significantly enhancing accessibility for MobAD users. By championing these principles, the research aims to surpass the limitations of current design practices and catalyse a substantial evolution in how built environments accommodate the diverse and dynamic needs of MobAD users. Each design approach is explored as a radical redefinition of inclusivity and functionality, aiming to create spaces where access is optimised for all MobAD users, regardless of their functional status.

1.3. Main aim and objectives

This thesis is influenced by the social model of disability and its repercussions for MobAD users. As explained in Chapter 1.1.1, this model suggests that disability is a result of the interaction between the person and an environment that is not designed to accommodate their needs. This model shifts the focus from the medical perspective, which views disability as a problem to be “fixed” within the individual, to a broader societal responsibility to create inclusive and accessible environments. As such, the social model of disability is crucial to understanding how the built environment can both exacerbate and alleviate the challenges faced by MobAD users. By recognising that physical barriers are primary causes of disability, spatial designers ought to work towards creating environments that cater to the needs of all individuals, regardless of their physical abilities.

Therefore, the *dual aim* of this research is to **identify how ill-designed spaces impact the experiences of MobAD users in the built environment and explore in what ways designers can create environments that are accessible to all MobAD users**.

The thesis is structured around four *research objectives (ROs)*, which break down the main aim into actionable components. These objectives provide specific, measurable steps that address the research questions effectively. The following lines describe these four research objectives in detail:

- ***RO1: Identify accessibility barriers in the built environment for MobAD users***.
- ***RO2: Engage with MobAD users to gather insights on challenges they face due to accessibility barriers and co-ideate possible solutions.***

- ***RO3: Develop solutions to enhance accessibility at critical points within the built environment using modern design techniques and advanced technologies.***
- ***RO4: Assess the effectiveness of the developed solutions in enhancing accessibility and usability for MobAD users.***

It is important to emphasise this thesis does not culminate in the development of a fully implemented, ready-to-use product. Rather, the preeminent contribution of this academic endeavour lies in the delineation of a methodical sequence of steps and methods, posited as a useful resource for other researchers who aspire to embark upon analogous projects in the future. Consequently, the significance of this thesis is predicated upon the establishment of a comprehensive and replicable design process, elucidating innovative methods and providing guidance for subsequent investigations in the field.

1.4. Process of knowledge generation

The process of knowledge generation is a critical aspect of any research endeavour, as it lays the foundation for the methodological rigour, theoretical grounding, and overall validity of the study's findings. This section aims to provide a comprehensive account of the various components that contributed to the generation of new knowledge in this PhD thesis, which explores how the design of built environments can affect MobAD users.

In the current research, the overarching question is centred around a dual aim, which essentially signifies the dichotomy between good and bad design in a spatial context. The research begins by identifying problematic spaces or areas where design falls short of meeting its intended purpose. Once these problematic spaces have been identified, the research then moves on to explore possible solutions to these issues. This approach allows for a comprehensive analysis of the current state of the built environment regarding physical accessibility and provides a basis for addressing design problems in a systematic and effective way for the benefit of MobAD users.

1.4.1. Research approach

The present thesis adopts a research-by-design approach, which entails the examination of design applications and the generation of novel architectural knowledge through experimental interventions and the process of designing (Hauberg, 2011). This integrates empirical research with practical design solutions, fostering a seamless interplay between theory and application. Employed across various disciplines, including architecture and industrial design, this iterative process empowers interdisciplinary collaboration, encourages stakeholder participation, and promotes the generation of context-specific and evidence-based solutions. By positioning design as an active research tool, research-by-design enables practitioners to tackle complex challenges, develop informed strategies, and contribute to the advancement of the professional knowledge base.

Research-by-design is an innately pragmatic approach, as it acknowledges two key parts in the progression of the research narrative: (a) understanding the problem and (b) designing the solution for the previously defined problem. This resonates the duality in the main aim of this research, as seen in Chapter 1.3. Following a research-by-design approach, this work initially investigates the phenomenon of physical inaccessibility in public spaces (Part A) before implementing a series of innovative design strategies aimed at resolving the issue and disseminating design knowledge (Part B). Figure 1.3 encapsulates the two-part approach of this thesis in a diagram.

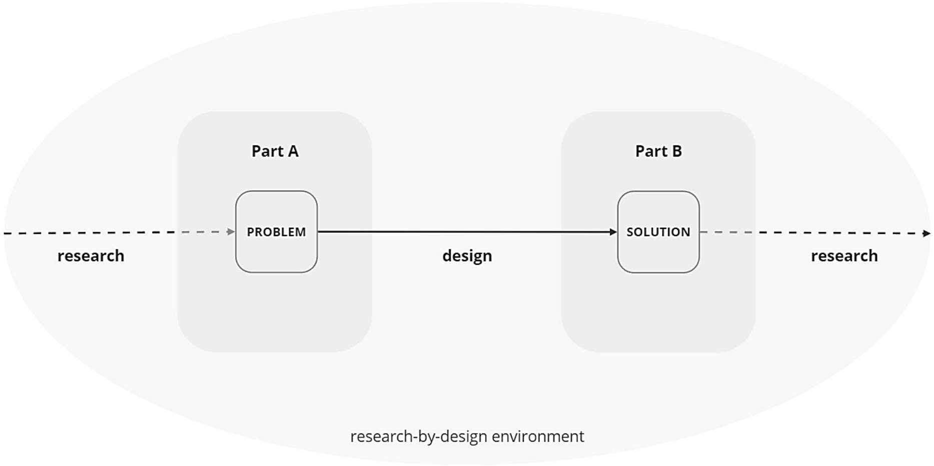


Figure 1.3: A research-by-design approach followed in this thesis.

In *Part A*, the thesis initially provides a critical overview of previous studies related to the research topic – i.e., MobAD-accessibility of public spaces. Also, an in-depth examination of the physical inaccessibility of public spaces is conducted, as well as an analysis of the subsequent needs of MobAD users. Work included in Part A addresses the first two research objectives (RO1 and RO2).

Part B focuses on developing a human-centred solution, which is facilitated through stakeholders' participation and implemented through contemporary digital technologies and adaptive design techniques. It embodies the design process followed for the intended solution, which encompasses four main steps: ideation, inspiration, formation, and evaluation. Part B addresses research objectives 2, 3, and 4 (RO2-4).

1.4.2. Research design

The research-by-design process implemented in this thesis encompasses six interrelated stages, two of which are dedicated to comprehending the problem (Part A), while the remaining four are dedicated to devising a solution to address the identified problem (Part B). To achieve those and to comprehensively address the research objectives, a mix of research strategies and tactics have been employed. Before delving into how these two elements have been incorporated, it is essential to clarify the distinction between them:

- A research *strategy* is a broader, high-level plan or approach that guides the research process. It includes the overall methodology employed to address the research questions and objectives. Research strategies are typically informed by the research problem and the nature of different stages throughout the research process.

- In contrast, a research *tactic* refers to the specific techniques or tools used to implement the research strategy. These tactics are employed to collect, analyse, and interpret data within the context of the chosen research strategy. Simply put, the research strategy outlines the overall approach, while research tactics are the specific techniques used to carry out that approach.

Each stage of the research process is guided by one or two distinct strategies designed to address the respective research objectives effectively. These strategies form the backbone of the research design, ensuring a systematic and coherent approach to the research problem. To execute these strategies, various research tactics have been employed, tailored to the specific needs of each stage. Table 1.1 provides an overview of the research design, outlining the specific stages of this thesis, alongside their corresponding strategies as well as the research objectives they realise.

Regarding the research tactics adopted in each stage, those are described in the respective chapters where they have been implemented. This approach serves the purpose of text cohesion and organisation as it allows for a more focused and contextual presentation of the tactics used. By describing the research tactics in their corresponding chapters, readers can better appreciate the rationale behind their usage and the specific ways in which they contribute to addressing the research objectives. This approach also enables a clearer understanding of the interplay between the research strategies and tactics, enhancing the overall narrative and flow of the thesis.

Stage	Strategies taken	Research objectives
Part A		
Literature review	Systematic review	RO1
Accessibility assessment	Access audit, social survey	RO1, RO2
Part B		
Design ideation	Interviews, design workshops	RO2
Design development	Archival search, simulation	RO3
Design evaluation	Usability evaluation	RO4

Table 1.1: Overview of study design

1.4.3. Thesis structure

The thesis is organised in 10 chapters, which largely correspond to different stages of the research-by-design process, as described in Table 1.1. Chapter 1, the current chapter, introduces the research topic, outlining the context, significance, purpose, and methodology for this research. Chapter 2 presents the theoretical background, forming the foundation for the study.

Chapter 3 offers a comprehensive review of current literature, highlighting the state of the field and identifying research gaps. Chapter 4 details the methods and results of the accessibility assessment, including the audit, survey, and analysis of current conditions and user needs. Chapter 5 provides a comprehensive presentation of the design problem and existing solutions.

Chapter 6 focuses on design ideation, describing the processes of interviews and workshops that lead to potential solutions. Chapter 7 delves into design development, taking inspiration from precedent projects and optimising design forms according to human needs and spatial requirements. Chapter 8 provides a comprehensive presentation of the proposed solution to the design problem, informed from design knowledge collected in previous chapters. Chapter 9 presents the design evaluation, including usability testing and feedback from stakeholders.

Chapter 10 synthesises the research findings and discusses the implications of the study, its limitations, and highlights the overall contributions of the study to academia, practice, and society. Table 1.2 briefly presents the thesis layout, including information on the alignment with the respective stages of the research-by-design process followed in this work.

1. Introduction	Research context, purpose, significance, and methodology
2. Theoretical background	Understanding the foundational concepts related to the research
3. Systematic review	A critical overview of previous studies
4. Integrative accessibility assessment	Identifying physical barriers and MobAD users' needs
5. Design problem definition	Clear description of the design problem
6. Collaborative ideation	Co-designing solutions according to MobAD users' preferences and ideas
7. Design development	Drawing inspiration from precedent designs and optimising those to satisfy human and spatial requirements
8. Proposed solution description	Detailed description of the proposed design solution
9. Usability evaluation	Assessment of the effectiveness and suitability of the proposed design solution
10. Discussion	Synthesis of research findings, research contribution, and limitations

Table 1.2: Thesis structure in chapters

It is noteworthy to emphasise that this thesis adheres to a *compilation format*, wherein each chapter conforms to the traditional research structure of purpose, methods, and results, which is widely employed in scholarly investigations (Figure 1.4). This structure is expected to result in a more in-depth analysis and a clearer presentation of the findings.

Also, the adoption of a compilation format for this thesis is attributed to the methodological contribution it intends to make, as this format facilitates the development and application of distinct methodologies across respective chapters.

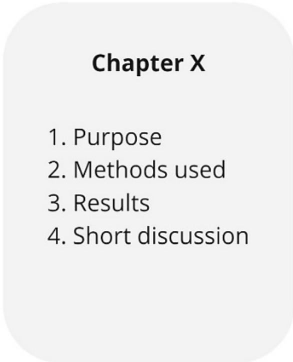


Figure 1.4: Structure of an example thesis chapter

In addition to the purpose, methods, and results sections, each chapter following a compilation format contains a short discussion component. This is separate to the general discussion included later in Chapter 10, which synthesises insights from all chapters and includes the overall contributions of this work. It is essential to clarify that the aforementioned format does not apply to Chapters 2 (i.e., Theoretical Background), 5 (i.e., Problem Definition), and 8 (i.e., Description of Proposed Solution), which possess a descriptive nature in contrast to the analytical character of the remaining chapters.

To ensure cohesion, bridge sections are incorporated between consecutive chapters that realise the research-by-design inquiry (i.e., Chapters 3-9, Figure 1.5), each of which provides a summary of the main concepts covered in the previous chapter and previewing the topics to be explored in the next chapter. This is to facilitate the transition between chapters, tie together different parts of the thesis, and indicate the reader's position in the research narrative.

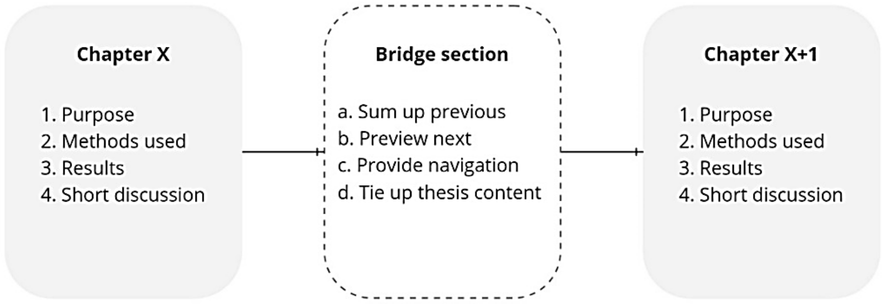


Figure 1.5: A bridge section between two example chapters.

As the thesis unfolds, each subsequent chapter will delve deeper into the methods used and generated outcomes, providing a thorough and nuanced understanding of the research problem and comprehensively presenting the undertaken steps to design a viable solution.

In conclusion, this chapter has presented the foundations upon which this thesis is built. By embracing a research-by-design approach, the research is guided by a practical and problem-solving orientation. The study design, encompassing seven interconnected stages and their respective strategies, ensures a systematic and comprehensive exploration of the research problem. The structure of the thesis, comprising ten chapters, serves to organise the research process and present the findings in a coherent and accessible manner.

2. Theoretical background

This chapter provides a thorough presentation of the theoretical background for the current research. The chapter aims to provide a comprehensive overview of the relevant theories, concepts, and methods in the field, which serve as the foundation for the thesis. By engaging with background knowledge, this chapter will guide the research approach, ensure the validity and reliability of the research, and facilitate the interpretation and discussion of the results. Furthermore, this chapter highlights the gaps in current knowledge and contributes to the advancement of the design field by proposing new perspectives, theories, or modifications to existing ones. The value of the thesis is thus enhanced by grounding it in a well-developed theoretical framework, allowing for a more robust understanding of the existing knowledge and its potential implications.

The theoretical background of this thesis encompasses four fundamental and interconnected elements: Universal Design, Collaborative Design, Computational Design, and Adaptive Architecture. Each section will delve into the various approaches and techniques that underpin these concepts, as well as present relevant case studies to illustrate their practical applications. The analysis provided in each subsection will be connected to the overall research objectives by expounding the specific ways in which the presented theories or methods are integrated into the design process. By doing so, this chapter will establish a strong theoretical basis and elucidate the interdisciplinary nature of the research, highlighting the synergies between these four key areas and their collective contribution to achieving the research objectives. The final pages will explicate the significance of this research by identifying a procedural gap that this thesis aims to fill.

2.1. Universal design

Universal Design is a design philosophy focused on creating products, environments, and systems usable by everyone, regardless of age, ability, or other factors, aligning closely with inclusive concepts like Inclusive Design and Barrier-free Design (Goldsmith, 2007; Clarkson et al., 2013). Originated by Ronald L. Mace at North Carolina State University in the 1980s, Universal Design addresses limitations traditional designs pose for disabled people. An example is an accessible picnic bench designed to accommodate both disabled and non-disabled users (Figure 2.1).

Figure 2.6: An inclusive picnic bench. Source: britishrecycledplastic.co.uk.

Mace developed the Seven Principles of Universal Design, which promote equitable use, flexibility, simplicity, perceptible information, error tolerance, low physical effort, and appropriate size and space. These principles guide the creation of accessible and inclusive products and environments (Center for Universal Design, 1997) and are further described in Table 2.1.

Equitable Use
The design must be accessible and useful for people with varying abilities, ensuring equal usage opportunities without stigma or segregation, while providing privacy, security, and safety to all users.

Flexibility in Use The design should cater to individual preferences and abilities, offering varied methods of use and adapting to different user paces and skill levels, making it broadly accessible.
Simple and Intuitive Use Designs should be straightforward, eliminating unnecessary complexity and providing clear instructions to be easily understandable for all, regardless of users' experience or language skills.
Perceptible Information Effective communication of vital information should be ensured through various communication modes, high contrast, and legibility, accommodating all sensory abilities.
Tolerance for Error Designs should minimise risks from accidental actions by incorporating fail-safe features, warnings, and error recovery mechanisms to ensure safety and ease of use.
Low Physical Effort The design should allow for efficient and comfortable use with minimal fatigue, reducing the need for repetitive actions and accommodating various user postures.
Size and Space for Approach and Use Adequate size and space should be provided for all users to approach, reach, and manipulate the design comfortably, accommodating different body sizes and postures and allowing for the use of assistive devices.

Table 2.3: Principles of universal design & desirable design characteristics. Adapted from North Carolina State University.

Each principle supports aspects of Universal Design aimed at improving quality of life by enhancing health, well-being, functional independence, and social participation (Hamraie, 2017). The Eight Goals of Universal Design reflect this by focusing on body fit, comfort, awareness, understanding, wellness, social integration, personalisation, and cultural appropriateness, ensuring designs meet diverse needs and promote inclusion (Table 2.2).

Body Fit The design accommodates a wide range of body sizes and abilities.
Comfort The design provides a comfortable and supportive environment.
Awareness The design ensures that necessary information is easily perceived.
Understanding The design makes the structure and operation of the product or environment clear.
Wellness The design promotes health and wellness by accommodating a range of abilities and disabilities.
Social Integration The design promotes social integration and facilitates communication and interaction among all users.
Personalisation The design offers options for personalization and choice.
Cultural Appropriateness The design is sensitive and responsive to cultural differences and preferences.

Table 2.4: The goals of universal design. Source: North Carolina State University.

Universal Design has influenced global accessibility standards and laws, such as the UN Convention on the Rights of Persons with Disabilities and the Americans with Disabilities Act, which advocate for equal participation and accessibility in public spaces (United Nations, 2006; ADA, 1990). Furthermore, international standards like ISO 21542:2021 echo these principles by setting guidelines for accessible buildings and outdoor spaces (ISO, 2021). By promoting the principles of accessibility and inclusivity, Universal Design has helped to break down barriers and promote greater social and economic participation for people with disabilities and other marginalised groups.

2.1.1. Universal design in the built environment

In many countries, accessibility regulations apply to all “public accommodations,” including public open spaces as well as privately owned buildings and amenities available to the public, such as shops, restaurants, amusement parks, and transport facilities (Steinfeld & Maisel, 2012). For instance, the Equality Act 2010 is the primary legislation that regulates the accessibility of public spaces or buildings and transport systems in the UK (UK Government, 2010). In addition to the Equality Act, there are several standards and guidelines that regulate accessibility in the UK. The Building Regulations 2010 set out requirements for the accessibility of new buildings and major refurbishments, while the BS 8300 standard provides guidance on the design of buildings to meet the needs of people with disabilities (BSI, 2018). Also, the UK Government's Inclusive Transport Strategy sets out a vision for a more accessible and inclusive transport system in the UK. The strategy includes a range of measures to improve accessibility, such as investing in infrastructure improvements and promoting the use of assistive technologies (UK Government, 2018). Additionally, the UK Government has published the Accessible Railway Stations: Design Standards guide to provide guidance on designing accessible railway stations and trains (UK Government, 2015). Overall, public accommodations are a vital area for Universal Design because they encompass major social participation activities, including involvement in civic affairs, employment, leisure, education, and community transport.

Accessibility regulations provide a solid basis for evaluating and retrofitting existing public environments as well as designing new ones. However, many researchers have criticised accessibility standards since they fail to reflect the needs of the universal user on many occasions (Steinfeld & Maisel, 2012; Hamraie, 2017; Null, 2013). For instance, researchers have indicated that accessibility standards regarding corridor width in buildings only correspond to the functioning needs of MobAD users with narrow devices such as manual wheelchairs and canes (D’Souza et al., 2011). This could be detrimental for users of larger devices (e.g. mobility scooters) as they would not be able to manoeuvre their way out of a narrow corridor. Most importantly, accessibility regulations totally omit strategies on how to design public accommodations for everyone through addressing broader aspects of quality of life, such as well-being, safety, and social participation (Steinfeld & Maisel, 2012). Accessibility standards only stipulate the minimal requirements that building owners and designers must meet in order to comply with anti-discrimination legislation. To achieve the goals of Universal Design, a new approach is required.

Researchers and organisations globally have been investigating innovative methodologies to optimise design inclusively for all users. The rest of this section outlines three significant cases of such research which offer strategies and guidelines for genuinely inclusive design of the built environment. Utilising these insights throughout this thesis has aligned with and furthered its research objectives, enabling informed decisions grounded in validated knowledge. In their seminal book titled "Universal Design – Creating Inclusive Environments", E. Steinfeld and J. Maisel (2012) put forward a set of strategies to complement existing accessibility regulations for public accommodations (i.e. open areas, buildings of public interest, and transport facilities). These strategies refer to items or aspects that have been either understated or completely overlooked within accessibility regulations worldwide, such as usability, safety, and security of pedestrian pathway systems. The strategies provided by Steinfeld & Maisel (2012) reflect the scope of Universal Design for public accommodations and include a list with extensive features falling under each spatial category of public accommodations. In the context of this thesis, these strategies have provided an advisory framework, acting as a supplement to legal requirements for evaluating the accessibility of existing environments (i.e. presented in Chapter 4) as well as designing new ones (i.e. presented in Chapter 7) for the benefit of the universal MobAD user.

The IDeA Center at the University at Buffalo, internationally renowned for its Universal Design research, has developed guidelines and tools to aid in creating inclusive public spaces. Specifically, the IDeA Center has developed a set of guidelines to help designers and urban planners create more accessible and inclusive public spaces. The Inclusive Design Guidelines for the Built Environment address a range of issues such as wayfinding, seating, lighting, and safety, and provide practical guidance for creating environments that are accessible and inclusive for all users (for example, D'Souza et al., 2011). To produce these, researchers from IDeA Centre conducted numerous design experiments and observation studies with users of diverse backgrounds, such as varying functioning capabilities and different types of assistive devices (IDEA Centre, 2023). These guidelines have been influential in the design industry and have helped to promote greater accessibility and inclusivity in public spaces around the world. Figure 2.2 provides an example of the IDeA-produced guidelines regarding clear space required for different types of MobAD users. This example indicates that empirical evidence from IDeA Centre contradicts current accessibility standards on clear space and corridor width in public buildings respectively. The Inclusive Design Guidelines from the IDeA Centre have been used as guides in manifold situations in this thesis, specifically in the design formation (Chapter 7) and evaluation (Chapter 9) stages.

In a UK context, the Helen Hamlyn Centre for Design at the Royal College of Art in London is a world-renowned research centre that focuses on applying Universal Design principles to product and service design, with a particular focus on improving the quality of life for older adults and people with disabilities (HHCD, 2023). One of the centre's primary contributions to the field of Universal Design has been the development of the Inclusive Design Toolkit. The Inclusive Design Toolkit is a comprehensive set of guidelines and resources co-developed by the Helen Hamlyn Centre for Design – together with the Cambridge Engineering Design Centre at University of Cambridge and Sagentia – to promote the principles of inclusive design (Clarkson et al., 2007). According to this toolkit, researchers recognise seven main categories of human performance in a bid to develop a framework for measuring functioning capacity, namely vision, hearing, thinking, communication, locomotion, reach & stretch, and dexterity (ibid.). The Inclusive Design Toolkit is widely used and influential in the design industry and has helped to assess the ability level that a product or environment demands in order to use it. In the context of this thesis, the Inclusive Design Toolkit has provided substantial guidance with respect to understanding the full spectrum of human performance. This has contributed towards ideating designs (i.e. as presented in Chapters 6 and 7) as well as evaluating those (i.e. presented in Chapter 9) for the benefit of the universal user of MobAD.

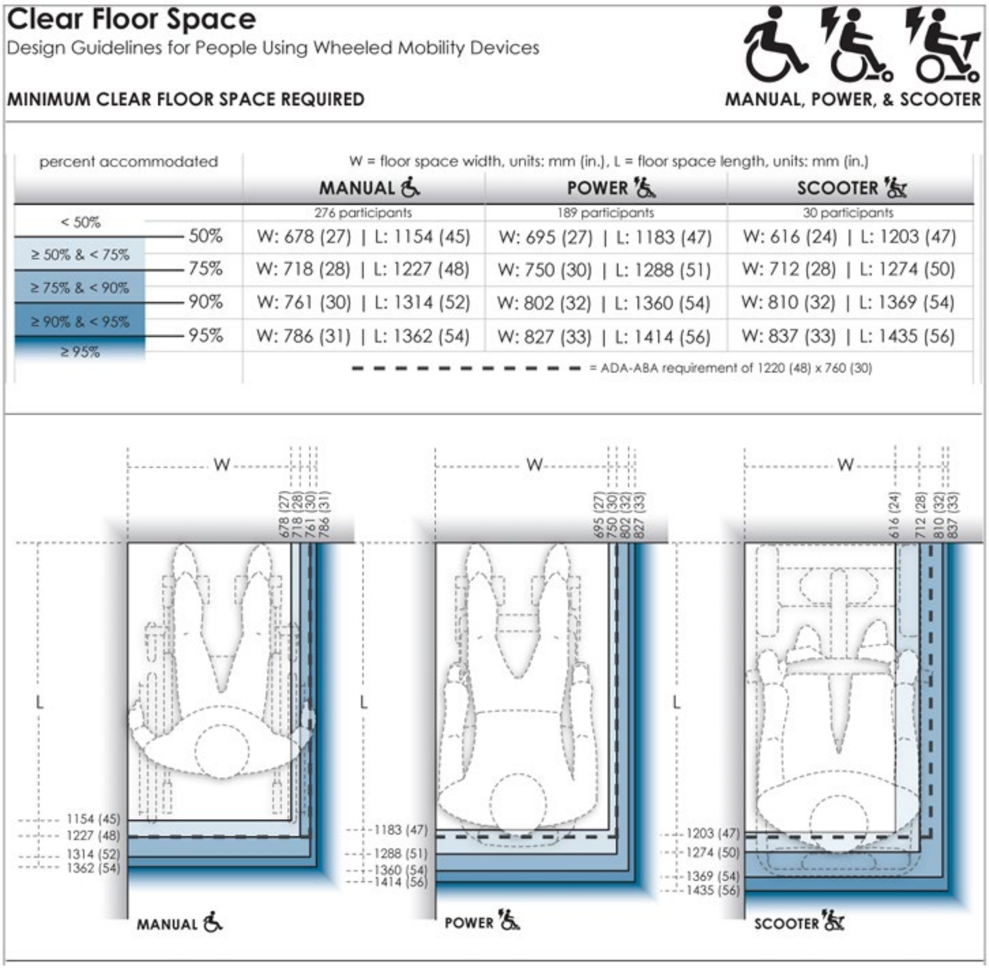


Figure 2.7: Clear floor space guidelines for MobAD users in the built environment. Source: University of Buffalo.

The principles and goals of Universal Design are central to the design-thinking process of this research effort, acting both as a medium for assessing existing built environments and as a vehicle to engender human-centred designs. The thesis draws on three comprehensive resources to ensure alignment with research objectives and make informed decisions based on validated knowledge. Specifically, the aforementioned resources have contributed to almost all stages throughout the design process, including assessment of existing environments, design ideation and formation, and user evaluation stages. Table 2.3 outlines what research objectives and design stages these resources help realise, thus indicating the significance of Universal Design for this thesis.

Universal design resource	Research objective(s)	Design stage(s)
Strategies for universal design (Steinfeld & Maisel, 2012)	▪ RO2: Engage with users ▪ RO3: Develop solutions	▪ Accessibility Assessment (Chapter 4) ▪ Design Development (Chapter 7)
Universal design guidelines (IDeA Centre – University of Buffalo)	▪ RO3: Develop solutions ▪ RO4: Assess solutions	▪ Design Development (Chapter 7) ▪ Design Evaluation (Chapter 9)
Inclusive Design Toolkit (Clarkson et al., 2007)	▪ RO2: Engage with users ▪ RO3: Develop solutions ▪ RO4: Assess solutions	▪ Design Ideation (Chapter 6) ▪ Design Development (Chapter 7) ▪ Design Evaluation (Chapter 9)

Table 2.5: Universal design resources and their application in different parts of the thesis.

The social model of disability naturally results in critiquing professional practices that omit end-users in the design process. Because the built environment is shaped by the social processes that generate it, it is important that all parts of society have a voice in those processes or risk having their perspectives marginalised in the end-product (Goldsmith, 2007). Steinfeld & Maisel (2012) write apropos:

“The more that people of diverse backgrounds are involved in the design process, the more likely that environments, products, and systems will reflect the needs of a wide range of end users. Some effort should be made to include representatives of end users in the design process of every design project. The wider the range of people involved, the better.”

The following section introduces ***collaborative design*** as a practical implementation of public engagement in design processes. The section also explores techniques and tools of collaborative design which are relevant to this doctoral research.

2.2. Collaborative design

Collaborative design (or co-design) refers to the application of public participation during the entire design process. According to Sanders & Stappers (2008), co-design is "*a collaborative creativity as it is used across the whole of a design process*" and "*the use of co-design in a wider sense refers to the creativity of designers and non-designers collaborating in the design development process*". This concept offered by Sanders & Stappers (2008) has gained widespread acceptance although it has not yet attained complete consensus.

Despite the fact that co-design tools and techniques have long been used by professionals and researchers in the field – yet usually without a framework to define them as such – the collaborative approach is relatively recent (Valtonen, 2005; Szebeko & Tan, 2010). In the last thirty years, co-design has become an emergent approach within design research and practice. Collaborative strategies have been regarded as the antidote to conventional design schemes, where design practitioners take every decision with respect to new products or services. Traditional design approaches are being replaced with procedures that can be moulded in accordance with the requirements and prerequisites of the users, and user participation is elevated to a central position in the design process (Antonini, 2021). This has brought to light several questions linked to the changing allocation of power (who decides what), which has the potential to disrupt the current top-down structures and roles as it entails a greater level of control to be held in the hands of end-users (ibid.).

In the sphere of the built environment, the benefits of co-design have been linked to either the characteristics of products and services or their compatibility with users' or customer's requirements, resulting in more efficient and streamlined design processes (Antonini, 2021). Many scholars have proclaimed co-design as a pathway to foster creativity (Franke & Piller, 2004; Steen et al., 2011). Involving end-users at the beginning of the design processes resulted in the generation of both radical and incremental ideas for new products according to a series of studies on product development (Trott, 2020). Other studies investigated the generation of ideas for future information and technology-based communication services (Kristensson & Magnusson, 2010; Kristensson et al., 2002). In several instances, users came up with more unique concepts than organisation-employed professionals. Other researchers have underlined the fact that designs produced by members of the public/end-users were found to be more heterogeneous than those of design professionals (Franke & Piller, 2004; Trischler et al., 2018). This conclusion emphasises the role of collaborative design as a tool for improving design space exploration when given the correct conditions. It is thus suggested that public or private organisations attempting to innovate their products and services would benefit from involving the end-users.

Public engagement in the design process can add extra value to products/services as well as have a positive effect on human relationships. Higher quality requirements and systems, a better match between the system and users' demands, and increased user or customer satisfaction are only some of the consequences Kujala (2003) identified in their analysis of the influence of user involvement within the design of ICT systems. In a similar vein, Alam (2002) reported improved public relations and longer-lasting relationships between service providers and customers as benefits of user participation. He also cited the creation of differentiated environments with unique benefits and better value for users, shorter development times, and education of users about the use, attributes, and specifications of a new service. Moreover, co-design approaches have been credited for increasing productivity and quality (Hoyer et al., 2010; Probst et al., 2014). As user feedback and designer’s feedback are combined, efficiency increases and failure risks are mitigated. This is because co-creation allows for continual product/service enhancements. Co-creation improves efficiency by fostering the development of goods that are a better fit for users' demands; this in turn boosts users' satisfaction with those products and services and strengthens the bonds between providers – e.g. a private firm, a public service, or a local authority – and people who use their products/services (Hoyer et al., 2010).

Co-design practices in built environment projects, while innovative, often encounter significant challenges stemming from inherent power imbalances and structural resistances. The ideal of co-design is to democratise the design process, involving a wide range of stakeholders including the community, professionals, and governmental bodies. However, this approach can exacerbate existing power dynamics, where dominant groups influence decisions disproportionately, thereby overshadowing less powerful stakeholders (Devendra et al., 2023). This imbalance can undermine the core democratic ethos of co-design, leading to resistance, particularly from traditional hierarchies accustomed to top-down decision-making. Such resistance not only hinders collaborative efforts but also impacts the overall efficacy and inclusivity of the project, potentially alienating key participants and stalling progress (ibid.).

Moreover, the complexity involved in coordinating various stakeholders in co-design processes often results in logistical challenges and inefficiencies. The need to align diverse interests and perspectives frequently leads to delays in decision-making, which can critically affect project timelines and outcomes (von Busch & Palmas, 2023). Additionally, the aim of inclusive participation, a cornerstone of co-design, sometimes inadvertently marginalises under-represented groups (ibid.). This occurs due to either the overwhelming presence of more vocal or powerful participants or through the unintended neglect of the unique needs and contributions of minority groups. Such outcomes not only contravene the foundational principles of equity and inclusivity in co-design but may also perpetuate the very disparities the approach seeks to mitigate, calling for meticulous planning and execution to truly realise its benefits (ibid.).

Current co-design practices in built environment projects often fall short in ensuring the active participation of disabled individuals, a failure which underscores deeper systemic issues within these participatory frameworks. Despite legislative advancements and increasing awareness regarding inclusivity, the physical setup and facilitation of co-design sessions frequently remain inaccessible. Proximity issues, such as the location of meetings being too remote or inadequately served by public transport, directly discourage participation (Combrinck & Porter, 2021). Additionally, physical barriers within the built environments themselves, such as non-compliant buildings or poorly designed meeting spaces, further exclude those with physical disabilities (Ni She & Harrison, 2021). This not only contravenes principles of equality and independence but also deprives projects of valuable insights that could enhance usability and accessibility for all. The persistent oversight of such fundamental inclusivity aspects in co-design reflects a significant disconnect between the theoretical ambitions of these practices and their practical implementations.

In a co-design context, methods are addressed by Bratteteig et al. (2012) as a "*coherent set of organising principles and general guidelines for how to carry out a design process from start to finish*"; yet co-design methods cannot be used as a "cookbook recipe" and must instead be taken into account in the setting and requirements of each particular co-design project (Bratteteig et al., 2012).

The *Community Planning Handbook* is a comprehensive exposition of over fifty tools and techniques (Figure 2.3) for implementing architectural planning and urban design procedures that incorporate end users as active participants (Wates, 2014). Sanoff (1999) has encapsulated some of the most frequently used co-design techniques and tools and grouped those thematically as in "awareness methods" (e.g. news media and walking tours), "indirect methods" (surveys and questionnaires), "group interaction methods" (e.g. workshops, focus groups, charrettes), "brainstorming and interactive brainstorming methods" (e.g. oral or written problem solving) and verbal/written method), and “open-ended methods” (e.g. notes and inquiries). Furthermore, recent technological advancements have amplified the methodological ecosystem of co-design. Immersive environments – such as user interaction in virtual or augmented reality – videoconferencing applications (e.g. Microsoft Teams) and online canvases (e.g. Whiteboard) are some example tools which can be used to facilitate co-design processes.

Methods A–Z

A selection of the most effective methods for helping people to get involved in physical planning and design.

Action planning event
Activity week
Architecture centre
Art workshop
Award scheme
Briefing workshop
Choice catalogue
Community design centre
Community planning forum
Community profiling
Design assistance team
Design fest
Design game
Design workshop
Development trust
Diagrams
Electronic map
Elevation montage
Environment shop
Feasibility fund
Field workshop
Future search conference
Gaming
Ideas competition
Interactive display
Local design statement
Mapping
Microplanning workshop
Mobile unit
Models
Neighbourhood planning office
Newspaper supplement
Open house event
Open space workshop
Participatory editing
Photo survey
Planning aid scheme
Planning day
Planning for Real
Planning weekend
Prioritising
Process planning session
Reconnaissance trip
Review session
Risk assessment
Road show
Simulation
Street stall
Table scheme display
Task force
Urban design studio
User group
Video soapbox

Figure 2.8: Participation tools for spatial design. Adapted from Community Planning Handbook.

Drawing on digital tools and building on the resources provided by the Community Planning Handbook, popular design methods have been employed to implement various tasks throughout this thesis. Specifically, design scenarios have been utilised to facilitate efficient collaboration with MobAD users during the design ideation stage as later presented in Chapter 6. As the entire design process was completed during the COVID-imposed lockdown period, remote digital tools (i.e. videoconferencing and whiteboarding tools) were harnessed to communicate effectively with MobAD users. Furthermore, prototypes (i.e. design models) were used to aid the user evaluation stage as later detailed in Chapter 9.

The subsequent sections (i.e. Chapters 2.2.1 – 2.2.3) outline the above-mentioned three co-design techniques or tools that have been utilised in the design process of this PhD project, particularly during the design ideation and evaluation stages in Chapters 6 and 9 respectively. To provide a frame of reference for the inquiry, relevant work conducted by other researchers in the realms of scenario-based design, distributed and remote design methods, and the use of prototypes for usability evaluations is included. The following lines present some recent research efforts organised in respective subsections.

2.2.1. Scenario-based design

The use of scenarios as a tool in the design of systems, services, and products has grown more common during the last decades (Yliriscu, 2004). The term "scenario-based design" refers to a group of methods in which the intended function of a future system is specified at an early stage of creation. After that, narrative descriptions of envisioned use episodes are used in a number of different ways to steer the construction of the system that would support these usage experiences (Rosson & Carroll, 2014). The main function of scenarios is to posit the “what if” question and momentarily create an alternative reality where designers and end-users collaboratively imagine how a system, service, or product could be. Conceptualising design through scenarios has many adjacent fields – including speculative design (Auger, 2013), critical design (Johannessen et al., 2019), design fiction (Lindley & Coulton, 2015), discursive design (Tharp & Tharp, 2019), and design futures (Maze, 2019). In fact, the above seem so similar in terms of format, medium, and dissemination style that they are often used interchangeably. This is probably because research on scenario-based design has not yet matured to a degree that can discern the epistemic differences within these fields.

In their book *Speculative Everything*, Dunne & Ruby (2013) emphasise the value of using scenarios in the design process to leverage progress in decision-making. Specifically, scenario-based co-design encourages end-users to question current solutions and engage in a thoughtful dialogue with designers over how things could change to satisfy their preferences (Dunne & Ruby, 2013). In fact, some researchers have suggested that the participation of end-users in scenario creation – instead of designers presenting them with ready-made ones – is likely to benefit the design process and improve future designs (Fuglerud et al., 2020; Svanaes & Segland, 2004). Scenarios can also be used as comparative media to effectively evaluate the performance of existing solutions (Rosson & Carroll, 2014). Another advantage of scenario-based design is its high level of tangibility as even a single scenario has the potential to be sufficiently evocative to allow for the illustration and discussion of design-related concerns brought up by a trade-off analysis (ibid).

Scenario-based design promotes multi-level communication among stakeholders, promising to make design activities accessible to many sources of expertise. A great example of the use of scenarios in the design ideation of built environments comes from the work of Schnaedelbach et al. (2019) who used a particular technique called "future envisioning" to understand a specific design space. Researchers held a series of workshops in which they invited a mix of participants including human-computer interaction (HCI) experts, built environment professionals, and graduate students (ibid). In these workshops, participants were asked to create new adaptive architectures, user experiences that could take place in those, and fictions to explore utopian and dystopian scenarios (ibid). Through this streamlined process, researchers were able to identify twelve recurring themes which formed the basis for their design exploration (ibid). In this case, the use of scenarios has assisted researchers to achieve their aim of identifying tensions arising from user interactions with adaptive architectures. Moreover, user-created fictions as co-creation objects could become a valuable source of feedback for researchers experimenting with adaptive architectures and HCI.

2.2.2. Remote co-design

While participation of members of the public in design processes is considered ideal, there are a few challenges to this practice, especially when participating parties are in different locations. In recent years, digital, online, and cloud technologies – for instance, videoconference applications such as Microsoft Teams – have assisted with mitigating this gap. The term remote co-design refers to a variety of practices in which all or the majority of the participants are geographically and maybe temporally scattered (Danielsson et al., 2008; Farshchian & Divitini, 1999; Gumm et al., 2006). To enable effective participation in and contribution to design efforts, this method calls for the coordination of activities across locations and/or time zones (Constantin, 2021). In most cases, the facilitation of a distributed co-design conversation is facilitated through digital platforms in an asynchronous[1], synchronous, online, offline, or hybrid mode (Read, 2022).

Remote co-design may maximise both the diversity and quantity of individuals engaged in the design process as this is independent from users' location and physical presence. For this reason, remote co-design is regarded a highly inclusive technique as it facilitates the involvement of vulnerable populations (e.g. disabled children) into the design conversation (Constantin, 2021). Since most of the design process is usually implemented remotely, this approach increases privacy and autonomy – for instance, participants can turn off their video camera and/or microphone (ibid). Moreover, the use of digital

[1] Asynchronous sessions do not happen in real time for every participant of the design team. Most of the times, participants complete requested design tasks at their own pace and place.

tools in itself could act as an attraction point for participants and bolster their engagement in the design discussion. On the other hand, participant inclusion and involvement and by extension group cohesion can be impacted by artificial contact and potential lack of proficiency in navigating within digital environments (Read, 2022).

A recent example of a remote co-design process for built environment purposes comes from a study by Winschiers-Theophilus et al. (2022). Researchers' intention was to bring children from different geographical zones (i.e. Finland, Namibia, and Malaysia) together to co-design elements of their own learning space (ibid). Within a period of six months, two series of workshops were undertaken whose participants included researchers, teachers, and students with their parents (ibid). Researchers used a videoconference application for remote communication in conjunction with online whiteboarding applications for completing design activities (ibid). In this way, this work achieved high levels of participation and cultural diversity, as well as nurtured student technical and social skills. The effectiveness and subsequent benefits of the adopted approach has led researchers to suggest that distributed co-design techniques and tools should be introduced in school curricula.

2.2.3. Prototype-mediated usability evaluation

Usability is defined as "*the extent to which the products can be used by specified users to achieve specified goals in the specific context of use with the particular environment*" according to the International Organization for Standardization (ISO, 2019). Additionally, ISO emphasises that the effectiveness, efficiency, and user satisfaction are the three fundamental criteria that are used to assess usability (ibid). As a result, usability evaluation (or user evaluation) focuses entirely on the experiences of users and their responses to the design and surroundings (Rubin & Chisnell, 2008). It is also connected to the human experience and the way in which it influences people's comprehension of the design environment in which it is used (Kortum, 2016). Usability studies are well recognised in connection to applications within architectural and industrial design, software engineering, and human-computer interaction (Barnum, 2011). It is therefore a common technique among designers in various fields to meet up with end-users during the latter stages of the design process and co-explore usability criteria. Discussions typically revolve around the functionality of the designed product or service, its friendliness toward users, and the extent to which it meets users' requirements (Harun et al., 2011). The collected user feedback then helps designers identify potential shortcomings, revise those, and inform the creative process.

However, it is not always possible for designers to present a complete solution to end-users in terms of material, size, or operation. Production costs and time are two of the most inhibitive factors. For this reason, researchers make use of prototypes to see if their ideas work in action. A prototype is a sample or model of a product or service; use of prototypes in usability evaluations is a common practice among researchers in architecture, industrial design, and software engineering (Hackney-Blackwell & Manar, 2015). Prototypes investigate several facets of a proposed design. They can represent all, nearly all, or some of the functionality of the final product or service (Lai & Locatelli, 2021). Other types of prototypes can correspond to the size and appearance but not the functionality of the proposed design (Soares & Rebelo, 2012). Some researchers use scaled models of the intended design created in different techniques or materials from the final product (Somiya, 2013). It is essential to understand that prototypes by definition reflect some compromise from the finalised design. This is attributable not just to the designer's expertise and decisions, but also to the fact that a prototype is an inexact and restricted imitation of a final product (Houde & Hill, 1997; Soares & Rebelo, 2012). Because of changes in materials, methods, and design accuracy, a prototype may fail to operate well even though the production design is good (Burry & Burry, 2017). Conversely and rather counter-intuitively, prototypes may work well while the production design and result fail, since prototyping materials and procedures may surpass their production equivalents. Nonetheless, creating the whole design is sometimes costly and time-consuming, particularly when performed numerous times – developing the full design, determining the issues and how to remedy them, then building another full design (ibid). Therefore, prototypes offer a less expensive and time-consuming alternative for researchers to test the usability of their designs together with end-users.

An example relevant to the purposes of this thesis comes from Bolster et al. (2021) who used prototypes to evaluate interventions for a physically active lifestyle in disabled children. The development team included end-users (i.e. disabled children), designers, researchers, and parents or paediatric physical therapists as part of a co-design approach (ibid). During the design process, the team engaged in three rounds of co-creation, four iterations of a week-long design sprint, living-lab testing, and two rounds of triangulation to build the intervention prototypes (ibid). Eleven prototypes were created: a mobile app to enhance communication between paediatric physical therapists and care sport coaches, four physical tools and two informational videos, and four physical tools and two informational videos to facilitate children's physical activity in their own environments (ibid). After testing prototypes in a lab environment, the study team conducted interviews with paediatric specialists (ibid). In this way, they identified obstacles and facilitators to the usability of the tools (ibid). These obstacles and facilitators were then used to optimise the final version of the intervention instruments (ibid). The methodological significance of this example is that researchers not only used prototypes in the latter stages of the creative process (i.e. evaluation), but also as a vehicle to arrive at certain designs based on feedback from end-users and experts.

The techniques and tools presented above are considered essential components of co-design processes that greatly enhance collaborative design efforts. However, it is unlikely that the majority of spatial designers are adopting co-design practices when designing public spaces. An obvious reason for that is some designers are not familiar with co-design practices or may underestimate their importance in creating inclusive spaces, leading to designs that are primarily based on the designer's perspective rather than the users' needs (Sanders & Stappers, 2008). In some cases, designers ascribe this lack of co-design thinking to financial restrictions or tight project timeframes which inhibit them from realising an extensive co-design process, including facilitating workshops, soliciting public input, and creating multiple iterations of designs (Hamdi, 2013). Also, it is not rare that some established design practices may resist adopting new methodologies, including co-design, due to a reluctance to change or a belief that their expertise alone is sufficient for creating functional spaces (Sanders & Stappers, 2008). Consequently, the lack of shared understanding of human needs might perpetuate the creation of spaces that do not cater to the specific needs and preferences of a diverse population. Looking to reverse this negative phenomenon, this thesis utilises co-design as a conduit to reconsider accessibility of public spaces.

Therefore, co-design methods are central to the design-thinking process of this research effort as they provide a framework for creating more inclusive, human-centred, and useful design solutions. The above-analysed resources (i.e. scenario-based design, distributed design, and usability evaluations) help implement the research objectives and produce novel design knowledge and outputs. These resources have contributed to the design ideation and user evaluation stages of the design process. Table 2.4 outlines what research objectives and design stages they help realise, thus indicating the significance of collaborative design for this thesis.

Co-design techniques	Research objective(s)	Design stage(s)
Scenario-based design	▪ RO2: Engage with users	▪ Design Ideation (Chapter 6)
Remote co-design	▪ RO2: Engage with users	▪ Design Ideation (Chapter 6)
Prototype-mediated usability evaluation	▪ RO4: Assess solutions	▪ Design Evaluation (Chapter 9)

Table 2.6: Co-design techniques and their application in different parts of the thesis.

Design approaches like Universal Design and co-design can be significantly empowered by computational tools, including BIM/CAD software, algorithms, and artificial intelligence. These advanced tools facilitate the seamless integration of accessibility features and user-centred design principles, empowering architects and designers to create inclusive spaces that cater to diverse populations with varying abilities. BIM/CAD software enhances collaboration, allowing stakeholders to engage in co-design by providing real-time visualisations and feedback loops, fostering a more democratic design process. Moreover, AI-powered algorithms can analyse and optimise designs to accommodate specific user needs, ensuring that built environments are both functional and aesthetically pleasing. By leveraging these cutting-edge technologies, designers can create more inclusive, equitable, and sustainable spaces, ultimately improving the overall quality of life for all members of society.

The integration of ***computational tools*** such as BIM/CAD software, algorithms, and artificial intelligence can significantly streamline and enhance the design process by offering a comprehensive suite of capabilities that allow for maximal creativity, seamless collaboration, iterative refinement, and optimisation. These tools empower designers to visualise, analyse, and modify their designs with unprecedented ease and precision, facilitating an iterative process that encourages experimentation and innovation. Ultimately, computational tools and methods help designers create more human-centred environments, fostering a design process that is both more efficient and effective in addressing the complex challenges in the built environment.

2.3. Computational design

Computational design refers to the use of computation-based methods – such as algorithms and specialist software – to aid in the design process (Menges & Ahlquist, 2011). This can include the use of computer-aided design (CAD) and building information modelling (BIM) software, parametric modelling, scripting, generative design, and other computational techniques to create, evaluate, and optimise design options (Sacks et al., 2018). It is an interdisciplinary field that involves the use of computer science, mathematics, physics, and other technical disciplines to inform the design process (Denning & Tedre, 2019).

Computational design is a problem-solving methodology that uses digital capabilities to develop advanced design solutions. Application of computational design in fields like architecture and industrial design is steadily growing as it offers significant benefits to design professionals. Designers can explore hundreds of design choices as opposed to the few that would be possible with manual workflows (Janssen & Stouffs, 2015). Additionally, they may be able to constantly improve the design methods via iterative refinement. Using iterative design procedures and user-friendly visual programming tools, designers are able to increase design quality beyond human capacity (Stefanescu, 2020). Once specific design processes are programmed into a computational tool, designers can essentially outsource design tasks to these programs (Poinet, 2020). Also, the number of people that are required to work on a project could be decreased as tedious design tasks and design thinking are transferred to computational tools (Garber, 2017). Designs that are developed computationally tend to have fewer technical faults, which will decrease the possibility of revisions being made (Aish & Bredella, 2017). In this way, project costs will decrease as a result of fewer resources and adjustments.

The application of computational design necessitates specialised understanding, thereby rendering it necessary for designers to acquire additional knowledge from other fields. The amalgamation of fields led to the creation of novel techniques and models from which new terms were derived. Those represent specific approaches and techniques within the broader field of computational design. It is beyond the scope of this thesis to compare different terms or develop taxonomies or new definitions. Instead, the following subsections will focus on two widely used approaches (i.e. *parametric* and *algorithmic design*), which are also employed in different parts of this work. The following parts will explain how these approaches have been adopted in a spatial design context and present precedent applications of theirs that are relevant to the purposes of this thesis.

2.3.1. Parametric design for the built environment

Parametric design is a design methodology that is based on numerical or other measurable parameters and utilises computer software to describe design sets and generate or explore design options (Schumacher, 2009; Caetano et al., 2020). It is worth mentioning that parametric design has its roots in the field of mathematics as it uses mathematical equations and rules to relate complex geometric elements (Bernstein, 2018). As a case in point, rather than creating walls by means of exact coordinates, lengths, heights, and widths, these properties are substituted by symbolic parameters that have restricted boundaries (e.g. 0.1m < wall width < 0.4m). The outcome is a symbolic manifestation of a set of walls. This approach is commonly used in BIM tools and is expressed in the concept of a family/object that describes sets of building elements.

The use of parameters in the designer's vocation has mostly been popularised by architects like Zaha Hadid, Frank Gehry, and Greg Lynn, as well as by firms such as Arup, BIG, and Foster + Partners, among others. Figure 2.4 presents the Serpentine Pavilion designed by BIG who utilised parametric tools to generate the complex geometric form. Parametric design gives designers the power of programming without the need to learn code. That is because most parametric design tools use visual programming as opposed to lines of text-based code

(Janssen & Stouffs, 2015). With visual programming, users connect outputs from one node to inputs of another, creating a program that travels from node to node by connectors (Caetano et al., 2020). The end result is a graphic representation or essentially a flowchart of the design process.

Figure 2.9: Serpentine Pavilion by BIG Architects. Source: Wikimedia.

In recent years, parametric design has become an increasingly popular approach in spatial design, with numerous applications in various aspects of the design process. The most common uses of parametric approaches concern form-finding processes, in which parametric design allows architects to explore and generate complex geometries and forms quickly and efficiently. Also, parametric design is being used to create responsive objects that can react to changes in the environment, user behaviour, and other external factors. Those two strands are of relevance to the research objectives of this present thesis. In Chapter 7, a parametric model is developed to express the design problem in mathematical terms. This mathematical definition allows for the generation of a broad range of design options, which are then evaluated based on the functioning requirements of MobAD users. Later in the same chapter, an additional parametric model is developed to assist in creating a dynamic object that adjusts its shape according to users' behaviour. To provide context for the present research, the following lines present some recent research works on relevant applications of parametric design.

Several studies have investigated the potential application of parametric design in form-finding processes (Ismail et al., 2022; Lee et al., 2019; Kim et al., 2022; Yu et al., 2021). A noteworthy work comes from Marathe & Adhikari (2019), who explored the potential of parametric design for the design of modular furniture systems. They developed a parametric model of a furniture system that allowed them to manipulate a set of parameters and rules to generate various configurations (ibid.). The authors evaluated the generated configurations based on their efficiency, adaptability, and stability (ibid.). The study demonstrates the potential of using parametric design to create modular furniture systems that can be adapted to different spaces and uses while still being efficient and stable.

There have been several studies investigating the potential of parametric design in creating dynamic products/environments that can adapt to changing needs and conditions (Youssef et al., 2019; Pelken et al., 2020; Ghaffarian-Hoseini & Clements, 2021). An interesting example emerges from the work of Alexopoulos et al. (2018) that explored the application of parametric design to develop a flexible and reconfigurable wall partition system adaptable to the changing needs of building occupants. Researchers employed parametric design tools and algorithms to create a modular wall partition system composed of adjustable and interchangeable components (ibid.). The system's flexibility allowed for the customisation of spatial layouts, responding to various functional requirements and user preferences. To test the performance of the proposed wall partition system, the authors used digital modelling and simulation tools to evaluate its structural stability, acoustic performance, and ease of reconfiguration (ibid.). The study also incorporated user feedback to assess the level of satisfaction with the reconfigurable wall partition system in real-life scenarios. The most significant result of this study was the successful development of a flexible wall partition system that could be easily reconfigured to accommodate different space requirements and user preferences, offering a sustainable solution for adapting to changing needs in residential and commercial buildings (ibid.). The parametric design approach enabled the creation of a versatile and adaptable building component, demonstrating its potential in designing flexible architectural elements.

Lastly, a number of studies have begun to examine ways in which parametric design could be utilised to support and assist disabled people. The vast majority of these studies have tested the efficacy of parametric design with respect to designing assistive and prosthetic devices (Burton et al., 2012; Kondyli et al., 2017; Romani & Levi, 2020; Kikuchi et al., 2021; Wang et al., 2013). In a very interesting study by Ballegaard et al. (2021), researchers developed a parametric model which effectively generated various floor plans that corresponded to challenges described by mobility-impaired individuals in co-design sessions. By inputting functioning needs of MobAD users with diverse backgrounds in the parametric model as design criteria, researchers produced new and unanticipated design solutions which were cognizant to MobAD users' experiences (ibid.). Overall, these studies provide converging evidence for the role of parametric design systems as powerful tools in designing accessible products and environments for the disabled population.

2.3.2. Algorithmic design for the built environment

Algorithmic design is an approach that uses algorithms to manipulate design models. Similar to parametric design, this approach relies on the utilisation of computational tools (e.g. BIM/CAD software, scripting) to generate, refine, or identify design objects. The main difference between algorithmic and parametric design is that the former draws on algorithms to handle design tasks while parametric design uses a set of parameters or rules to define a design. Algorithmic design tends to be more flexible and versatile, allowing for greater exploration of design possibilities and implementation of several tasks in the design process, while parametric design is more focused on optimising a specific design based on a set of predefined rules or parameters.

Recently, algorithmic design has been heavily linked to applications of artificial intelligence (AI). AI-driven techniques, such as machine learning and evolutionary computation, is not a new concept in the realms of built environment. However, the utilisation of machine learning and evolutionary computation throughout the design process is a relatively new area of investigation. Applications of these techniques in design are departmentalised into two major schools of thought. The first is *design optimisation*, which refers to the process of systematically improving the performance of a design by iteratively testing and refining different design options (Martins & Ning, 2021). The goal of design optimisation is to find the best design solution that meets a set of predefined performance objectives, such as material usage, spatial constraints, and energy efficiency (Papalambros & Wilde, 2000). On the opposite end of the spectrum is the investigation into the challenge of *design exploration*, which includes the tasks of identifying (mostly through pattern recognition processes) and generating a wide range of design options in order to identify the best possible solution for a given design problem (Maher et al., 1996). Despite the fact that pattern recognition and generation tasks are difficult to transfer into code since they are not quantifiable, recent advancements in the field of AI have led to a proliferation of research focusing on the use or development of new tools (e.g. deep learning networks and evolutionary algorithms) to support design exploration.

Investigation into the fields of design optimisation and design exploration is crucial in algorithmic design, as demonstrated in various sections of this thesis through the implementation of tasks using advanced tools like neural networks and evolutionary computation. Specifically, in Chapter 7, an algorithm-driven model is developed to recognise design patterns, enabling the retrieval of precedent projects from various design databases to enhance design inspiration. In the same chapter, evolutionary computation tools are employed to generate alternative design forms which are subsequently optimised to meet specific performance criteria and users' functional requirements. To frame this inquiry, previous research efforts in the areas of design optimisation and exploration is presented in the following lines.

In recent years, many studies have utilised algorithmic techniques for design optimisation in various fields, ranging from architectural engineering to furniture design (Almeida et al., 2016; Jones et al., 2023; Taborda, 2018). An interesting example can be found in the work of Johnson et al. (2023). Researchers investigated the use of convolutional neural networks (CNNs) – a machine-learning tool – combined with evolutionary algorithms for optimising furniture design with the goal of maximising functionality, aesthetic appeal, and ergonomics (ibid.). The researchers developed a CNN-based model to evaluate furniture design based on a set of predefined criteria (ibid.). The model was trained on a large dataset of 3D furniture models annotated with expert ratings on functionality, aesthetics, and ergonomics. An evolutionary algorithm was employed to generate new design variants which were evaluated by the CNN model (ibid.). The optimisation process was iteratively refined to achieve designs that scored highly on the predefined criteria (ibid.). The proposed method has the potential to revolutionise the furniture design process, streamlining design iterations and producing high-quality, cost-effective, and sustainable solutions.

Many researchers have recently proposed AI-driven pattern recognition models to retrieve of precedent projects from architectural databases (Evangelou et al., 2021; Kalsekar et al., 2022). For example, Ahmed et al. (2014) designed a rule-based algorithmic system that would enable the user to easily access knowledge from precedent projects. The user searches for semantically similar floorplans just by drawing parts of the new plan (ibid.). Essentially, an automatic floorplan recognition system analyses the floor plans and finally retrieves the corresponding semantic information. The retrieved structural and semantic information can be saved in a repository for later access during retrieval (ibid.).

A growing body of research has emerged in recent years showcasing the remarkable potential of algorithmic techniques for supporting the design generation process (Chaillou, 2019; Viny et al., 2018). A distinctive example derives from Mueller & Ochsendorf (2015), who proposed a computational approach to the exploration of design alternatives that extends evolutionary algorithms to include designer preferences (Figures 2.5-2.6). This would allow them to set the evolutionary parameters (i.e. population and randomness of candidate solutions as well as selection of parent ones) to drive the exploration of conceptual designs (ibid.). Their approach could improve upon existing methods by giving the designer control over the diversity of designs considered, the rate of convergence, and the multi-objective trade-off between formulated quantitative goals (e.g. structural volumes) and unformulated qualitative goals such as architectural value.

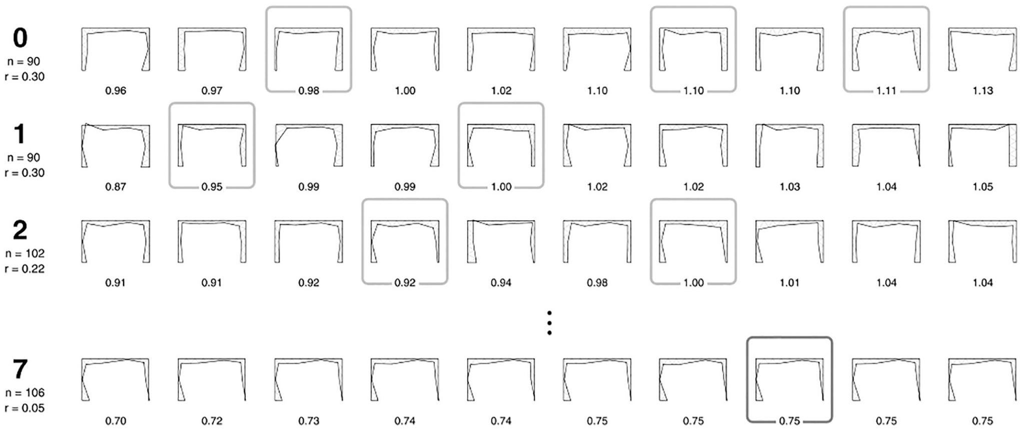


Figure 2.10: Excerpt of eight successive generations for a hybrid exploration approach in which designs are selected by the user based on qualitative aesthetic characteristics and quantitative performance. Source: Mueller and Ochsendorf (2015).

Figure 2.11: Two options for the design of the lateral and gravity structural system for an airport terminal: (left) a standard rigid frame and (right) a shaped rigid frame. The shaped frame uses a similar amount of material and creates a more architecturally expressive interior spaces.

Outside the domains of design optimisation and design exploration, algorithmic techniques have been applied in a number of design projects which aimed at creating products or environments for the universal user (Jonsson et al., 2018; Walsh & Wronsky, 2019). An interesting study comes from Vidal et al. (2022), who presented a co-design process that involved multiple stakeholders, including architects, builders, and potential homeowners, to develop a cloud-based tool for mass customisation in housing. In the context of housing, mass customisation can enable the production of personalised living spaces that meet the diverse needs and preferences of homeowners, including disabled people (ibid.). Researchers used different sets of evolutionary and generative algorithms to develop a tool which could provide users with a range of customisation options, including the layout and configuration of living spaces, materials, finishes, and appliances (ibid.). The tool utilised evolutionary and generative algorithms to automatically create a variety of layouts that can satisfy diverse needs (ibid.).

Overall, the importance of computational design approaches in shaping the built environment cannot be overstated. As demonstrated above, the integration of parametric models, machine learning, and evolutionary computation within design processes revolutionises how architects and designers approach complex, multi-faceted projects. These algorithmic techniques offer a sophisticated toolset for efficiently navigating vast design possibilities, significantly enhancing the ability to identify optimal solutions swiftly and accurately. In spatial as well as industrial design, where the balance of aesthetic appeal, functionality, and sustainability is paramount, the capacity of computational design to generate and evaluate numerous alternatives quickly is invaluable. This ability expedites the design process and fosters innovation by revealing unexpected and innovative solutions that traditional methods might overlook.

Despite the several benefits of computational design, there remains a notable gap in its application to Universal Design within the built environment. Universal Design principles aim to create spaces that are accessible to all, regardless of age, ability, or status, and computational design methods could greatly enhance this endeavour. By employing algorithms to simulate and analyse diverse user needs and preferences, computational techniques can anticipate and solve accessibility challenges at an early stage in the design process, thereby embedding inclusivity into the very fabric of architectural and industrial design projects.

In this thesis, various computational design approaches are harnessed to address different aspects of design as detailed in Table 2.5. Parametric design is utilised to create adaptable and responsive design solutions that can adjust dynamically to user requirements, thereby aligning closely with the principles of Universal Design. Algorithmic design, on the other hand, facilitates the exploration and optimisation of complex design problems, ensuring that solutions are efficient as much as inclusive. Together, these methodologies underscore the potential of computational design to revolutionise both the process and the outcome of creating universally accessible built environments.

Computational technique	**Research objective(s)**	**Design stage(s)**
Parametric design	▪ RO3: Develop solutions	▪ Design development (Chapter 7)
Algorithmic design	▪ RO3: Develop solutions	▪ Design development (Chapter 7)

Table 2.7: Computational design approaches and their application in different parts of the thesis.

In terms of realising computational design concepts, ***structural adaptation*** can play a pivotal role, enabling designers and engineers to push the boundaries of innovation and aesthetics in the built environment. By incorporating adaptive strategies that respond to specific environmental, material, and functional demands, computational design tools can optimise structures for efficiency, resilience, and performance. This synergy between structural adaptation and computational design allows for the creation of adaptive, dynamic, and environmentally responsive architectural solutions, resulting in efficient use of resources and reduced environmental impact. Additionally, the integration of advanced materials and technologies, such as adaptive façade systems and kinetic structures, enhances the potential for novel and sustainable design solutions. Thus, structural adaptation empowers designers to not only conceive but also actualise cutting-edge computational design concepts, fostering a new era of architectural innovation.

Structural adaptation has the potential to foster inclusive environments for disabled people, ensuring their equal participation in society. By thoughtfully incorporating design elements tailored to the needs of individuals with diverse abilities, designers and engineers can create spaces that are not only functional but also empathetic. Key adaptations may include the provision of automatic doors, expandable desks, as well as the seamless integration of assistive technologies within the built environment. Universal Design principles, which emphasise equitable access for all users regardless of age, size, or ability, can serve as a guiding framework for these structural adaptations. By embracing this holistic approach, designers can create barrier-free spaces that empower disabled individuals, promoting their autonomy, dignity, and well-being. Ultimately, structural adaptation demonstrates how the built environment can be a catalyst for social change, enabling disabled people to thrive and engage fully within their communities.

2.4. Structural adaptation

As discussed in Chapter 1, *structural adaptation* is central to the scope of this thesis as it allows for designs that are more human-centred and functional. Structural adaptability or reconfigurability can capacitate spatial and industrial elements to modify their form. In the context of this thesis, structural adaptability is a significant design quality as it can potentially engender easily modifiable elements which could better adapt to the needs and functioning capabilities of MobAD users. As such, structural adaptation has driven the design formation stage (Chapter 7) and helped realise the usability evaluation of the produced design (Chapter 9).

The following section presents a conceptual framework on Adaptive Architecture, which was proposed by the architect and researcher Holger Schnädelbach in 2010. The framework draws on structurally reconfigurable elements that adapt to evolving needs and preferences of their users, as well as to changing environmental conditions. The design components and strategies stemming from this framework have been cornerstones for the implementation of a design solution which can improve spatial accessibility for the benefit of MobAD users. The framework has also influenced the theoretical contribution of this PhD project as this thesis endeavours to expand the framework's research ambit.

2.4.1. The Adaptive Architecture Framework

The Adaptive Architecture Framework devised by Schnädelbach (2010) offers a structured approach to understanding and implementing adaptive architectural designs. This framework is conducive for accommodating dynamic changes in environments, user needs, and technological advancements within architectural contexts. It is structured around six main components, namely (ibid.):

1. *Motivations and drivers*: These form the foundation, highlighting the cultural, societal, organisational, and environmental reasons for adopting adaptive designs. This includes accommodating changes such as social dynamics, environmental conditions, and usage shifts.
2. *Reaction to*: This component addresses the stimuli or changes to which the adaptive architecture responds. This could include environmental factors, user interactions, or other internal and external triggers.
3. *Elements adapted*: Specifies which parts of the architecture are subject to change, such as structural elements, interior layouts, or external facades.
4. *Methods of adaptation*: Outlines the techniques and technologies used to facilitate adaptation, such as sensors, actuators, and digital control systems.
5. *Effect of adaptations*: Discusses the outcomes and impacts of these adaptations, assessing their effectiveness in meeting the intended goals of flexibility and responsiveness.
6. *Overall strategies*: This final component integrates the previous elements into cohesive design strategies.

The “overall strategies” component of the Adaptive Architecture Framework encapsulates a holistic view of how different strategies can be applied in the design of adaptive environments. Each strategy plays a crucial role in ensuring the adaptability of architectural structures to meet changing needs and conditions. The following lines provide a detailed description of the “overall strategies” component, accompanied by a few examples that typify strategies relevant to the purposes of this thesis:

- Mobility: This strategy involves designing buildings or their components to be movable or adaptable. This could mean physical relocation or structural adaptability to different environments and uses, akin to mobile infrastructures like caravans or boats. The *House in Bordeaux* (Figure 2.7) demonstrates how mobile structures can facilitate vertical access of disabled individuals between different floors in a home environment.

Figure 2.12: House in Bordeaux - a mobile platform allowing vertical navigation of wheelchair users in operation. Source: OMA.

- Levels of prescription: This refers to the extent to which building adaptations are predefined. A high level of prescription specifies all potential changes in advance, ensuring readiness for future needs. Conversely, a low level of prescription allows for greater flexibility, letting occupants modify spaces as needs arise.
- Reusability and standardisation: Focuses on using modular or standardized components that can be reused or reconfigured. This strategy supports environmental sustainability by facilitating easy updates and reducing waste, while also allowing for quick adaptations to changing needs.
- Automation and human intervention: Determines the balance between automated adaptations and manual control by occupants. Automated systems may react autonomously to environmental changes or user inputs, while manual controls

offer users direct influence over their surroundings, enhancing personalisation and comfort. The *Jet d'Eau Bridge* (Figure 2.8) is a very characteristic example of an automated adaptation, as a network of sensors and actuators automatically drive the adaptation stages of the bridge according to user needs: flat state to facilitate wheelchair users (Figure 2.9-a) and raised state to accommodate movement of boats (Figure 2.9-c).

Figure 2.13: Jet d'Eau Bridge - raised state. Source: Ingeni.

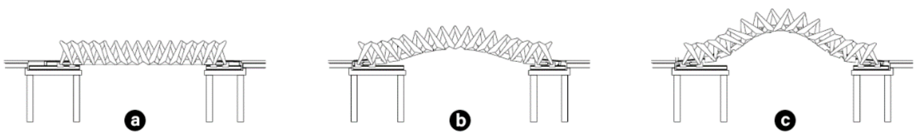


Figure 2.14: Jet d'Eau Bridge - the structure in (a) a flat; (b) an adapting; and (c) a raised state. Source: Schumacher et al. (2019).

- Time scales: Considers the different periods over which adaptations might be required. Short-term adaptations respond immediately to user interactions or environmental shifts. Intermediate adaptations evolve based on changing usage patterns over months or years. Long-term adaptations anticipate broader trends such as demographic shifts or climate change.

- Inhabitant-focused transformation and building independence: This strategy varies adaptive responses based on the level of interaction with occupants. Some adaptive features directly respond to user behaviors, while others operate independently, allowing the building to adjust its functions without human input, based on programmed algorithms or learned behaviors over time. The main entrance of the *Royal Opera House* in Stockholm (Figure 2.10) is a characteristic case of a human-focused adaptation, where a principal element of a public building modifies in structure, i.e., a flight of steps - Figure 2.11-a to a lifting platform - Figure 2.11-c, to fully meet different human functioning capabilities.

Figure 2.15: Stockholm Opera - the lifting platform in operation. Source: Guldmann Co

Figure 2.16: Stockholm Opera - steps (a) adapting to (b) a lifting platform (c). Source: Guldmann Co.

Overall, in the Adaptive Architecture Framework, Schnädelbach (2010) pinpoints some key benefits of adaptation in spatial design. Adaptive architecture can help create more efficient and sustainable buildings, as those can be designed to respond to their environment and inhabitants in order to reduce energy consumption. Additionally, adaptive architecture can bring about more personalised experiences for inhabitants as structures are designed to respond to their needs and preferences. Finally, adaptive environments are inherently interactive and engaging spaces due to their capability to respond to stimuli in real-time.

The realised examples mentioned above in this section (i.e. the House in Bordeaux, the Stockholm Royal Opera, and the Jet d'Eau Bridge) indicate physical accessibility as an additional dimension of adaptive design which has not been mentioned in Schnädelbach's (2010) framework. Looking through the lens of Universal Design, accessibility is a crucial parameter that should characterise spatial adaptations, at least the human-centred ones. Also, designing for human well-being, safety, and functioning are some subsequent factors that could expand the scope of the Adaptive Architecture Framework towards Universal-Design-oriented paradigms. This thesis will utilise structural adaptation to design for MobAD-accessibility and intends to augment the ambit of the Adaptive Architecture Framework in the direction of Universal Design.

The aforementioned examples characterise (a) human-centred, (b) highly deployable or mobile, and (c) automation-enabled adaptations. These three adaptation strategies have helped realise different research objectives and characterise the latter part of the design process in this present research (i.e. Chapter 7 – Design Development and Chapter 9 – Usability Evaluation). Based on these three strategies, it is intended that a flexible structure will be created which will respond to the needs of MobAD users in the built environment. Table 2.6 summarises the integration of the aforementioned components into various parts of this thesis alongside their correspondence to the research objectives, thus indicating the significance of the Adaptive Architecture Framework for this thesis.

Adaptation component	Research objective(s)	Design stage(s)
Human-centred	▪ RO3: Develop solutions ▪ RO4: Assess solutions	▪ Design Development (Chapter 7) ▪ Design Evaluation (Chapter 9)
Highly deployable or mobile		
Automation-enabled		

Table 2.8: Adaptive Architecture Framework components and their application in different parts of the thesis.

2.5. Summary

The four previous sections of this current chapter have analysed theoretical concepts that underpin this doctoral research. As a human-centred approach, Universal Design harnesses knowledge from anthropometrics and biomechanics to create products and environments which can improve the quality of life of all people regardless of age, gender, or capabilities. The chapter also introduced co-design as a process of community engagement and presented various methods which can help design professionals and researchers carry out collaborative activities from start to finish. Given the recent progress in data-driven technologies, computational techniques and tools can drastically contribute to many stages along the design process, such as inspiration, optimisation, and even generation of new design forms. Finally, the framework on adaptive architectures indicates how structural adaptation can create products and environments that are dynamic, thus accommodating the needs of their users in a timely and efficient manner.

Those theories will significantly influence the design approach followed in this research effort. Universal Design principles will guide the accessibility assessment, ideation, formation, and evaluation stages, providing both methodological frameworks and practical objectives (see Table 2.3). Co-design methods will be crucial for engaging users and gathering feedback throughout the accessibility assessment, co-creative ideation, and evaluation processes (see Table 2.4). Computational design techniques will enable the implementation of the design development stage through algorithmic and parametric approaches, allowing for the retrieval and optimisation of design knowledge (see Table 2.5). Structural adaptation techniques, particularly components of the Adaptive Architecture Framework, will facilitate the development of flexible design solutions that could adapt to the needs of MobAD users, enhancing both the design development and evaluation stages (see Table 2.6). Together, these elements create a powerful synergy that propels design practice into new realms of innovation and inclusivity.

3. Systematic review on MobAD-accessibility of public spaces

Public spaces play a critical role in fostering social cohesion, promoting health, and enabling mobility, particularly for MobAD users. Yet the physical accessibility of these spaces remains a significant issue, potentially undermining the quality of life (QoL) for MobAD users. While various studies have delved into this concern, they often focus on specific public spaces like transportation facilities, public buildings, or natural open spaces, neglecting a holistic city-wide perspective. Moreover, the breadth of impacts resulting from inaccessible spaces, especially beyond mobility and daily activities, is often overlooked.

Several reviews have recently explored the level of physical accessibility of public spaces for MobAD users (Unsworth et al., 2019; Welage & Liu, 2011); the impact of inaccessible public spaces on MobAD users (Cooper et al., 2011; Zhang et al., 2017); or both topics (Atoyebi et al., 2019; Bigonnesse et al., 2018). However, most of these attempts solely focused on individual types of public spaces – such as transportation facilities (Unsworth et al., 2019), public buildings (Welage & Liu, 2011), and natural open spaces (Zhang et al., 2017) – or even special features of the micro-environment of public spaces, e.g., sidewalk cross-slopes (Cooper et al., 2011). Other reviews were not characterised by a systematic methodological approach (Atoyebi et al., 2019; Welage & Liu, 2011). Although one review was particularly enlightening on addressing the level of physical accessibility of public spaces for MobAD users as well as the impact of inaccessible public spaces on MobAD users (Bigonnesse et al., 2018), it only focused on physical environments close to MobAD users' homes. That is, it did not encompass uses and spaces across the urban public realm. Moreover, the same review discussed effects of inaccessible spaces on users' mobility and community participation but omitted possible effects on other aspects of independence – for instance, reach capability – as well as health-related impacts.

In the context of existing knowledge, the rationale for this review can be found in two research gaps that remain. Firstly, no pieces of academic work have evaluated existing literature on the level of physical accessibility of public spaces for the entirety of the urban environment – i.e., public open spaces and buildings of public interest in a city-wide context. Secondly, only a few reviews have been undertaken on the relationship between physical accessibility and aspects of QoL. Indeed, most of those have only focused on mobility and activities of daily living, namely shopping and use of public transport.

3.1. Purpose

In order to address the aforementioned gaps, this review scrutinises physical elements of both open spaces and buildings in the urban public realm to provide aggregated findings regarding accessibility for MobAD users. The review also discusses possible repercussions of inaccessible public spaces through a wider range of QoL aspects, including physiological condition, recreation, and educational opportunities.

3.2. Materials and methods

A systematic review of research was conducted to compile a list of the most obstructing physical barriers for MobAD users in public urban spaces and investigate the effects of inaccessible public urban spaces on the quality of life of MobAD users.

Systematic reviews use explicit, systematic methods to identify, select, and critically appraise relevant research. These methods are applied to minimise bias, thus providing more reliable findings from which conclusions can be made (Higgins et al., 2019). To adhere to the aforementioned standards, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009) were adopted, which comprise (1) the clarification of the research topic, (2) the selection of data sources, (3) the identification of search words (or search strategy), (4) the application of eligibility criteria, (5) the selection of studies, (6) the assessment of methodological quality, and (7) data extraction.

3.2.1. Data sources and search strategy

To find relevant works, the following information sources were selected: Scopus Database, Web of Science Database, and PubMed Database, considering them particularly congruent to the three thematic review axes of "mobility assistive devices," "public spaces OR (constituent) physical elements," and "quality of life." The search includes papers published between January 2005 and December 2021.

To access relevant articles within the previously mentioned sources, an integrative search strategy was selected with respect to title, abstract, and keywords fields using combinations of English-language terms related to MobAD users (e.g., mobility device, wheelchair, walking cane, pushchair, stroller, mobility impaired), quality of life (e.g., access, health, wellbeing, safety, daily activity/tasks, comfort, fatigue, pain), and physical elements (e.g., pathway, sidewalk, pavement, ground surface, curb, ramp, entrance, door, corridor, stair, public space). Terms for "physical elements of public spaces" and "quality of life" were identified with the help of the American with Disabilities Act Accessibility Guidelines - ADAAG (ME Department of Justice, 2010) and the World Health Organisation Quality of Life Assessment Tool - WHOQOL (WHO, 1997). The final terms used are all shown in Table 3.1, organised according to the three review axes – namely, MobAD, quality of life, and physical elements.

Searched terms lists			
MobAD users	**QoL aspects**	**Physical elements**	
"mobility device*"	access*	pathway*	built
wheelchair*	"quality of life"	footpath*	architectur*
scooter*	health	sidewalk*	environmental
"walking frame*"	well-being	pavement*	"public space*"
"walking stick*"	safety	"street furniture"	"open space*"
rollator*	"daily activities"	"ground surface*"	"public building*"
"walking cane*"	"daily tasks"	"walking surface*"	"green space*"
crutches	comfort	"curb ramp*"	square*

pushchair*	fatigue	"curb cut*"	plaza*
stroller*	pain	entrance*	park*
"mobility impair*"	psychological	door*	water*
"mobility disab*"	psychosocial	transport*	librar*
"wheeled device*"	"self-esteem"	"bus (transport* or platform*)"	school*
"mobility assistive device*"	emotional	"train (transport* or platform*)"	universit*
	"bodily image"	"tram (transport* or platform*)"	cinema*
	independence	parking	shop*
	transport	"emergency exit*"	retail
	transfer	"evacuation point*"	museum*
	maneuverability	"ground surface*"	store*
	mobility	"floor surface*"	restaurant*
	"reach range"	corridor*	market*
	"reach *abilit*"	aisle*	church*
	grip	ramp*	mosque*
	force	"platform lift*"	café*
	"vision range"	elevator*	playground*
	participation	stair*	stadi*
	recreation*	step*	theatre*/theater*
	leisure	handrail*	fitness
	spirituality	"dining surface*"	urban
	religion	"work surface*"	cit*
	education*	"service surface*"	
	"social relations*"	counter*	
		shelf/shelves	

Table 3.9: Construction of the search query used for retrieving relevant literature.

3.2.2. Eligibility criteria

The next step included collecting and reviewing quantitative and qualitative journal peer-reviewed publications which were (a) written in English, (b) published between January 2005 and December 2021, (c) reporting the results of original research, and (d) investigating MobAD-accessibility of the urban built environment or the impact of physical barriers on aspects of QoL of MobAD users.

The selected methodology omitted articles that referred to any types of the built environment other than spaces of public interest as per ADAAG directions. ADAAG categorises public spaces into eight macro-environments according to their functions: building blocks, accessible routes, general site and building elements, plumbing elements and facilities, communication elements and features, special rooms/spaces/elements, built-in elements, and recreation facilities. Each macro-environment consists of meso- and micro-environments that refer to different constituent elements of public spaces, for instance, “walking surfaces” is a subcategory of the “accessible routes” macro-environment. Elements not referring to physical infrastructure or public spaces were also omitted in this review. The boarding ramp, which could be considered both physical and non-physical infrastructure, was included due to its significance to MobAD users.

Articles that investigated the impacts of physical inaccessibility but did not refer to aspects of QoL were not included in this review. The WHOQOL tool was used as a reference point. Specifically, the WHOQOL tool distinguishes physical and psychological health, level of independence, social relationships, environment, and spirituality/religion/personal beliefs as aspects of quality of life of individuals. Studies that did not focus on any of those aspects were excluded.

The selected methodology also omitted studies that did not refer to users of MobAD (i.e., manual or powered wheelchairs, mobility scooters, canes, crutches, walkers, and strollers). Articles with a purely medical focus or on different thematic topics (e.g., MobAD mechanics) were excluded too. Lastly, papers that could not be retrieved through the library of the authors' respective institutions were excluded.

3.2.3. Study selection

Two investigators independently screened all titles resulting from the electronic searches. Those titles of interest were imported into the Mendeley reference management software (Version 1.19.5; Elsevier, 2019) to remove duplicates, and then the remaining abstracts were reviewed. After excluding papers not meeting the review’s inclusion criteria, the two investigators independently reviewed the full papers of all remaining studies. A backward-forward citing analysis was conducted on selected publications (i.e., exploration of references and citations of each article) to cover their thematic scope, which led to selecting additional publications. Disagreements on papers to exclude at all stages were resolved through discussion with a third investigator. Figure 3.1 accounts the selection process, which details the number of papers included/excluded at each step and reasons for the exclusion of papers.

3.2.4. Assessment of methodological quality

The peer-reviewed Mixed Methods Appraisal Tool (MMAT) was used to assess the quality and strength of evidence presented in the included articles. The MMAT, already used by more than 100 systematic reviews, is designed for systematic reviews that include qualitative, quantitative, and mixed-methods studies. It allows the use of one tool for concomitantly appraising the most common types of empirical studies (Hong et al., 2018). Each included study is rated in its appropriate methodological category, namely mixed methods, qualitative, quantitative, which are subdivided into three sub-domains: randomised controlled, non-randomised, and descriptive. Category criteria generally refer to data collection methods, data analysis strategies, risk of bias, sampling, confidence, and methodological consistency (Hong et al., 2018) and are rated either “yes,” “no,” or “can’t tell.”

Two authors of this review conducted the methodological quality assessment independently. In case of disagreement, the third author of the review intervened as a mediator, and consensus was achieved through general discussion. For every met criterion (i.e., rated as “yes”), the examined article was given one star, resulting in a possible maximum 5-star rating. Articles that received less than three stars were regarded as obscure in terms of methodological quality and thereby excluded from the review.

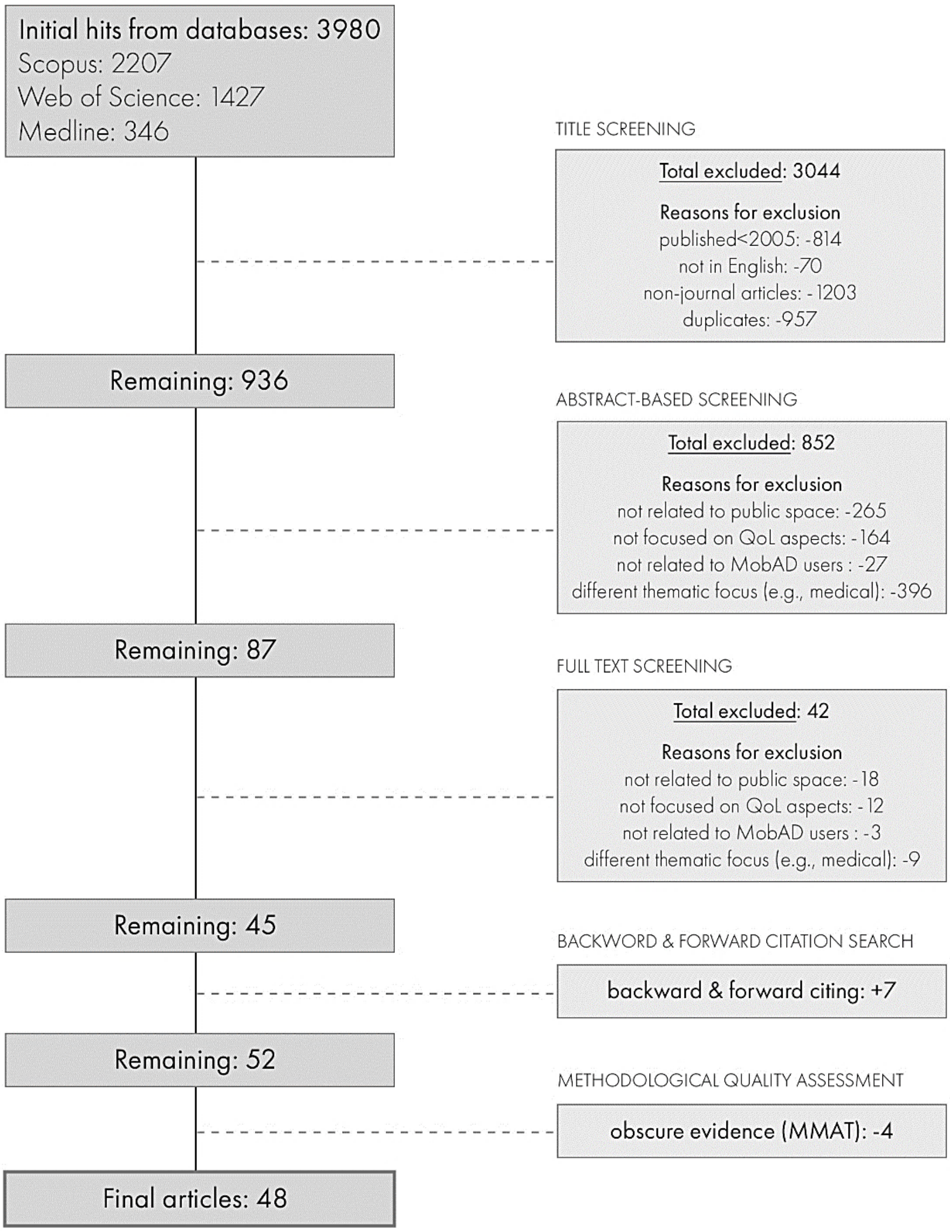


Figure 3.17: Study selection and eligibility criteria

3.2.5. Data extraction

A unique coding scheme was created to extract information from the reviewed articles in relation to the objectives of this review. The qualitative data analysis computer software NVivo (Version 11.0; QSR International, 2020) was used to code the articles according to (a) article characteristics (author, year of publication, country, methodological approach, quality of evidence), and (b) objective-related insights (purpose, main findings).

Two authors of this review were responsible for building the coding scheme. In case of disagreement, the third author of the review intervened as a mediator and consensus was achieved through general discussion. Some codes, particularly those concerning objective-related insights, were further divided into sub-categories to gain analytical understanding of the studied subject and help with synthesising the review findings. Table A.1 of the Appendix section presents the coding scheme and created codes per class of information.

3.3. Results

The electronic database search resulted in 3980 papers. Of these papers, 936 abstracts were reviewed, and subsequently, 87 articles were selected to read in their entirety. After reading these papers, 42 were excluded, resulting in 45 articles. Another 7 articles were added to those after a backward- and forward-citing process. After assessing those 52 papers in terms of methodological quality, 4 articles were found to be of substandard quality and excluded from this review. Consequently, 48 articles were included in this review. The flow diagram in Figure 3.1 has been constructed according to PRISMA guidelines and identifies the numbers of papers excluded at each stage and reasons for their exclusion.

The results are structured around the coding scheme of Chapter 3.2.4 – Data Extraction. Table 3.2 briefly summarises the collected content according to the seven main codes of the coding scheme. Specifically, it includes an aggregated analysis of the 48 reviewed articles, listed alphabetically in relation to their publication details, purpose and types of MobAD examined, methodological approach, quality of evidence, and key findings.

Publication details	*Purpose & type of MobAD examined*	*Study design* *Data analysis & collection methods; Sample size* *MMAT rating; Limitations*	*Key findings*
1. Abu Tariah et al. (2018); Saudi Arabia	To explore ***wheelchair*** accessibility of mosques in Riyadh from the perspective of users.	Descriptive QUANT., Social survey; N=48 80%; sample representativeness	Mosques were inaccessible for wheelchair users. This impacted their spiritual condition.
2. Aldersey et al. (2018); Bangladesh	To explore barriers and facilitators for ***wheelchair*** users.	Exploratory QUAL., Interviews; N=20 80%; inefficient data collection methods	Participants mentioned a few barriers in public spaces (pathways, ramps, bus stops) that affected them diversely.
3. Alm et al. (2008); Sweden	To document the prevalence of shoulder pain, interference in activities of ***manual wheelchair*** users.	Descriptive QUANT., Social survey; N=88 60%; sampling strategy, sample representativeness	The highest median intensity of shoulder pain was reported for pushing the wheelchair up ramps or inclines outdoors.
4. Bennett et al. (2009); Canada	To determine how much curb ramps in an urban area met a set of accessibility guidelines.	Descriptive QUANT., Spatial survey; N=79 60%; sample representativeness, sampling strategy	Only a small proportion of the studied curb ramps met all the accessibility guidelines. This may impact users' navigation.
5. Bentzen et al. (2020); USA	To explore effects of tactile walking indicators on users of **wheelchairs, rollators, canes, and crutches**.	Descriptive MIXED, Observation & Social survey; N=38 100%	Crossing either orientation of tactile indicators caused some increase in effort and instability for more than half of participants.
6. Bromley et al. (2007); United Kingdom	To explore the experiences of ***wheelchair*** shoppers in city centres.	Explanatory MIXED, Social survey & interviews; N=120 80%; sample representativeness	Aisles, shelves, counters, and sidewalks made shopping a frightful experience for wheelchair users.
7. Carlsson & Lundalv (2019); Sweden	To extract and analyse national ***power wheelchair***-related accident and injury data.	Descriptive QUANT., Official records analysis; N=301 80%; sampling strategy limitations	The reason for many of the single accidents and injuries was a difference in ground level (34%, typically a curb).
8. Chen et al. (2011); Taiwan	To report ***wheelchair***-related accidents characteristics.	Descriptive QUANT., Interviews; N=95 60%; sample representativeness, confounders	Accidents frequently were caused by narrow pathway passages and uneven surfaces.
9. Chiwandire & Vincent (2017); South Africa	To describe and assess accessibility measures in South African universities.	Exploratory QUAL., Interviews; N=13 80%; inadequate data collection	Challenges with promoting higher education accessibility for wheelchair users include badly designed toilets, libraries, and transport facilities.
10. Cooper et al. (2012); USA	To identify and evaluate cross-slope surface characteristics that impact ***manual wheelchair*** mobility.	Descriptive QUANT., Social survey; N=107 80%; survey measurements	Severe cross-slope angles could make it challenging for manual wheelchair users to safely and independently traverse sidewalks.
11. Corazon et al. (2019); Denmark	To explore the experiences of users of ***wheelchair, scooters, canes, and crutches*** when using green spaces.	Exploratory QUAL., Interviews; N=25 100%	Lack of access - due to uneven surfaces, slopes, inadequate ramps, and poor parking spaces - led to feelings of exclusion and outsideness.

12. Daamen et al. (2008); Netherlands	To assess the gap between public transport vehicles and platforms as a barrier for ***wheelchairs, rollators, scooters, and canes.***	Descriptive QUANT., Observation; N=165 100%	The 10 cm X 10 cm gap constituted a serious problem for more than half of the participants. Access for nearly all requires a gap size no larger than 5 cm X 2 cm.
13. Dolbow & Figoni (2016); USA	To determine for fitness centres the level of compliance with ADA.	Descriptive QUANT., Spatial survey; N=10 60%; sample representativeness, inadequate analysis	All surveyed facilities were found to be partially compliant, with none of the facilities being 100% compliant. Service surfaces, confined spaces, and doors were least compliant.
14. Dutta et al. (2011); Canada	To determine space needed for powered mobility ***scooters*** to manoeuvre indoors.	Explanatory QUANT., Lab trials; N=1 80%; sample representativeness	None of the scooters tested could complete all manoeuvres within the confined space limits allowed by existing standards.
15. Duvall et al. (2013); USA	To develop a guideline for public pathways and sidewalks for users of ***wheelchairs***.	Explanatory MIXED, Observation & survey; N=61 100%	Surfaces with wide and frequent cracks subjected wheelchair users to harmful whole-body vibrations and were uncomfortable for users of wheelchairs.
16. Evcil (2018); Turkey	To evaluate ***wheelchair*** users' participation in recreation activities in a heritage site.	Descriptive QUANT., Social survey; N=125 80%; weak sampling strategy	There are significant physical obstacles that hamper access to leisure activities, such as pathway characteristics, absence of ramps, existence of stairs, and problematic entrances.
17. Evcil (2009); Turkey	To determine the compliance of public buildings to ***wheelchair*** accessibility guidelines.	Descriptive QUANT., Spatial survey; N=26 60%; sample representativeness, sampling strategy	Ramps, doors, parking spaces and sidewalks were the found to be the most problematic elements.
18. Frost & Bertocci (2010); USA	To characterise ***wheelchair & scooter*** adverse incidents on transit vehicles.	Descriptive QUANT., Official records analysis; N=115 80%; non-response bias	Wheeled mobility devices users have a greater chance of incurring injury during ingress/egress on boarding ramps.
19. Frost et al. (2020); USA	To solicit feedback on boarding ramp related incidents and difficulties from **wheelchair & scooter** users.	Descriptive MIXED, Social survey; N=384 80%; non-response bias	Steep ramp slope was the primary contributing factor to most incidents. Users questioned ramps accessibility.
20. Gamache et al. (2020); Canada	To objectively describe environmental obstacles encountered by **wheelchair, scooter, crutches, and canes** users.	Descriptive MIXED, Spatial survey & Interviews; N1=20, N2=10-15 80%; sampling strategy	Access ramps and washrooms should be considered for improvement.
21. Grange-Faivre (2016); France	To determine the maximum gap between transport vehicle & platform for ***wheelchairs & canes*** users.	Descriptive QUANT., Observation; N=46 80%; existence of non-accounted confounders	Nearly half the manual wheelchair users failed the gaps of 50 mm × 50 mm and larger.
22. Henje et al. (2021); Sweden	To identify obstacles and risks for ***power-wheelchair*** users by exploring their behaviour and experiences in traffic environments.	Exploratory QUAL., Interviews; N=15 60%; sampling strategy, sample representativeness	Uneven and non-uniform pathways are major obstacles and causes of accidents for users of powered mobility devices.

23. Holliday et al. (2005); Canada	To determine ***power wheelchair*** manoeuvrability factors for reach range in confined space.	Exploratory MIXED, Social survey & Lab trials; N1=123, N2=1 60%; sample representativeness, sampling strategy	Power wheelchairs users would not achieve maximum reach capability within the space width allowed by existing standards.
24. Hurd et al. (2008); USA	To evaluate ***manual wheelchair*** propulsion across level ground conditions.	Explanatory QUANT., Observation; N=14 60%; inappropriate measurements, confounders	Carpet flooring and aggregate concrete were found to be the most physically-demanding for indoor and outdoor use, respectively.
25. Jang et al. (2019); Canada	To explore everyday experiences of ***scooter*** users as they navigate outdoors.	Exploratory QUAL., Interviews; N=20 80%; data collection methods	Common barrier locations included existence of steps, uneven sidewalk surfaces, and doors.
26. Khalili et al. (2021); Canada	To evaluate how personal, environmental, and device-related factors impact the perceived autonomy of users of **wheelchairs & scooters**.	Descriptive QUANT., Social survey; N=123 80%; sample representativeness	Manoeuvrability on uneven/rough terrains and at confined spaces vastly impacted autonomy of MobAD users.
27. Kim et al. (2014); Korea Republic	To understand the effects of ramp slope and height on ***wheelchair*** users' propulsion force.	Explanatory QUANT., Lab trials; N=30 80%; sample representativeness	Accessibility of the ramp decreased as the slope increased, and accessibility difference between slopes increased as the height increased.
28. Koontz et al. (2020); USA	To identify facilitators and barriers to ***wheelchair*** **& scooters** transfers in the community.	Descriptive QUANT., Social survey; N=112 80%; sample representativeness	Wheeled mobility device users had limited transferability with respect to wrongly-located grab-bars and facility surfaces, confined spaces, and toilets.
29. Koontz et al. (2010); USA	To determine minimum space required for 4 different types of turns for ***wheelchair & scooters***.	Explanatory QUANT., Lab trials; N=213 80%; sample representativeness	Between 10% and 100% of users would not be able to manoeuvre in spaces that meet current Accessibility Guidelines for Buildings and Facilities specifications.
30. Labbe et al. (2020); Canada	To explore the experiences of older adult ***powered wheelchair*** users.	Exploratory QUAL., Interviews; N=19 80%; data collection methods	Participants mostly identified issues with entrances and toilets in stores, restaurants and public buildings, and the inadequate conditions of the sidewalks.
31. Lee et al. (2020); USA	To identify environmental and personal barriers to healthy eating among people with mobility impairments*.	Descriptive MIXED, Social survey; N=112 60%; sample representativeness, sampling strategy	Reaching high or deep store shelves, high tills or check-out surfaces, as well as narrow aisles in convenience stores are access barriers for MobAD users.
32. Lenker et al. (2016); USA	To assess the usability of ramp slope for ***wheelchairs & canes*** users.	Explanatory MIXED, Lab trials & social survey; N=27 60%; sample representativeness, confounders	The 1:4 slope was too steep. The 1:6 slope was also considered challenging, in terms of safety and fatigue.
33. Leong & Higgins (2010); Singapore	To explore needs of ***wheelchair***-bound young people regarding library services.	Exploratory QUAL., Interviews; N=11 60%; inadequate data collection & findings representation	The main problem in using libraries was getting through doors. Within the library premises, there were problems relating to stairs, curbs, furniture, shelves, and counters.

34. Lid & Solvang (2016); Norway	To explore accessibility aspects from a user perspective for ***wheelchairs & crutches.***	Exploratory QUAL., Observation; N=14 100%	MobAD users' access to urban areas was hampered mainly due to sidewalk characteristics, thus hampering their participation in society, and damaging their self-esteem.
35. Lindemann et al. (2016); Germany	To develop intelligent wheeled ***walkers*** by investigating possible access problems.	Exploratory QUAL., Social survey; N=60 80%; quantitative measurements lacked consistency	Walking downhill and uphill, stairs, and walking outdoors over uneven ground were major problems identified.
36. Mafatlane et al. (2015); Botswana	To assess accessibility of supermarkets for ***manual wheelchair*** users.	Explanatory MIXED, Spatial survey & interviews; N1=30, N2= 6 80%; sample representativeness	The interior design (aisles, shelves) of the supermarket increased dependency of shoppers who use wheelchairs on activities such as picking items, paying, and reading price tags.
37. Mojtahedi et al. (2008); USA	To assess the impact of the built environment on access to healthy foods for MobAD users.	Descriptive QUANT., Spatial survey; N=82 80%; sample representativeness	MobAD users are at a disadvantage in staying healthy due to physical obstacles in getting healthy foods (e.g., high shelves & counters, narrow aisles, and inaccessible entrances).
38. Owusu-Ansah et al. (2019); Ghana	To study the spatial needs of the mobility impaired within the built environment.	Descriptive MIXED, Spatial survey & social survey; N=100 60%; sample representativeness; sampling strategy	Mobility-impaired people navigated through the built environment with great difficulty. Poorly design parking, uneven surfaces and existence of stairs were big challenges.
39. Pierret et al. (2014); France	To quantify strains during ***manual wheelchair*** travel on cross slopes.	Explanatory QUANT., Lab trials; N=25 100%	An 8% cross-slope is subjectively sensitive and impose physiological costs. A 12% cross-slope is unachievable for some users and should therefore be prohibited.
40. Prescott et al. (2021); Canada	To explore challenges that users of wheelchairs and scooters face navigating unfamiliar pedestrian environments	Exploratory MIXED, Interviews; N=14 80%; sample representativeness	Uneven and sloped pathway surfaces were key navigational challenges for study participants.
41. Stafford et al. (2019); Australia	To study neighbourhood experiences of young users of ***wheelchairs & crutches***.	Exploratory QUAL., Interviews; N=12 100%	Children who use mobility aids must compromise safety when navigating on sidewalks due to physical barriers such as narrow space and or poorly designed curb ramps.
42. Torkia et al. (2015); Canada	To describe ***power wheelchair*** driving challenges from a user perspective.	Exploratory QUAL., Interviews; N=12 80%; data collection methods	Confined spaces, doorways and uneven sidewalks were indicated as the biggest challenges for navigation and manoeuvrability.
43. Toro et al. (2013); USA	To determine physical elements impact on ***wheelchair*** users' transferability.	Explanatory QUANT., Observation; N=120 80%; confounder affected design and results	Transfer surface heights above and below the device seat height, gaps, and obstacles posed serious transfer-related accessibility problems for MobAD users.
44. Tripathi et al. (2017); Singapore	To describe ***pram and stroller*** injuries and identify possible risk factors.	Descriptive QUANT., Official reports analysis; N=248 60%; inadequate measurements & nonresponse bias	1 out of 10 patients sustained injuries while the strollers and prams were on escalators and stairs.
45. Velho (2019); United Kingdom	To explore the barriers faced by ***wheelchair*** users in the transit network.	Exploratory QUAL., Interviews; N=34 80%; inadequate analysis	Crowded and confined spaces impacted autonomy of MobAD users. Reliance on transport staff to deploy ramps aggravated this situation.

46. Velho et al. (2016); United Kingdom	To research the barriers faced by ***manual wheelchair*** users in public transport.	Explanatory MIXED, Observation & interviews; N1=7, N2=21 60%; sample representativeness, inadequate analysis	As the gradient of the boarding ramp incline increased, upper limb demand and injury risk increased.
47. Vredenburgh et al. (2009); USA	To evaluate ramp accessibility and perceived effort required for ***wheelchair users***.	Explanatory MIXED, Observation & survey; N1=43, N2=27 100%	For a transit distance up to 6 m (20ft.), a ramp should not exceed a maximum cross slope of 5% or a maximum running slope of 7%
48. Wretstrand et al. (2010); Sweden	To estimate the incidence of ***wheelchair***-seated passenger injuries related to transit systems.	Descriptive MIXED, Official data analysis & interviews; N1=159, N2=1000 60%; quantitative measurements lacked reliability	Boarding and alighting were deemed to be the most impactful conditions. Most passengers sustained injuries because of their interaction with boarding ramps.

Table 3.10: Analysis of general characteristics and methodology of the reviewed content

Explanations: “Wheelchairs” refer to both manual and power wheelchairs, unless stated differently. MIXED = Mixed methods, QUAL. = Qualitative, QUANT. = Quantitative. “Evidence quality” level expresses agreement with 5 criteria of MMAT subject to study methodology. * The authors did not specify types of MobAD users surveyed in this study

3.3.1. Characteristics and quality of selected articles

The review included 48 articles published from 1.1.2005 until 31.10.2021, of which over 50% were published during 2015 and 2021. A quarter of these articles were published in 2019 (Articles 11, 19, 22, 26, 27, 40 in Table 3.2) and 2020 (Articles 5, 11, 20, 28, 30, 34 in Table 3.2). Those are indicators that research in the area is growing.

Approximately 3 out of 4 studies were carried out in high-income countries of the Global North. Most studies were conducted in the United States (Articles 5, 10, 13, 14, 15, 18, 19, 24, 28, 29, 31, 32, 37, 43, 47 in Table 3.2 – 14 studies in total), followed by Canada (Articles 4, 14, 20, 23, 25, 26, 30, 40 in Table 3.2 – 8 studies in total), and Sweden (Articles 3, 7, 22, 48 in Table 3.2 – 4 studies in total). Regarding the types of MobAD examined, wheeled devices (e.g., manual and power wheelchairs - Articles 14, 18, 20, 32, 43, 47 in Table 3.2) far outnumbered devices that support the activity of walking (e.g., canes and crutches - Articles 16, 17, 33, 39, 44 in Table 3.2). These data show that the collected literature was not equally distributed in terms of demographics.

In terms of thematic relation to the main purpose of this review, 8 articles focused on physical accessibility assessments (Articles 1, 2, 3, 8, 17, 33, 36, 42 in Table 3.2). Another 25 articles reported effects of physical elements on QoL of MobAD users (Articles 4, 5, 6, 7, 9, 10, 11, 12, 13, 14, 18, 19, 21, 22, 23, 24, 25, 26, 27, 29, 31, 34, 38, 40, 41 in Table 3.2). The remaining 15 articles focused on both themes (Articles 15, 16, 20, 28, 30, 32, 35, 37, 39, 43, 44, 45, 46, 47, 48 in Table 3.2). These data imply that quality of life is a dominant theme, as it was addressed by over 80 per cent of the selected studies.

The majority of the reviewed content (Articles 4, 5, 7, 9, 10, 11, 13, 14, 15, 17, 18, 20, 21, 22, 23, 25, 26, 27, 29, 31, 34 in Table 3.2 - 21 studies in total) employed a descriptive research approach in the sense that they primarily focused on describing what physical barriers exist in the built environment. More than half of the studies (Articles 4, 5, 6, 10, 11, 13, 14, 18, 19, 20, 22, 23, 24, 25, 26, 27, 29, 30, 31, 32, 34, 37, 41, 48 in Table 3.2 – 24 studies in total) utilised quantitative data analysis methods. Regarding data collection techniques, social surveys (Articles 5, 9, 10, 11, 13, 14, 15, 17, 18, 20, 21, 23, 25, 29, 31, 34, 40 in Table 3.2 – 17 studies in total) and personal interviews (Articles 4, 5, 9, 10, 11, 13, 14, 15, 18, 21, 22, 25, 26, 29, 31 in Table 3.2 – 15 studies in total) were adopted most frequently. Those are indicators that most studies directly involved human participants (i.e., MobAD users) to provide conclusions and influence decision-making regarding the phenomenon of physical inaccessibility.

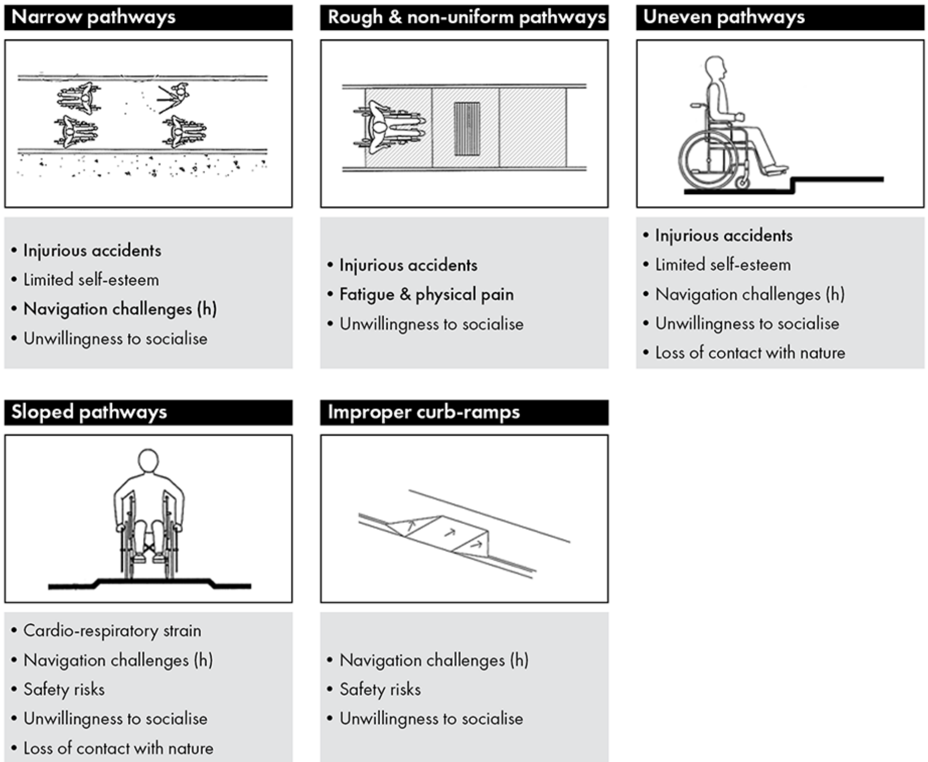
Quality of evidence of the reviewed articles was assessed using the MMAT. 39 studies met with over 80% of the MMAT Criteria (Articles 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40 in Table 3.2), while 15 therein met with 100% (Articles 3, 4, 6, 8, 9, 10, 11, 12, 13, 17, 18, 19, 22, 26, 27 in Table 3.2). Therefore, the majority of the reviewed content deemed to be of substantial quality. Study limitations were the primary factor for quality shortcomings. Low sample representativeness was the most recurrent limitation as mentioned in 20 studies (Articles 4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 18, 20, 21, 22, 23, 24, 26, 27 in Table 3.2). In most of these cases, the full range of MobAD users was not represented or the sample size was too low. This means that results of those studies should be used with caution before generalised.

3.3.2. The impact of inaccessible public spaces on life aspects of users of Mobility Assistive Devices

Reviewed studies that assessed the accessibility of public spaces indicated a substantial number of problematic elements for MobAD users. These elements were categorised into four macro-environments – i.e., outdoor environments, transport, physical facilities, building approach, and indoor facilities – according to their spatial location and function. The rest of the section examines their impact on QoL aspects of MobAD users.

3.3.2.1. Outdoor environments

Inaccessible pathways monopolised the research interest with respect to outdoor environments. This can be attributed to the fact that many disabled people find their journeys outdoors interrupted at the very first stage – the sidewalk. Figure 3.2 summarises the impact of pathway characteristics on various QoL aspects for MobAD users.



*Grey boxes include impacted QoL aspects per element according to our results. **The most common aspects identifed in the reviewed content are shown in bold. ***(h) refers to horizontal navigation, (v) refers to vertical navigation.

Figure 3.18: Impact of pathway characteristics on QoL aspects of MobAD users

3.3.2.1.1. Problematic pathway characteristics – a source of safety hazards and health maladies. Numerous studies indicated that pathway characteristics – namely narrow, rough, uneven, or sloped sidewalks – were key factors for limited MobAD-accessibility outdoors (Aldersey et al., 2018; Cooper et al., 2012; Evcil, 2018; Henje et al., 2021; Jang et al., 2019; Labbé, et al., 2020; Lid & Solvang, 2016; Lindemann et al., 2016; Torkia et al., 2015). The large volume of research that has been dedicated to problematic pathway characteristics underscores their significance with respect to urban accessibility.

The safety of MobAD users was mostly challenged by physical barriers in pathways. Specifically, Chen et al. (2011) concluded that wheelchair-related accidents, predominantly tips-and-falls, were frequently caused by narrow, rough, or uneven pathways. These types of accidents could cause minor, moderate, severe, or even fatal injuries to users of power mobility wheelchairs and scooters as Carlsson and Lundälv (2019) indicated. Despite the fact that Carlsson and Lundälv only investigated injuries resulting from accidents involving powered mobility devices, it is presumed that these findings apply to – perhaps with lesser propensity – users of manual wheelchairs as well. These findings suggest that appropriate replacement or further development of physical infrastructure – for instance, lowering curbs – would contribute to increased safety and navigation for MobAD users.

Fatigue and physical pain due to pathway characteristics was another issue studied by researchers. Pierret et al. (2014) suggested that pathway cross-slopes – i.e., slopes perpendicular to the direction of travel – exceeding a critical threshold (i.e., 8%) could impose noteworthy cardio-respiratory strain on users of manual wheelchairs. Despite the importance of these findings, fatigue is a highly subjective parameter and a function of several user attributes such as the nature of the disability, physical and mental fitness, and MobAD characteristics. That is, further work is needed to confirm the impact of pathway cross-slopes on the physiological condition of MobAD users as a whole.

Outdoor walking surfaces with wide and frequent cracks – such as brick sidewalk surfaces – subjected wheelchair users to harmful whole-body vibrations, which could be associated with increased health risks such as pain in the back and neck as well as muscle fatigue according to Duvall et al. (2013). The core value of the previous study derives from its findings, which were used to develop a meaningful standard for surface roughness to augment existing accessibility guidelines (i.e., ADAAG, 2010). Similarly, Hurd et al. (2008) reported that rough materials used for paving – such as aggregate concrete – could considerably increase body fatigue levels for users of manual wheelchairs. The previous two studies seem to agree that some widely used paving techniques are inappropriate for MobAD users' physical condition. Their findings are significant sources for infrastructure planners, engineers, and urban designers to understand the implications of these terrain characteristics for MobAD users.

Tactile paving or Tenji blocks, which are used internationally to provide location and directional information at crosswalks to blind pedestrians, could impede the smooth navigation of MobAD users. Specifically, these types of tactile guides were found to inflict fatigue and increase instability for people using a wide range of MobAD – especially due to uneven surfaces perpendicular to the direction of travel (Bentzen et al., 2020). The case of Tenji blocks typifies a clash of accessibility provisions between two special interest groups. This is because an accessibility facilitator for visually impaired individuals was deemed to be a barrier for MobAD users. A possible solution for city professionals would emerge through parallel trials where researchers could compare crossing behaviour of both groups (ibid.). Outcomes from these studies could provide a scientific basis for performance-driven crosswalk design patterns, which would universally cater for both visually impaired and mobility-impaired people according to their functional capabilities.

3.3.2.1.2. Safety concerns and subordinate effects due to inaccessible pathways.

Safety fears as a direct result of problematic pathway characteristics had spill-over effects on MobAD users' independent navigation. Cross-sloped sidewalks exceeding accessibility thresholds made it challenging for users of manual wheelchairs to safely navigate over sidewalks (R. Cooper et al., 2012). Moreover, curb ramps – which failed to meet accessibility guidelines – entailed the risk of MobAD users tipping over or being struck by road traffic (Bennett et al., 2009). For Bromley et al. (2007), lack of curb ramps maximised inconvenience in independent navigation of MobAD users in a city-centre environment. Another study by Khalili et al. (2021) showed that safety concerns due to non-uniform or rough terrains – such as gravel-made sidewalks or grassy pathways

– was the primal impediment to MobAD users' manoeuvrability outdoors. An interesting remark derives from Prescott et al. (2021) who highlighted the role of street infrastructure as a barrier to independent navigation. Specifically, excessively tall road signs and high crosswalk buttons were found to hamper the orientation of few MobAD users in a university campus as most of those sit lower than ambulatory pedestrians. Despite the variations in study populations and spatial contexts, the above findings suggested that the construction of public pathway infrastructure without considering a wide breadth of functional capabilities might adversely impact a range of MobAD.

MobAD users often find themselves psychosocially dysfunctional due to insecure pathway conditions. Lid and Solvang (2016) conducted a study to unveil the lived experiences of vulnerable people navigating in urban environments. The study found that unsafe pathways – primarily due to uneven or narrow sidewalk surfaces – diminished MobAD users' willingness to navigate outdoors as well as damaged their self-esteem. In a different setting, Stafford et al. (2019) explained that children MobAD users were reluctant to navigate or socialise on sidewalks due to physical barriers – predominantly absent curb ramps, rough surfaces, and narrow sidewalks – because of personal safety risks. In the same vein, Corazon et al. (2019) reported that safety fears due to excessively sloped or uneven pathways deterred MobAD users from visiting natural spaces such as parks. Results from the above studies suggested that inaccessible pathways can coerce MobAD users into isolating from urban life and society as well as impose psychological damage on vulnerable individuals.

3.3.2.2. Transport facilities

The physical gap between platforms/stops and vehicle floors was deemed to be a significant burden for MobAD users. Boarding ramps were also found to jeopardise users' safety and autonomy. Inaccessible transport infrastructure hampered the autonomy and personal development of MobAD users. Figure 3.3 illustrates the impact of transport physical infrastructure on different facets of QoL of MobAD users.

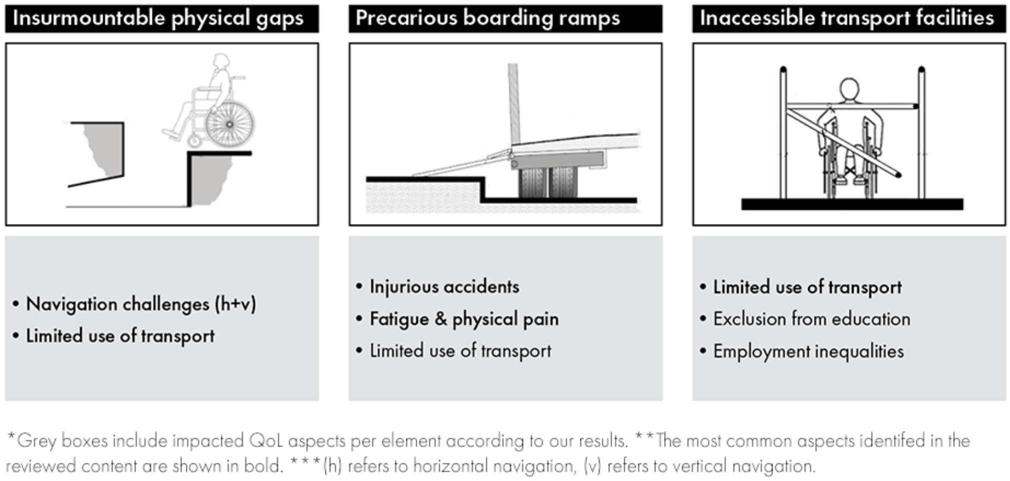


Figure 3.19: Impact of transport physical infrastructure on QoL aspects of MobAD users

3.3.2.2.1. Insurmountable physical gaps and precarious boarding ramps. Existing physical gaps between platforms/stops and vehicle floors were non-negotiable for MobAD users. Two experimental studies undertaken in different research contexts – i.e., in the Netherlands and France respectively – agreed that gaps of more than a certain threshold (i.e., 50mm x 50mm measured in width x height) could inhibit users from boarding/alighting transport vehicles (Daamen, de Boer & de Kloe, 2008; Grange-Faivre et al., 2017). In other words, these types of gaps would obstruct both horizontal and vertical access to transport vehicles. However, both experiments were conducted in mock-up environments and ruled out significant actual parameters – such as the flow of fellow travellers – which could influence MobAD access in real-life situations. Nevertheless, results from both studies are valuable indicators of acceptability thresholds for transport infrastructure regarding independent navigation of MobAD users. It is probable that most transport systems are not in a position to align with the aforementioned standards due to inconsistent physical infrastructure. For example, uneven terrain at bus drop-off points could expand the vertical gap between the bus floor and ground surfaces, thus compounding the difficulty of MobAD users when boarding/alighting buses (Frost et al., 2020).

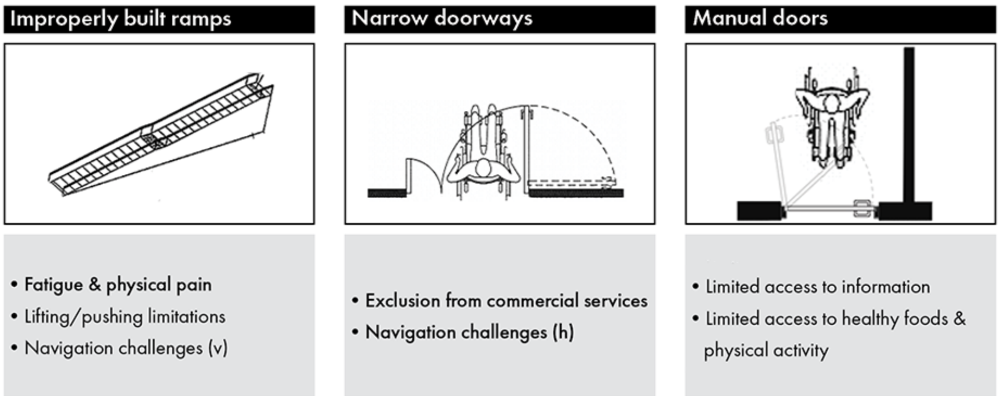
A temporary solution for bridging physical gaps in transport operations is boarding ramps, which are extensively used in train stations and bus stops. However, boarding ramps were frequently found to exceed the allowable slope thresholds (Frost et al., 2020; Lenker et al., 2016). In many cases, this can be attributed to careless ramp deployment combined with operator practices – e.g., not fully kneeling buses – or physical constraints, for instance, due to limited available space between buses and ground-fixed bus shelters. Excessive ramp slopes could result in injurious accidents (e.g., concussions and femur fractures) and physical strain for MobAD users when boarding or alighting transport vehicles (Frost & Bertocci, 2010; Wretstrand et al., 2010). Specifically, it was observed that as the gradient of the ramp incline increased, upper limb demand (i.e., musculoskeletal fatigue) and injury risk for wheelchair users also increased (Velho et al., 2016). Another research cohort disputed the capacity of boarding ramps to securely accommodate MobAD users even within acceptable limits by accessibility regulations. D'Souza et al. (2019) found that ramp slopes within permissible limits (i.e., 1:6 gradient as per the Americans with Disabilities Act Guidelines, 2010) caused physical discomfort to wheelchair and scooter users. This agreed with Lenker et al. (2016), who argued that ramp slopes within the previous limits were likely to obstruct unassisted boarding and alighting for wheelchair users. Both study samples did not include users of ambulation aids, for instance, canes and crutches who comprise a large population of MobAD users. Although further research is yet needed with this population, findings from all above studies indicate that using boarding ramps can be a taxing task for the majority of MobAD users.

3.3.2.2.2. Inaccessible transport infrastructure – an obstacle for autonomy & personal development.

Apart from jeopardising MobAD users' health and safety, inaccessible transport infrastructure can affect their independence and development. Confined and crowded places, for instance, train platforms had a significant impact on MobAD users' autonomy in terms of using public transport (Khalili et al., 2021). Another study showed that many MobAD users experienced a “loss of autonomy” and feelings of exasperation due to reliance on the presence of transport staff in order to use boarding ramps (Velho, 2019). Those findings possibly infer that inaccessible infrastructure dissuaded MobAD users from using public transport for performing everyday tasks. According to Aldersey et al. (2018), this could heavily impact MobAD users’ participation in community activities such as shopping as well as employment opportunities. Likewise, Chiwandire and Vincent (2017) indicated that transport deficiencies – mainly due to the physical gap between bus stops and bus floors – could inhibit many young MobAD users from accessing university campuses. Evidence generated by these studies highlights that inaccessible transport could curtail equal opportunities among members of society, especially in employment or education.

3.3.2.3. Building approach

Building approach areas were found to include problematic elements that imposed multifaceted issues on MobAD users. Built ramps and entrance characteristics – such as doors and doorways – were most frequently discussed by the collected content. Figure 3.4 outlines the impact of building approach elements on different QoL aspects of MobAD users.



*Grey boxes include impacted QoL aspects per element according to our results. **The most common aspects identifed in the reviewed content are shown in bold. ***(h) refers to horizontal navigation, (v) refers to vertical navigation.

Figure 3.20: Impact of building approach elements on QoL aspects of MobAD users

3.3.2.3.1. Built ramps – a cause of physical pain and discomfort.

Ramps are internationally used for providing access to MobAD users to approach building entrances; nevertheless, their usability and safety have been questioned by many researchers. Results from a cross-sectional study concluded that propulsion on inclined ramp surfaces was the primary cause of shoulder pain for users of manual wheelchairs (Alm et al., 2008). The same study underlined that chronic shoulder pain could cause upper-extremity activity limitations (ibid.). These findings denote that prolonged ramp propulsion can probably affect the lifting or pushing capabilities of MobAD users and eventually lead to functional performance deficits. Other researchers studied wheelchair users' physiological strain and vertical navigation challenges in relation to ramp characteristics – i.e., running slope, cross-slope, running length, and height – and proposed their own guidelines for designing ramp slopes accordingly (Kim et al., 2014; Vredenburgh et al., 2009). While both studies identified that physical strain increased as ramp slope increased even within permissible limits (i.e., 1:12 gradient as per the Americans with Disabilities Act Guidelines, 2010), accessibility designers and architects should consider that those studies only referred to wheelchair users. It would be useful for design practitioners to examine the whole range of MobAD users – including, for instance, scooter and cane users – before generalising these guidelines. Even so, improperly built ramps would be difficult to amend given their intrinsic structural rigidity. The above findings might propel the discussion that a more flexible means of providing access to buildings should be sought.

3.3.2.3.2. Ill-suited building entrances as impediments to healthy habits and social participation.

Entrance features – such as doors and doorways – were accredited with inflicting manifold issues on MobAD users as per the reviewed literature. Narrow doorways and limited pull spaces were deemed to most deter MobAD users from entering commercial stores by a number of studies (Aldersey et al., 2018; Bromley et al., 2007; Lindemann et al., 2016; Torkia et al., 2015). This may have a grim economic impact on local businesses due to lack of accessible entryways provision to a great number of potential customers. Door features and materials also impacted MobAD users. Abu Tariah et al. (2018) suggested that doors with high handles inhibited MobAD users from accessing mosques. This situation forced MobAD users to pray in isolation in their homes, thus preventing them from participating in an important part of their faith (ibid.). In addition, Leong and Higgins (2010) reported that heavy manually-operated doors were the biggest challenge for MobAD users with respect to accessing public libraries. It was therefore probable that wheelchair users had less access to information than other members of society (ibid.). The above findings suggest that problematic entrance characteristics can be critical factors for the exclusion of MobAD users from social activities and commercial services. This might impel design practitioners to embrace responsive techniques – for instance, automatically-actuated doors and door handles – or comply with relevant accessibility guidelines (such as in ADAAG, 2010) so as to create entrances that could adapt to the needs of MobAD users.

An emerging topic is the possible association between entrance accessibility and healthy habits of MobAD users. Problematic entrances of groceries and fitness centres were deemed to deprive MobAD users of access to healthy foods and physical activity respectively. Mojtahedi et al. (2008) examined MobAD-accessibility of grocery stores in an urban area and found that more than half of those had inaccessible entrances – mainly due to heavy manual doors with limited pull space. The study suggested that entrance inaccessibility was a major barrier for MobAD users in accessing healthy foods (e.g., lean meat and fruits); a condition that could gradually lead to malnutrition (ibid.). Elsewhere, Dolbow and Figoni (2015) explored the level of MobAD-accessibility of fitness centres in a metropolitan area. They found that half of the facilities required the ability to grasp a door handle and manually open heavy entrance doors. This could impede access to fitness centres for MobAD users and decrease their levels of physical activity consequently (ibid.). While findings from both studies cannot necessarily be generalised to other geographic areas, they can serve as valuable reference points for future studies on possible effects of inaccessible entrances on healthy habits of MobAD users.

3.3.2.4. Indoor facilities

Indoor facilities of buildings of public interest included a great number of inaccessible physical elements. Confined spaces – i.e., narrow corridors and restrooms – were often mentioned as a burden for MobAD users' independence. Moreover, retail interior environments – such as shopping malls, commercial stores, and groceries – encompassed safety threats and functioning barriers for MobAD users. Figures 3.5 and 3.6 summarise the impact of building indoor facilities on different facets of MobAD users' lives.

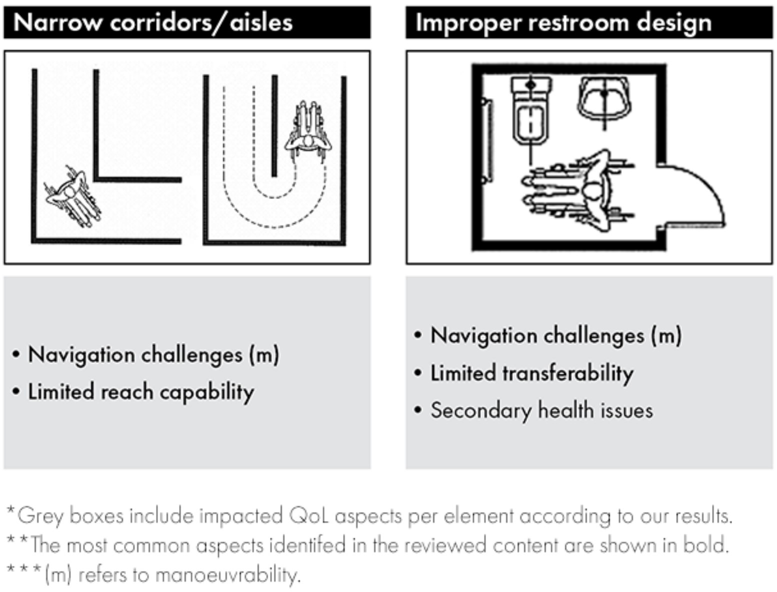
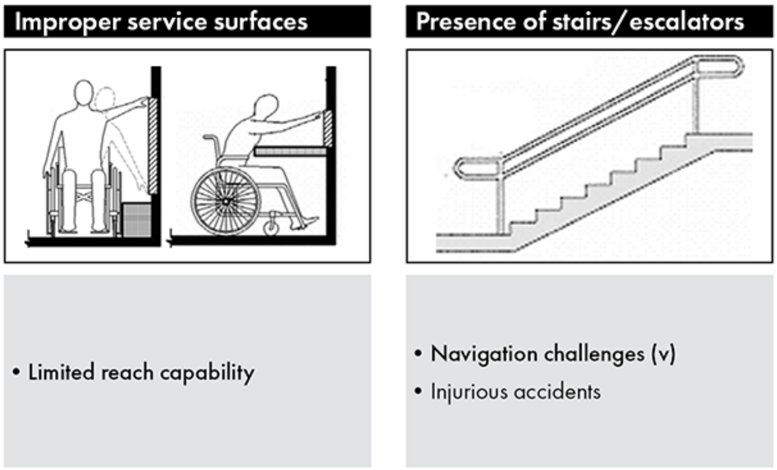


Figure 3.21: Impact of indoor facilities on QoL aspects of MobAD users – I



*Grey boxes include impacted QoL aspects per element according to our results.
**The most common aspects identifed in the reviewed content are shown in bold.
***(v) refers to vertical navigation.

Figure 3.22: Impact of indoor facilities on QoL aspects of MobAD users – II

3.3.2.4.1. Confined spaces obstructing independent living. Narrow corridors were found to impede the independent navigation of MobAD users. Koontz et al. (2010) argued that the majority of MobAD users could not successfully complete 90° and 180° turns through corridors of legally permissible width (i.e., with minimum openings of 91.5 cm and 152.5 cm respectively as per the Americans with Disabilities Act Guidelines, 2010). The study omitted the synergistic effects of surface friction, which can negatively influence users' manoeuvrability over rough surfaces such as carpet floorings (Hurd et al., 2008). However, the special weight of this study derives from its methodological robustness as researchers tested a large and diverse sample (i.e., 213 users of manual and power wheelchairs as well as scooters) to reach the previous conclusions. Later findings reinforced the negative impact of narrow corridors on MobAD users' manoeuvrability as Dutta et al. (2011) suggested that scooter users could not complete 90° and 180° turns through corridors that complied with both American and Canadian accessibility guidelines. In addition to manoeuvrability impediments, the study found that narrow corridors could diminish the reach capability of scooter users. That is, no scooter users would be able to perform a side approach to a counter within a confined space allowed by existing standards (ibid.). This was also true for users of power wheelchairs as indicated by Holliday et al. (2005). Their results showed that users might enter a space; however, they had limited reach capability and were only able to exit the space without collisions by driving in reverse (ibid.). Consequently, overall findings from the previous studies imply that a revision of existing accessibility guidelines is required so that MobAD users can successfully negotiate corridor-type conditions in public buildings such as dead-end halls, cordoned-off queues, or approaching sinks in restrooms.

Physical characteristics of restrooms included substantial barriers for MobAD users. Narrow public restrooms impeded the manoeuvrability of MobAD users as a number of international studies indicated (Chiwandire & Vincent, 2017; Gamache et al., 2020; Owusu-Ansah, Baisie & Oduro-Ofori, 2019; Torkia et al., 2015). Absence or ineffective placement (i.e., higher or lower than MobAD users' achievable height) of handhelds/grab-bars could negatively impact the ability of users to transfer themselves from their devices to toilet seats (Koontz et al., 2020; Toro et al., 2013). Outside transferability, restroom inaccessibility might inflict indirect health problems on MobAD users. One study revealed that a few MobAD users experienced relevant health issues – for instance, urinary tract infections – as a consequence of inability to toilet due to inappropriate restroom design (Aldersey et al., 2018). While these results cannot be generalised due to their regional character, they signify a new field for further investigation since restrooms are closely connected with personal hygiene.

3.3.2.4.2. Barriers for independent functioning and safety threats lurking in retail interior environments.

Problematic features of retail environments were a common topic among the literature. The existence of stairs was an insurmountable barrier for wheelchair and scooter users in various commercial environments, which completely hindered their vertical navigation among building floors (Evcil, 2018; Jang et al., 2019). For Tripathi et al. (2017), stairs and escalators were predominant causes of injurious incidents – including head-related injuries – in shopping malls. This was the only study among the reviewed content which examined possible impacts of problematic elements of public spaces on users of strollers and prams – i.e., infants and young children. Few studies reported that store aisles and service surfaces (e.g., counters and shelves) were amongst the least accessible elements in retail interior environments as they were frequently found not to comply with statutory standards (Bromley et al., 2007; Evcil, 2009; Mafatlane et al., 2015; Mojtahedi et al., 2008). Narrow aisles and inaccessible elements would probably have dramatic effects on MobAD users' independent manoeuvrability and reach capability respectively; however, limited evidence was found within the reviewed content. Other researchers indicated that narrow aisles significantly hampered MobAD users' manoeuvrability within convenience stores (Lee et al., 2020; Mafatlane et al., 2015). Moreover, improper placement of service surfaces (i.e., exceedingly low, high, or deep elements) diminished the users' ability to reach items from overhead shelves or pay at checkout counters (Lee et al., 2020; Mafatlane et al., 2015). Due to the regional focus of those studies, more empirical evidence is needed to corroborate the previous outcomes on an international level.

3.4. Discussion

This review identified the most significant physical barriers in public spaces and explores the impact of inaccessible spaces on QoL aspects of MobAD users. Findings indicated a substantial number of inaccessible elements for MobAD users in public spaces. Pathway characteristics, boarding ramps, entrance features, confined spaces, and service surfaces were deemed to be the least accessible elements. These barriers have multifaceted effects on MobAD users' QoL, with aspects of physical health and safety, mobility, and use of public transport being most affected. The above findings partly address research objective 1 (RO1 - identification of physical barriers) as previously defined in Chapter 1.3.

Design characteristics of existing physical elements of public spaces were often found not to comply with accessibility guidelines. Height differences, limited widths, and excessive slope gradients are common factors for the observed incongruence. Those outcomes agree with international studies which have found that the actual design of several physical elements does not harmonise with accessibility standards (Alagappan et al., 2018; Edlich et al., 2010; Farzana, 2019). A possible explanation for this might be that a substantial portion of public spaces had been constructed before accessibility standards were introduced. Other scholars have attributed this incongruence to a common perception among spatial designers that the application of accessibility laws can be too restrictive in terms of aesthetics and forms, diminish spatial usability, or increase construction costs (Mazumdar & Geis, 2003; Sherman & Sherman, 2012). Failure to comply with accessibility regulations has resulted in much of the urban environment having been built in a way that does not correspond to MobAD users' functional capabilities.

In an international context, accessibility regulations safeguard that spaces and buildings of public interest are accessible to all individuals regardless of their functional statuses (UK Government, 2010; ME Department of Justice, 2010). Nevertheless, the review indicated that several physical elements within allowable accessibility standards impede the independent functioning of a large percentage of MobAD users. Specifically, confined spaces and excessively high service surfaces were frequently linked to setbacks in manoeuvrability, transferability, toileting, and reach capability of MobAD users. An underlying reason for this can possibly emerge from advisory frameworks – i.e., research that underpins accessibility standards development – shortcomings. Field experts have argued that advisory frameworks often ignore variation in body sizes, functioning capacity, and MobAD technologies (D'Souza et al., 2009; Steinfeld et al., 2010). As a result, much of the built environment has been structured as though individuals have identical needs and functioning capabilities (Burton & Mitchell, 2006; Liebermann, 2019). This can prove to be detrimental for MobAD users at the lower end of the functioning spectrum.

A direct consequence of the limitations in functioning is reflected in the degree of MobAD users' participation in society and everyday activities. The review found that several aspects of social participation for MobAD users are affected due to inaccessible spaces, predominantly the use of public transport. The results indicated that inaccessible transport infrastructure could prompt a deficit in education and employment opportunities for MobAD users when compared to non-disabled individuals. These findings confirm the association between transport accessibility and social inequality (Bastiaanssen et al., 2020; El-Geneidy et al., 2016). Furthermore, inaccessibility of entrances of public buildings is found to be a critical factor for the exclusion of MobAD users from social activities and commercial services. These outcomes are in agreement with previous research that associated lack of physical accessibility to socioeconomic inequalities internationally (Dari et al., 2020; Grisé et al., 2019). Significantly, societal exclusion can exacerbate stigma amongst MobAD users, thus making them lose their sense of belonging (C. Edwards & Imrie, 2003). At the same time, employment and education inequalities for MobAD users are most likely to engender macro-economic losses for societies (Buckup, 2009).

The review suggested that MobAD users bear a greater health impact compared to the general population. It foregrounded some latent health issues – such as physical inactivity, malnutrition, and chronic shoulder pain – as indirect consequences of accessibility barriers in public spaces. Evidence from other studies has shown low healthcare utilisation amongst MobAD users due to inaccessible environments in healthcare facilities, as in prenatal care (Iezzoni et al., 2015) and cancer services (Edwards et al., 2020). It can thereby be presumed that access barriers in the built environment propel health inequalities for MobAD users. According to WHO (2011), such inequalities can lead to premature mortality and increased healthcare costs.

Taken together, results of this review really underline assertions of various disability scholars and activists who have contended that the presence of physical barriers increases exclusion and inequalities (Finkelstein, 1993; Goldsmith, 1997). This is particularly true for public spaces that abound with single-function rigid elements – for instance, confined spaces, concrete steps, stairs, and manual doors. Previous research has also shown similar types of inflexible elements constrain human activities by failing to accommodate people of diverse needs and capabilities (Fox & Kemp, 2009; Hertzberger, 2005). Another example of spatial inflexibility derives from the ineffectiveness of most physical elements in accommodating more than one MobAD user at a time – e.g., elevators. While fully functioning individuals are seldom affected by inflexibility, such elements are found to be insurmountable access barriers for MobAD users as results indicate. It is therefore possible that inflexible elements are disabling features of the built environment, thus perpetuating social and spatial injustice in public spaces.

This review provided a holistic assessment of the level of physical accessibility of public spaces in the urban environment. That is, it examined multiple components of the built environment in relation to everyday activities of MobAD users – such as navigating outdoors or using public transport. This has led to the discovery of many possible linkages between problematic physical elements and life aspects of MobAD users.

The current findings provide additional evidence on the role of inflexible elements of public spaces as disabling features, which can totally exclude MobAD users or compel them to conform to unsafe or inconvenient spatial situations. These results can be particularly meaningful to policymakers and built environment professionals as they are obvious indicators that more effective approaches should be sought to ensure that public spaces can support human performance for all.

This review is the first to report possible effects of physical inaccessibility on health and safety aspects of MobAD users. The findings suggested that poorly designed public spaces can be regarded as a double health burden as they can threaten the physiological state of MobAD users as well as deter their access to healthy lifestyles. However, more research is required to corroborate these findings, which would also benefit policymakers.

Previous research did not manage to establish the impact of physical barriers on separate mobility aspects of MobAD users. Contrastingly, the current review includes several experimental or observational studies of commendable methodological quality which determined the impact of manifold physical forms on independent mobility. This has helped identify in what ways spatial factors – especially narrow corridors and wide/high gaps between transport vehicles and platforms/stops – affect different mobility activities (i.e., horizontal and vertical navigation and manoeuvrability).

Another strength of this review is that it extends the scope of research on urban accessibility by exploring possible effects of physical barriers on functioning aspects of MobAD users beyond mobility. Specifically, associations between physical inaccessibility and setbacks in transferability, reach capabilities, and toileting were reported.

Finally, it becomes evident that current design practices deliver public spaces of substandard quality insofar as disability access is concerned. This is due to (a) their disregard for the functional capabilities of a diverse population and (b) the innate inflexibility of physical elements. These two factors have systematically rendered public spaces inadequate to cater to the needs of those who do not fit the criterion of fully-functional capabilities – including MobAD users. Hence, the design of the built environment becomes an actor of disablement and has a tremendous impact on MobAD users’ lives.

B1. Bridge section: transitioning from a theoretical to an empirical accessibility assessment

In the third chapter of this thesis, a comprehensive review of current literature was conducted to identify the main physical barriers in public spaces and to understand the impact of inaccessible spaces on the quality-of-life aspects for MobAD users. The findings revealed that pathway characteristics, boarding ramps, entrance features, confined spaces, and service surfaces are among the most significant barriers, with a considerable impact on MobAD users' quality of life in terms of physical health, safety, mobility, and the use of public transport. However, while this chapter provided valuable insights into the challenges faced by MobAD users in public spaces, the literature review primarily focused on theoretical understanding and previous research. To address this gap and generate empirical evidence, the next chapter seeks to assess the accessibility of public spaces in a specific city-centre area.

As the thesis gradually transitions from revealing significant physical barriers (Research Objective 1) to identifying access needs of MobAD users (Research Objective 2) stage, Chapter 4 shifts the focus to an empirical study, which investigates the MobAD-accessibility of public spaces in the city-centre of Birmingham. By assessing both objective and subjective aspects of accessibility, this chapter aims to enrich the theoretical findings from the systematic review in Chapter 3 with practical, real-world insights.

The significance of combining objective and subjective assessments of accessibility cannot be overstated. Objective assessments provide a factual basis for understanding the physical features of public spaces, enabling researchers to identify potential barriers and areas for improvement. On the other hand, subjective assessments offer invaluable insights into the lived experiences of MobAD users, shedding light on how these individuals perceive and navigate public spaces in their daily lives. By integrating both perspectives, this study aims to present a holistic understanding of accessibility issues and highlight the complex interplay between the built environment and the needs of MobAD users.

4. Integrative accessibility assessment

Accessibility assessment is a process that establishes how well a public open space or building performs in relation to access and ease of use by a wide range of potential users including users of MobAD. Accessibility assessment criteria can be objective or subjective. Objective approaches to accessibility usually assess compliance of built elements to existing regulations (Hovbrandt et al. 2007). Access audits are among the most common objective procedures to evaluate the ease of access to and use of buildings or outdoor spaces by disabled people. An access audit would typically cover all elements of the built environment such as pathways, open spaces, transport physical infrastructure, building approaches and entrances, and building facilities. In a British context, access audits usually measure and compare dimensions of built elements against the design recommendations provided by British Standard 8300: 2018 (Centre for Accessible Environments 2019). Subjective (or perceived) assessment is about how people rate accessibility conditions of places they have experienced (Hjalmarson et al. 2013). This type of accessibility assessment consists of perceptions that stem from disabled people regarding the level of ease of access and use of the built environment. Perceived accessibility captures the subjective aspect of accessibility and complements objective approaches.

Accessibility is a fundamental property of the built environment and has been the subject of systematic investigation in recent years. Several attempts have been made to assess the accessibility levels of public spaces around the world (Bigonnesse et al. 2018; Welage & Liu 2011; Zhang et al. 2017). These efforts have highlighted a number of physical obstacles – for instance, problematic boarding ramps and building entrance features – that reiterate in the built environment and can cause serious distress to MobAD users (Harris et al. 2015; Keysor et al. 2010). What is known about accessibility of the built environment and relative obstacles is derived from either objective or perceived assessments of public spaces. So far, however, there has been very little published research utilising a combined approach to evaluate MobAD-accessibility of the built environment (Sanchez et al. 2000; Voss et al. 2002). Moreover, most of these studies have been restricted to the analysis of individual parts or functions of public buildings such as health centres. Only one research effort has been acknowledged to use a mixed approach to produce evidence for the entirety of the built environment (Labbe et al. 2020). Despite the methodological novelty and robustness of this work, much uncertainty still exists about (a) the relationship between physical accessibility and MobAD users of different characteristics and (b) the frequency and distribution of physical obstacles – both indoors and outdoors – in a city-centre environment.

4.1. Purpose

The main aim of this research is to scrutinise city-centre environments in terms of MobAD-accessibility. Three objectives seek to realise the research aim: (a) to investigate the level of accessibility of different spatial categories and their components; (b) to identify the most challenging physical obstacles; and (c) to examine possible associations that develop between several physical obstacles and individuals with varying demographic and functioning characteristics.

4.2. Methods

This present chapter outlines an integrative approach to assessing the accessibility of public spaces in Birmingham city-centre, UK. This environment was selected due to its significant population and characteristics common to Western cities such as mixed-use activities and dense urban fabric. The assessment was divided into two parts: objective measurement (Part A) and subjective evaluation (Part B).

4.2.1. Part A – Objective accessibility assessment

The objective assessment involved measuring the physical accessibility of selected public spaces - Figure 4.1 presents the study area in relation to the city of Birmingham - and comparing these measurements against the British Standard 8300: 2018, which provides guidelines for designing accessible and inclusive environments.

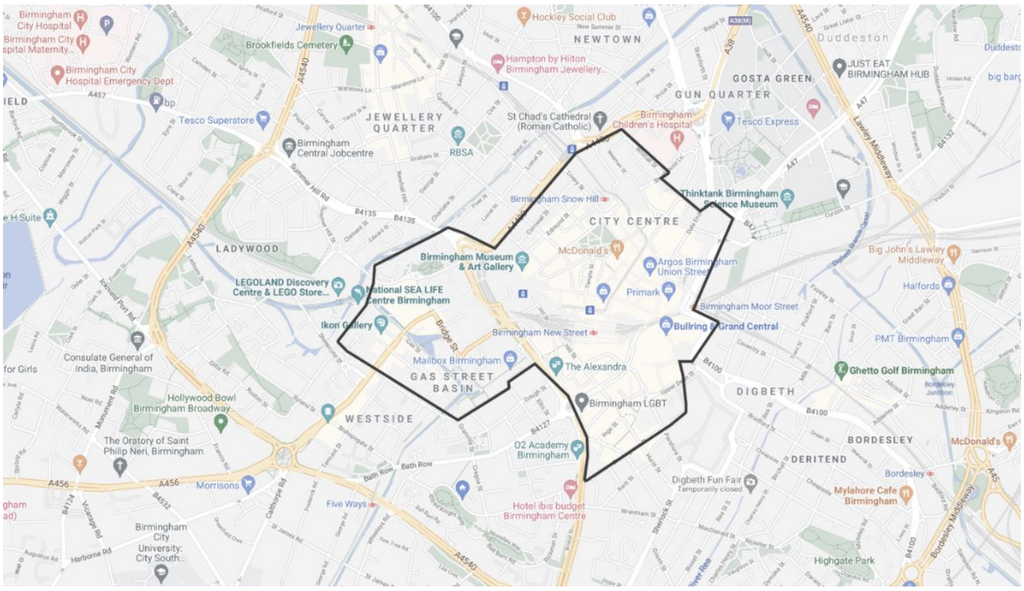


Figure 4.23: Study area in a Birmingham (UK) context

The following steps were taken:

a) Sample selection: Public spaces and buildings were randomly selected using a finite population correction to determine sample size (see Equations A.1-A.2 in the Appendix section). The random selection was conducted using NumPy's random choice function in Python (Python, Version 3.8).

b) Instrument development: An audit instrument was developed based on the British Standard 8300: 2018. It categorised the built environment into ten sections including streets, open spaces, and building facilities. Each section was further divided to assess specific features like automatic doors and elevator functionality based on the design framework provided by Steinfeld & Maisel (2012) titled "Design Strategies for Universal Design" as described in Chapter 2.1.1. An audit form was completed for every inspected public space. Each form consisted of the ten spatial sections preceded by an additional section with geographic information. A copy of the audit instrument is presented in Table 4.1.

c) Data collection: Measurements were taken using a physical and a digital tape. Each space's compliance with the standards was scored on a scale from non-compliant (0) to compliant (1) with a semi-compliant (0.5) category for features not fully meeting the guidelines. This was according to the rating system introduced by Evcil (2018).

d) Data analysis: Compliance data was analysed using Stata statistical software package (StataComp, Version 17.0) to determine overall accessibility levels.

Section and Elements	Recommended threshold	Score
Section 1 - Description of space		
- Name		
- Address		
- Type		
Section 2 - Pathways & streets		
- Provision of kerb ramps		
- Even and uniform pathway surfaces		
- Criterion: Materiality	Specified material types	
- Adequate pathway width	Min. width 1200mm	
- Accessibility of info boards/signage		
- Criterion: Height	Max. height 1400mm	
Section 3 - Open spaces		
- Accessibility of landscaping features		
- Accessibility of meeting and information points		
- Accessibility of permanent attractions or temporary events		
- Accessibility of seating or standing arrangements		
Section 4 - Transport (physical) facilities		
- Accessibility of ticket machines and gate barriers		
- Criterion: Height	Max. height 1200mm	
- Transport point accessibility		
- Criterion: Clear access routes	Unobstructed path	
- Criterion: Unobstructed turning space	Min. turning radius 1500mm	
- Provision of boarding/alighting aids		
- Accessibility of boarding/alighting aids		
- Criterion: Safe deployment	Max. deployment slope 1:10	
Section 5 - Parking areas		

- Provision of designated disabled parking bays	
- Accessibility of designated disabled parking bays	
- Criterion: Unobstructed access route	Continuous unobstructed path
- Criterion: Clear access zone between & around bays	Min. width 3600mm
- Accessibility of drop-off points/waiting areas	
- Criterion: Clear turning space	Min. turning radius 1500mm
- Ticket-machine accessibility	
- Criterion: Ticket dispenser height	Max. height 1200mm
Section 6 - Building entrance/approach	
- Visibility of accessible entrance/ramp	
- Ramp accessibility	
- Criterion: Recommended length	Max. slope 1:12
- Criterion: Width	Min. width 1000mm
- Criterion: Slope	Max. slope 1:12
- Criterion: Material	Non-slip surface
- Criterion: Provision of handrails	Handrails on both sides
- Door area accessibility	
- Criterion: Recommended door pull-space	Min. space 300mm
- Criterion: Handle height	Max. height 1000mm
- Criterion: Automatic/manual opening mechanism	
Section 7 - Building circulation	
- Provision of lifts	
- Accessibility of interior doorways and doors	
- Criterion: Clear width	Min. width 800mm
- Criterion: Recommended door handle height	Max. height 1000mm
- Clear space to manoeuvre (for corridors, aisles)	Min. width 1200mm
Section 8 - Facilities in buildings	
- Accessibility of automatic or self-service facilities – e.g., lockers, vending machines, and ATMs	
- Criterion: Recommended depth	Max. depth 400mm
- Criterion: Height	Max. height 1200mm
- Accessibility of service furniture arrangements	
- Criterion: Recommended depth - knees and toes clearances	Min. depth 700mm
- Accessibility of shelves	
- Criterion: Recommended height	Max. height 1200mm

Section 9 – Counters and reception desks	
- Accessibility of counters/desks	
- Criterion: Recommended height	Max. height 1200mm
- Criterion: Width	Min. width 800mm
- Criterion: Depth	Min. depth 600mm
- Clear space to maneuver in front of reception space	
- Accessibility of queuing control barriers (stanchions)	
- Criterion: Clear space to maneuver	Min. width 1200mm
Section 10 – Audience and spectator facilities	
- Provision of MobAD-accessible seating	
- Accessibility of seating arrangements	
- Criterion: Clear sight lines	Unobstructed view
- Criterion: Clear space to maneuver	Min. space 1500mm
- Provision and accessibility of MobAD seating at raked floors	
- Criterion: Unobstructed sightlines	Min. clear sightline angle of 12-15 degrees
- Criterion: Clear space to turn	Min. turning radius 1500mm
- Criterion: Provision of handrails	Handrails provided
- Criterion: Recommended depth	Min. depth 900mm
Section 11 – Sanitary accommodation	
- Provision of MobAD-suitable sanitary facilities	
- Accessibility of fittings and amenities	
- Criterion: Recommended height of washbasins/taps	Max. height 800mm
- Criterion: Shelves	Max. height 1200mm
- Criterion: Provision of grab rails	Rails provided
- Criterion: Clear turning space	Min. space 1500mm

Table 4.11: A copy of the accessibility audit form. Recommended thresholds are according to BS 8300/2018 and Steinfeld & Maisel (2012).

4.2.2. Part B – Subjective accessibility assessment

The subjective part involved a digital survey conducted to understand how MobAD users perceived accessibility in the same areas. The following steps were taken:

a) Ethical approval: The survey was approved by the University of Nottingham Ethics Committee (reference number 2019/82). It was designed to be distributed online via Microsoft Forms and advertised through email communication and social media.

b) Participant selection: Participants were required to be users of MobAD familiar with Birmingham city-centre and over 18 years old. Duplicate responses from the same IP were prevented. Participant recruitment stopped once the efficient sample size had been reached. The formula for calculating the sample size of this study is given at Equation A.1 at the Appendix.

c) Survey design: The survey contained questions about (a) sociodemographic background (Section A), (b) access to public spaces (Section B), and (c) a photo-elicitation task focusing on perceived accessibility of the ten least accessible environments as indicated by the objective assessment – Part A (Section C). In Section C, the selection of the ten worst-performing scenarios from Part A was a strategic decision aimed at concentrating the study on the most significant accessibility challenges within Birmingham city-centre. This focus helps highlight critical issues that require urgent attention, assesses the impact of severe barriers on MobAD users, and validates the objective assessment findings by correlating them with subjective experiences. This methodological choice ensures that the research remains focused on addressing the most pressing barriers, thereby enhancing its practical relevance and impact without diluting the significance of the findings with less critical scenarios. In Sections B and C, a five-point Likert scale was used (Norman 2010). A copy of the questionnaire can be found in the – Figure A.1.

d) Data analysis: Responses were comprehensively analysed to explore the influence of sociodemographic variables and to identify significant differences in accessibility perceptions. Specifically, the following analyses were performed:

i. Regression analysis for sociodemographic impacts, to explore how sociodemographic variables such as age, gender, mobility aid type, and visit frequency impact the perceived difficulty of accessing public spaces. A multiple regression model included these variables as predictors and the reported difficulty levels as the dependent variable. Statistical significance was determined by a p-value of less than 0.05, indicating that significant findings are unlikely to be due to chance. Equations *A.3-A.5*, which were used to build the regression model, can be found in the Appendix section.

ii. One-way analysis of variance (ANOVA) for group differences, to determine if there are statistically significant differences in accessibility difficulties reported by different demographic or MobAD groups. ANOVA compared mean difficulty scores across these groups to identify variations in experiences (Equation A.6 in the Appendix section).

iii. Regression analysis for specific physical elements, focused on assessing the correlation (see Equations A.3-A.5 in the Appendix) between the perceived accessibility of specific physical elements and the overall accessibility rating of the space categories they are part of. It involved using regression models to see if elements that were problematic for over 50% of respondents influenced the overall accessibility perceptions of associated space types, such as pathways or buildings.

4.3. Results

4.3.1. Part A – Objective accessibility assessment

The study area comprised 118 buildings, with 95% involving public interest uses such as commercial, food-and-beverage services, or transport stations. Sample size was calculated using Equation A.1 with parameters z=1.645, ε=0.05, and p̂=0.95, representing the proportion of buildings with public interest activities. This initial calculation was adjusted for a finite population of 118 buildings (N=118) as per Equation A.2, resulting in an effective sample size of 37 buildings. Following the methodology described earlier, 37 buildings were randomly selected for inspection. Additionally, due to their manageable size, all elements in open spaces and streets were inspected, amounting to 58 and 8 respectively.

Compliance and accessibility levels of inspected elements were assessed using Stata (Version 17.0), with results summarised in Table 4.2. This table includes a description and count of features per spatial section. The scores column in Table 4.2 displays the aggregate compliance scores which could be 0 (non-compliant), 0.5 (semi-compliant), or 1 (compliant) according to the design guidelines adherence. The accessibility level column shows the ratio of aggregate scores to the maximum possible score for each feature, indicating the accessibility for MobAD users. Additionally, the table presents mean accessibility levels for each section calculated from the individual component feature scores.

Sections & features	Scores	Accessibility level (%)
Section 2 - Pathways & streets		
Total spaces inspected: 58; Maximum attainable score: 58		
Provision of kerb ramps	42	72%
Even and uniform pathway surfaces (criterion: materiality)	31.5	54%
Adequate pathway width	27	47%
Accessibility of info boards/signage (criterion: height) (observed: 14)	6	43%

		Mean (weighted): 57%
Section 3 - Open spaces		
Total spaces inspected: 8; Maximum attainable score: 8		
Accessibility of landscaping features	7.5	94%
Accessibility of meeting and information points	5	63%
Accessibility of permanent attractions or temporary events	4.5	56%
Accessibility of seating or standing arrangements	3.5	44%
		Mean: 64%
Section 4 - Transport (physical) facilities		
Total spaces inspected: 23; Maximum attainable score: 23		
Accessibility of ticket machines and gate barriers (criterion: height) (observed: 3)	3	60%
Transport point (bus or tram stop shelter, train platform) accessibility (criteria: clear access routes; unobstructed turning space)	9.5	41%
Provision of boarding/alighting aids	14	61%
Accessibility of boarding/alighting aids (criterion: safe deployment)	6.5	28%
		Mean (weighted): 44%
Section 5 - Parking areas		
Total spaces inspected: 26; Maximum attainable score: 26		
Provision of designated disabled parking bays	25	96%
Accessibility of designated disabled parking bays (criteria: unobstructed access route; clear access zone between & around bays)	20	77%
Accessibility of drop-off points/waiting areas (criterion: clear turning space)	19.5	75%
Ticket-machine accessibility (criterion: ticket dispenser height)	18	69%
		Mean: 79%
Section 6 - Building entrance/approach		
Total spaces inspected: 37; Maximum attainable score: 37		
Visibility of accessible entrance/ramp	30.5	82%
Ramp accessibility (criteria: recommended length, width, slope, and material; provision of handrails)	29.0	78%
Door area accessibility (criteria: recommended door pull-space and handle	25.5	69%

height; automatic/manual opening mechanism)		
		Mean: 77%
Section 7 - Building circulation		
Total spaces inspected: 37; Maximum attainable score: 37		
Provision of lifts	**32.0**	**86%**
Accessibility of interior doorways and doors (criteria: clear width; recommended door handle height)	**28.0**	**76%**
Clear space to manoeuvre (for corridors, aisles)	**13**	**35%**
		Mean: 66%
Section 8 - Facilities in buildings		
Total spaces inspected: 37; Maximum attainable score: 37		
Accessibility of automatic or self-service facilities – e.g., lockers, vending machines, and ATMs (criteria: recommended depth and height)	**27.5**	**74%**
Accessibility of service furniture arrangements (criteria: recommended depth and height - knees and toes clearances)	**13.5**	**36%**
Accessibility of shelves (criterion: recommended height)	**9**	**24%**
		Mean: 45%
Section 9 – Counters and reception desks		
Total spaces inspected: 37; Maximum attainable score: 37		
Accessibility of counters/desks (criteria: recommended height, width, and depth)	**25**	**68%**
Clear space to manoeuvre in front of reception space	**19.5**	**53%**
Accessibility of queuing control barriers (stanchions) (criterion: clear space to manoeuvre) (observed: 11)	**4 (out of 11)**	**36%**
		Mean (weighted): 57%
Section 10 – Audience and spectator facilities		
Total spaces inspected: 15; Maximum attainable score: 15		
Provision of MobAD-accessible seating	**13**	**87%**
Accessibility of seating arrangements (criteria: clear sight lines, clear space to manoeuvre)	**8**	**53%**

Provision and accessibility of MobAD seating at raked floors (criteria: unobstructed sightlines; clear space to turn; provision of handrails; recommended depth)	5.5	37%
	Mean: 59%	
Section 11 – Sanitary accommodation		
Total spaces inspected: 37; Maximum attainable score: 37		
Provision of MobAD-suitable sanitary facilities	36	97%
Accessibility of fittings and amenities (criteria: recommended height of washbasins/taps and shelves; provision of grab rails; clear turning space)	29.5	80%
	Mean: 89%	

Table 4.12: Accessibility levels per section and spatial feature in Birmingham city-centre

The results presented in Table 4.2 reveal notable variations in the accessibility of different spatial categories and elements across the studied city-centre environments. In general, areas such as parking (79% mean accessibility) and sanitary accommodations (89% mean) exhibited high levels of accessibility compliance. For example, the provision of designated disabled parking bays and MobAD-suitable sanitary facilities scored particularly high at 96% and 97% respectively, indicating robust adherence to design guidelines in these categories.

Conversely, the accessibility in transport facilities (44% mean) and building facilities (45% mean) was notably lower. Specific areas of concern include the accessibility of boarding/alighting aids and the safety of their deployment, which scored only 28% in compliance. Similarly, service furniture arrangements and shelf accessibility in buildings significantly lagged with scores of 36% and 24% respectively, highlighting critical gaps in accommodating MobAD users.

Pathways and streets showed a moderate level of accessibility (57% mean), with kerb ramps scoring 72%, but pathway width and the height of information boards/signage falling below expected standards at 47% and 43% respectively. This indicates a mixed compliance scenario where not all essential features meet accessibility needs effectively.

The overall level of accessibility for the study area was 63%. That is approximately 4 out of 10 spatial elements have not been designed according to accessibility guidelines so as to accommodate MobAD users. Figure 4.2 compares mean accessibility rates among the ten spatial sections.

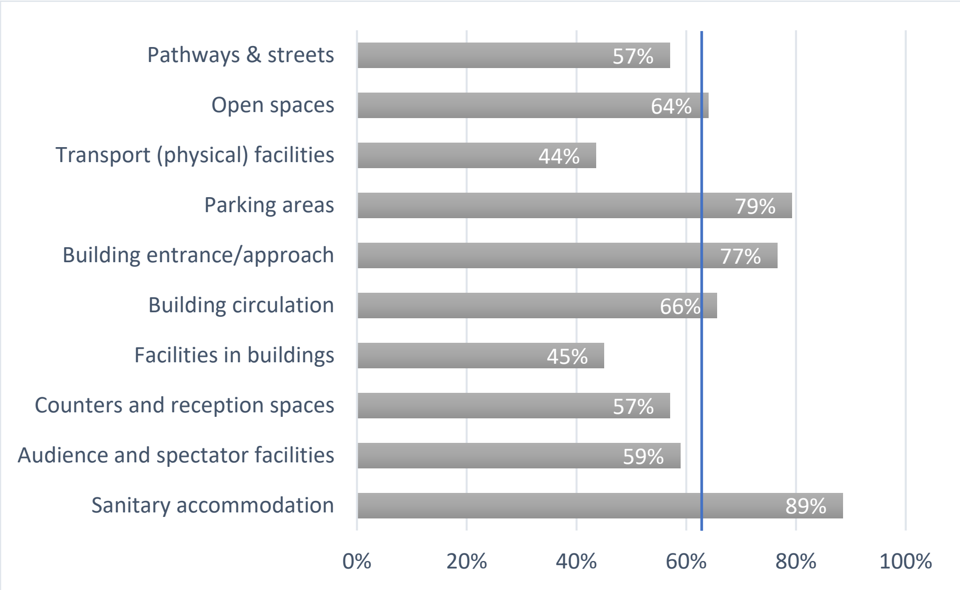


Figure 4.24: Mean accessibility rates per section & study area average (coloured line) – objective assessment

4.3.2. Part B – Subjective accessibility assessment

Since the number of people that use Birmingham city-centre on a daily basis is infinite, the sample size for this study was calculated according to Equation A.1, for z=1.645, e=0.05, and $\hat{p}$=0.11 (part of total population in UK that are mobility-disabled[2]); the effective sample size was found to be 107 people.

The first set of questions (Section A) aimed to garner sociodemographic data from the study sample. Simple statistical analysis was used to report the collected information. Figure 4.3, Figure 4.4,Figure 4.5, and Figure 4.6 provide an overview of the study population – in terms of gender, age group, status of MobAD-dependence, and type of MobAD used, respectively. These findings indicate that respondents had a diverse background. Specifically, of the 107 participants of this study,

[2] UK Government, 2023.

45 were women and 62 were men. More than half (61) of total respondents were between 36-60 years old. 40% (43) of the study population were semi-dependent on their MobAD for both outdoor and indoor environments. The majority of the respondents (65) were wheelchair users, with most of those (43) using powered wheelchairs.

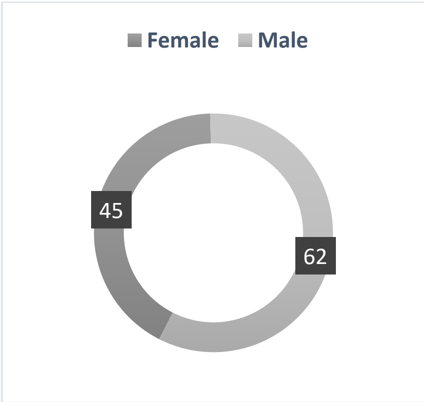


Figure 4.25: Participants' gender distribution

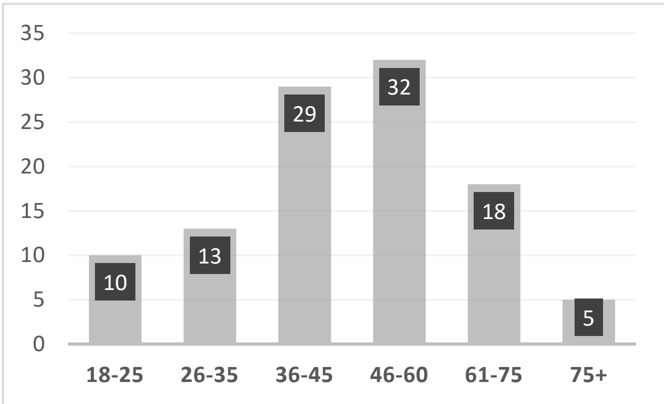


Figure 4.26: Participants' age distribution

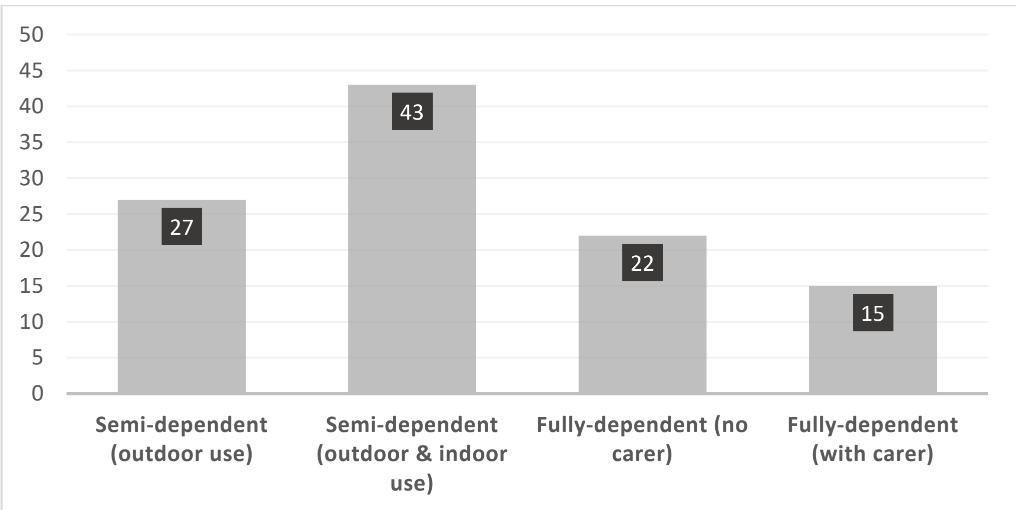


Figure 4.27: Distribution of participants' MobAD-dependence status

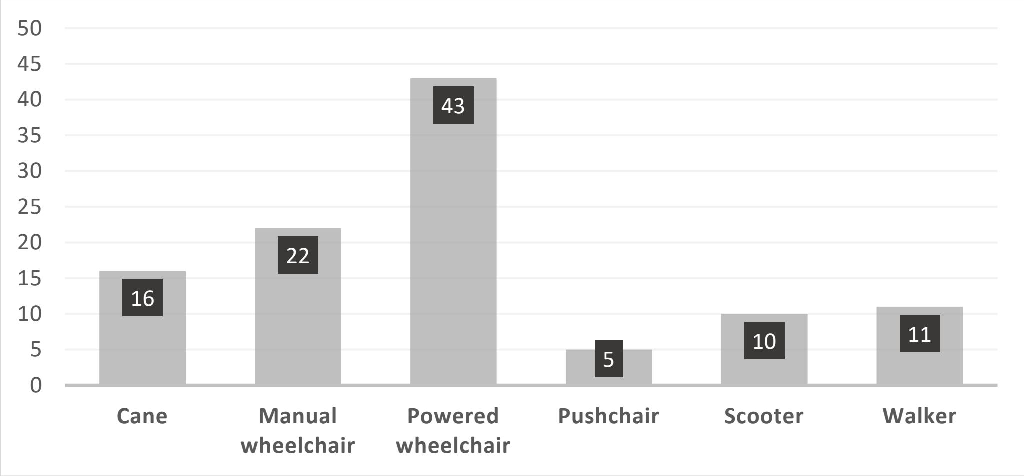


Figure 4.28: Distribution of participants' type of MobAD

The following set of questions (Section B) investigated the extent to which study participants could access or use eleven different categories of public spaces in Birmingham city-centre. Figure 4.7 presents a summary chart of total responses for Section B.

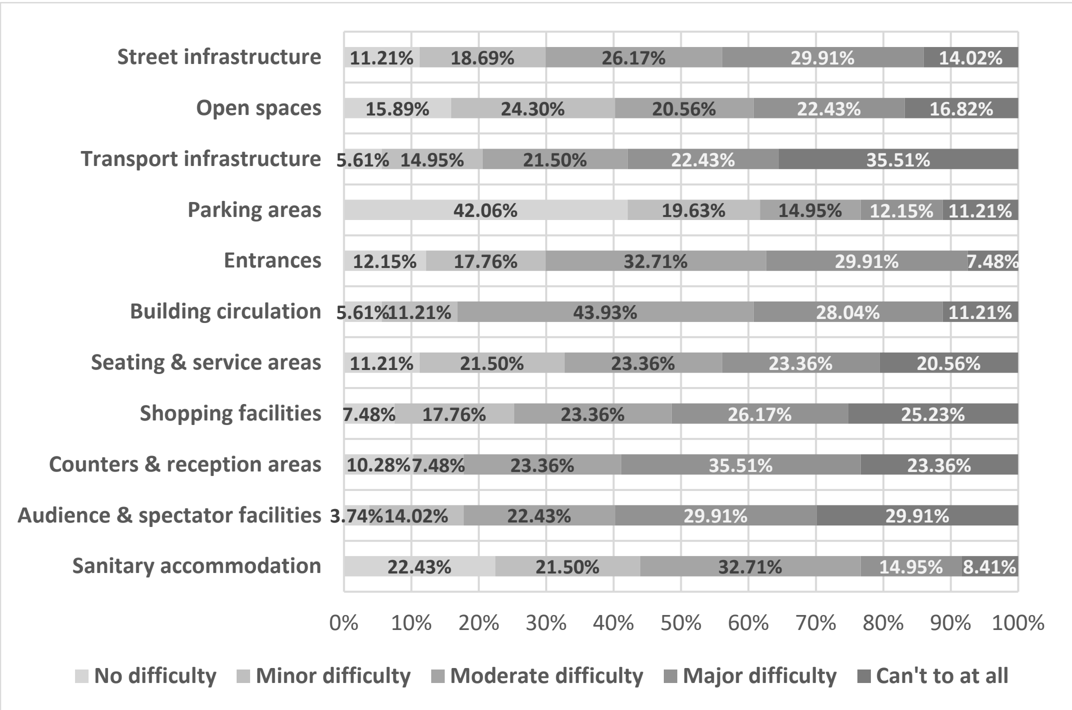


Figure 4.29: Experienced difficulty level when accessing or using different types of public spaces at Birmingham city-centre

As can be seen from Figure 4.7, nearly over a third (36%) of the study population could not use or access public transport facilities at all. 6 out of 10 respondents either experienced major difficulty or could not use audience or spectator facilities as well as counters or reception areas.

Over half (51%) of the study participants struggled with using shopping facilities. What stands out in Figure 4.7 is that more than 40% of the study population experienced no difficulty with accessing parking areas at Birmingham city-centre.

A regression analysis estimated the combined effect of sociodemographic factors on respondents' experienced difficulty to use or access public spaces. Table 4.3 presents results from this analysis; the shaded fields indicate statistically significant ($p<0.05$) values. In Table 4.3, the first row refers to the adjusted R2 value per analysed type of public spaces. This number is always between 0 and 1, and the higher it is, the better the regression model usually fits the study observations. The remaining rows contain the regression coefficients per analysed type of public spaces which describe the relationship between predictor variables (in this case, gender, age group, MobAD-dependence, and type of MobAD) and experienced difficulty levels. The correlation coefficients are measured on a scale that varies from + 1 through 0 to – 1. Complete correlation between two variables is expressed by either + 1 or -1. When one variable increases as the other increases, the correlation is positive; when one decreases as the other increases, it is negative.

	Street infrastructure	**Open spaces**	**Transport infrastructure**	**Parking areas**	**Entrances**	**Building circulation**	**Seating & service areas**	**Shopping facilities**	**Counters & reception areas**	**Audience & spectator**	**Sanitary accommodation**
Adjusted R^2	*0.1084*	*0.7938*	*0.7558*	*0.0244*	*0.6907*	*0.1794*	*0.0333*	*0.3434*	*0.0842*	*0.6706*	*0.2669*
Gender	0.1761	0.1670	0.0524	0.1262	0.0384	0.2934	-0.1608	-0.1375	-0.1850	-0.2470	0.1429
Age group	0.0111	0.7075	0.4224	0.1025	0.4000	0.1165	0.1126	0.2271	0.2610	0.0490	0.3071
Dependence	0.3534	0.5020	0.4989	0.2233	0.5435	0.2254	0.2295	0.3950	-0.3370	0.5207	0.4007

MobAD	0.1293	-0.0562	0.1019	0.0605	0.0941	-0.2094	0.0350	-0.1438	-0.1449	-0.1420	-0.1334

Table 4.13: Types of correlation between sociodemographic factors & difficulty levels

Looking at Table 4.3, it becomes obvious that the level of difficulty increases with MobAD-dependency with respect to all but three spatial categories. That is, it is more likely for people who are fully dependent on MobAD to experience greater difficulty when accessing or using public spaces in Birmingham city-centre. Also, a positive correlation was found between ageing and experienced difficulty in 6 out of 11 spatial categories. Closer inspection of Table 4.3 reveals that there is a strong positive correlation among MobAD-dependency, age, and difficulty to access to open spaces. A similar – yet less powerful – trend is apparent with respect to entrances and transport infrastructure. No statistically significant correlation was found between gender and difficulty across the whole breadth of analysed public spaces. From these models, it was not possible to determine the types of relationships between types of MobAD and experienced difficulty.

To investigate possible associations between different types of MobAD and levels of experienced difficulty, ANOVA tests across all spatial categories were implemented. P-values (row 1) and means (rows 2-6) per MobAD type and spatial category are displayed in Table 4.4. Experienced difficulty was measured on a 1-5 scale; therefore the higher a mean value is, the greater was the reported difficulty for a group of MobAD users on average.

	Street infrastructure	**Open spaces**	**Transport infrastructure**	**Parking areas**	**Entrances**	**Building circulation**	**Seating & service areas**	**Shopping facilities**	**Counters & reception areas**	**Audience & spectator facilities**	**Sanitary accommodation**
p-value	*0.035*	*0.072*	*0.001*	*0.592*	*0.046*	*0.023*	*0.045*	*0.037*	*0.037*	*0.012*	*0.083*

Cane	3.313	3.438	4.500	2.375	3.688	2.750	3.375	2.688	3.313	2.688	2.313
Manual Wheelchair	4.227	3.045	4.318	2.636	4.636	2.864	3.818	4.091	3.000	4.455	2.864
Powered Wheelchair	2.698	3.047	3.140	2.140	2.581	4.158	2.953	3.953	3.814	3.233	2.814
Pushchair	3.000	1.000	2.200	2.400	1.400	2.600	1.600	1.000	3.400	2.000	1.400
Scooter	2.600	2.000	2.800	1.800	2.800	4.300	3.300	2.900	4.100	3.000	2.300
Walker	3.273	3.909	4.727	2.636	3.545	3.182	3.364	2.818	3.455	2.818	3.000

Table 4.14: Associations between different types of MobAD and experienced difficulty

In Table 4.4, there is a clear trend that users of manual wheelchairs experienced major difficulties when accessing or using street and transport infrastructure, entrances, as well as shopping and audience or spectator facilities. Users of canes, as well as walkers, struggled with transport infrastructure with very high mean rates of experienced difficulty – i.e. 4.5 and 4.7 respectively. Table 4.4 also reveals that users of powered wheelchairs considered audience or spectator facilities very challenging in terms of access. On average, users of scooters reported great distress with circulating in buildings and accessing counters or reception areas. From the ANOVA test, there is strong evidence that transport physical infrastructure was deemed to be particularly problematic for users of non-powered MobAD – namely, manual wheelchairs, canes, and walkers. On the contrary, users of pushchairs appeared to be the less affected group with respect to almost every spatial category.

In the final section (Section C) of the survey, respondents were shown ten photographs depicting various public spaces in Birmingham city-centre. These images represented the environments identified as least accessible in the objective assessment (detailed in Chapter 4.3.1). Participants were asked to evaluate the accessibility of specific physical elements shown in these images, based on how well they could accommodate their functional needs. *Figure 4.8* illustrates a frequency chart showing the spatial situations that respondents found to be very difficult or impossible to access, as indicated by over 50% of the participants.

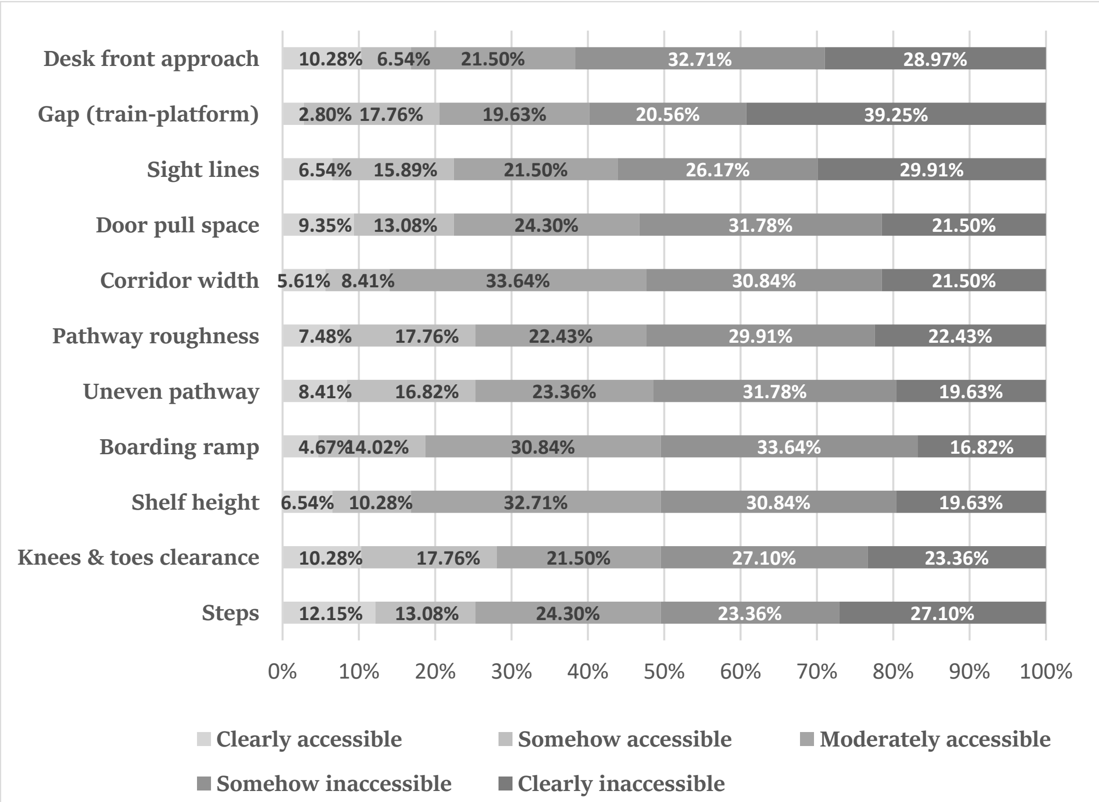


Figure 4.30: Perceived accessibility level of spatial elements presented in photographic representations

From Figure 4.8, it is clear that the physical gap between trains and platform was considered the least accessible element of all those included in the photo-elicitation task by a significant proportion (39%) of the study population. A resounding 60% of respondents regarded the approach area of the illustrated reception desk as inaccessible – either partly or fully. What is interesting about the data in Figure 4.8 is that two out of eleven most problematic cases (i.e., steps and pull space behind a door) referred to elements that feature in entrance environments. This is a rather unexpected result as previous data from this survey (Figure

4.7) showed that only 8% of the respondents found entrances to be a prohibitive barrier when visiting buildings of public interest.

To assess whether accessibility levels of the most problematic – according to respondents' perceptions – elements were representative of their parent environments, a regression analysis was conducted. Table 4.5 presents results from this analysis; the first column contains the most problematic elements organised under their parent spatial categories. The second column refers to the adjusted R^2 value per analysed element. The remaining rows contain the regression coefficients and p-values, respectively.

Spatial (parent) categories & problematic elements	Adjusted R^2	Correlation coefficients	p-values
Street infrastructure			
Path roughness	0.7728	0.854029	0.022
Uneven path	0.9678	0.938278	0.013
Transport infrastructure			
Gap (train-platform)	0.9503	0.99883	0.003
Boarding ramps	0.8004	0.840945	0.012
Entrances			
Steps	0.5285	0.521035	0.166
Door pull-space	0.6983	0.662995	0.078
Building circulation			
Corridors	0.8275	0.831709	0.015
Seating and service areas			
Knees and toes clearances	0.9018	0.951866	0.005
Shopping facilities			
Shelf height	0.4995	0.786611	0.097
Counters & reception areas			
Desk front approach	0.8057	0.876219	0.01
Audience & spectator facilities			
Sightlines	0.8142	0.832509	0.011

Table 4.15: Correlation between problematic elements and parent spatial categories regarding level of accessibility

As Table 4.5 shows, there was strong evidence that respondents' experienced difficulty when accessing public spaces and accessibility of physical elements as per respondents' perceptions are positively correlated. An almost linear correlation was reported for physical gaps between train and platforms (transport infrastructure), uneven paths (street infrastructure), and insufficient space for knees and toes (seating and service areas). Also, significant correlation was observed for steep or narrow boarding ramps (transport infrastructure), narrow corridors (building circulation), insufficient space for knees and toes (seating and service areas), insufficient space to execute a front approach to reception desks (counters and reception areas), and blocked sightlines (audience and spectator facilities). These are indicators that the more difficult it was for respondents to use public spaces in Birmingham city-centre, the more likely it was that these spaces would contain the aforementioned problematic elements.

4.4. Discussion

This study aimed to evaluate the accessibility of public spaces in Birmingham city-centre for users of mobility aids (MobAD). It employed both objective measures using an access audit instrument to assess compliance with accessibility guidelines in 101 public spaces or buildings and subjective measures through online questionnaires capturing the perceptions of 107 MobAD users regarding ease of use and access.

An initial objective was to examine the level of MobAD-accessibility of different spatial categories and their components. The access audits revealed that sanitary accommodation facilities notably complied with accessibility guidelines. Conversely, the transport infrastructure displayed the lowest compliance, a finding that aligns with participant feedback indicating significant difficulties in accessing public transport for many MobAD users. This lack of access is concerning as previous studies have shown that inadequate transport facilities can effectively exclude MobAD users from social activities, hinder personal development, and diminish employment opportunities compared to their non-disabled peers (Bastiaanssen et al. 2020; Grise et al. 2019).

Another objective of this study was to identify challenging situations that exist in public open spaces and buildings. Again, transport facilities were identified as particularly problematic in terms of MobAD-accessibility, largely due to issues with boarding ramps. The objective assessment highlighted frequent problems such as the absence of ramps or their inappropriate deployment, with issues often related to incorrect angles or insufficient widths. These findings align with international research on transport accessibility, which consistently points to boarding ramps as one of the least accessible elements in transport infrastructure (Unsworth et al. 2019). Improper ramp deployment can lead to steep angles that not only cause discomfort but also increase the risk of accidents (Pierret et al. 2014). Additionally, the subjective assessment underscored that gaps between trains and platforms are a significant barrier for many MobAD users. These gaps often exceed recommended dimensions, exacerbating accessibility challenges (Daamen et al. 2008; Grange-Faivre et al. 2017). The above findings partly address research objective 1 (RO1 - identification of physical barriers) as previously defined in Chapter 1.3.

The integrative approach of this study facilitated a comprehensive exploration of different result combinations addressing the initial objectives and deriving meaningful insights from multiple perspectives. Analysis of combined results highlighted audience and spectator facilities as particularly challenging for MobAD-accessibility. A significant barrier identified was the lack of clear sightlines at MobAD-designated seating areas. Empirical studies focusing on accessibility in such settings (e.g. lecture halls, movie theatres) are scarce, suggesting a need for further research in this area. Additionally, counters and reception areas fell below the average accessibility compliance for the study area, primarily due to inadequate manoeuvring space in front of desks and counters, which restricts access for MobAD users. Building facilities were also identified as problematic, with shelves positioned at excessively high or low levels posing significant barriers. Moreover, seating arrangements in service areas often lacked sufficient knee and toe clearances, further hindering access for MobAD users. It remains uncertain to what extent these spatial situations impact MobAD users despite the clear inhibitive factors such as lateral and horizontal reach and the clearances needed for independent functioning. This underscores the need for more focused studies to quantify the specific impacts of these barriers on MobAD users' accessibility and independence.

The last objective of the study was to identify possible relationships between physical obstacles and MobAD users with varying demographic and functioning characteristics. A key finding from this study is that users of manual wheelchairs face more challenges than those using other types of mobility aids when accessing public spaces, particularly in street, transport, and shopping environments. This observation aligns with prior research indicating that physical barriers in these areas can significantly impact manual wheelchair users. For instance, Chapter 3 highlighted that rough pathways could physically tax manual wheelchair users and excessively sloped ramps at building entrances could hinder their ability to engage in various activities. Conversely, users of powered wheelchairs and scooters reported fewer difficulties in general but faced challenges navigating within buildings. This difficulty can be attributed to dimensional constraints; earlier studies have noted that larger mobility aids such as powered wheelchairs and scooters may struggle to manoeuvre in tight corridors or aisles (Holiday et al. 2005). This underscores the need for design considerations that accommodate the specific spatial requirements of different types of mobility aids. The above findings partly address research objective 2 (RO2 – exploration of MobAD users' needs) as previously defined in Chapter 1.3.

The analysis revealed that age significantly influences physical accessibility, with older MobAD users experiencing greater difficulties in accessing public spaces, particularly open areas, compared to their younger counterparts. This disparity may be partly attributed to younger users' more frequent utilisation of online or mobile accessibility guides, such as navigation apps, which help navigate through complex environments like urban parks and open-air markets. Such tools are less likely to be used by the ageing population, a trend noted by several researchers. Additionally, the study found a strong correlation between the level of dependence on MobAD devices and the extent of accessibility challenges encountered. Individuals fully reliant on mobility aids reported more obstacles across most spatial categories examined. These insights contribute preliminary evidence to the understanding of how physical accessibility varies among different groups within the MobAD community. However, while informative, these findings should be approached with caution. The regression analysis only partially accounted for these relationships, suggesting that other unobserved factors may also influence the observed outcomes. This underscores the need for further research into the complex interactions between MobAD user characteristics and the physical accessibility of public spaces.

This study adopted an integrative approach to evaluate accessibility in Birmingham city-centre, aligning findings from both objective measures and subjective user experiences. The concordance between these two analyses suggests a robust correlation between perceived and actual accessibility, indicating that areas failing to meet British accessibility standards (British Standard 8300/2018) pose significant challenges for MobAD users. This alignment supports the notion that the current standards effectively reflect the functional needs of the majority of MobAD users in accessing public spaces. However, the generalisability of these findings beyond the local context requires further investigation to confirm their national applicability. Future research could expand this integrative approach to assess accessibility across different urban environments, such as neighbourhood scales or different sectors like housing or transportation. Such studies are crucial for identifying additional barriers through both objective compliance and subjective experience, potentially uncovering gaps between existing standards and the actual functional capacities of MobAD users.

This study has enhanced understanding of the critical factors impeding MobAD users' access in city-centre environments, highlighting previously underexplored aspects such as sightlines and knees-and-toes clearances. The findings reveal that certain demographics, specifically older individuals and those fully dependent on non-powered mobility aids, are disproportionately affected by physical barriers. This information is particularly relevant given the projected global increase in urban elderly populations and individuals dependent on mobility aids (Clark & Gallagher 2013; Harris et al. 2015). Consequently, these insights are crucial for policymakers and practitioners aiming to improve urban infrastructures. By acknowledging and addressing these spatial factors as significant barriers, cities can better accommodate the needs of their most vulnerable residents, enhancing accessibility and inclusivity in urban planning initiatives.

4.4.1. Study limitations and critical appraisal

A number of limitations need to be noted regarding the present research. Firstly, the study's focus solely on Birmingham city-centre could limit the generalisability of its findings. Birmingham has unique urban characteristics and demographic profiles that may not be representative of other city-centres either within the UK or globally. This specificity means the accessibility issues identified, while thoroughly analysed within this context, may differ significantly in cities with different layouts, infrastructure qualities, or population dynamics. Therefore, the conclusions drawn from this study might not be applicable in broader or differing urban settings without additional localised research. To enhance the generalisability of the findings, future research should aim to replicate this study across various urban environments both within the UK and internationally. A comparative approach involving multiple cities with varying sizes, designs, and demographic compositions could provide a broader understanding of accessibility challenges faced by MobAD users.

Utilising an instrument derived from the standardised British Standard 8300/2018 to measure accessibility built a foundation upon recognised guidelines, ensuring that the study aligned with established norms. However, the absence of a formally validated audit tool might introduce variability in how accurately the instrument measured intended accessibility variables. This limitation highlights an area for further refinement rather than a fundamental flaw, as it offers an opportunity to deepen the instrument's robustness in future studies. This could be effectively achieved through pilot testing with a subset of the target population to identify any operational inconsistencies or gaps in the instrument's design. Additionally, consulting accessibility experts during the instrument review process can provide critical insights into its functionality and suggest necessary adjustments.

Regarding the subjective assessment, not including MobAD users in the survey design process in this study was an oversight that potentially limited the ability to capture the full spectrum of accessibility challenges and experiences directly from the affected population. Involving MobAD users in the creation of the survey could significantly enhance the relevance and sensitivity of the questions, ensuring they reflect the real-world experiences and needs of those they aim to represent. This would likely lead to more accurate data, enhancing the conclusions drawn from them. To address this in future research, it is crucial to adopt a more inclusive approach to survey design. Organising collaborative workshops that bring together MobAD users, caregivers, and researchers can facilitate a deeper understanding of the critical issues affecting this community. Such an inclusive design process should ideally be iterative, allowing continuous feedback from MobAD users to refine the survey tool progressively.

The design of the social survey in this study faced several challenges, primarily due to constraints related to time and budget. The use of unbalanced Likert scales may have introduced response bias, potentially skewing the results towards one end of the spectrum and obscuring the true sentiments of respondents. The predefined categories within these scales might not have fully captured the diversity of experiences and opinions, possibly limiting the breadth of data collected. Additionally, the requirement for respondents to select only one type of mobility aid, despite some users employing multiple aids depending on various factors, could have restricted the survey's ability to gather detailed information on how different aids influence accessibility. The exclusion of caregivers from the survey process also likely resulted in missed opportunities to gain broader insights into accessibility challenges, especially given that caregivers can often articulate issues that MobAD users themselves might overlook or be unable to communicate. Furthermore, the lack of open-ended questions constrained the depth of data, as such questions allow respondents to express nuanced views and explain the reasons behind their choices, offering richer context essential for a thorough understanding of complex accessibility issues.

To address the limitations in the survey design of the study, future work should focus on improving the survey structure and inclusiveness. First, balanced Likert scales should be adopted to ensure fair representation of responses, along with a revision of category selections to capture a broader spectrum of experiences, thereby minimising response bias. Additionally, the survey design should allow respondents to select multiple types of mobility aids they use, enhancing the granularity and accuracy of data regarding accessibility perceptions. Including caregivers in the survey could provide further valuable insights into the challenges faced by MobAD users, enriching the overall data collected. Finally, integrating a few open-ended questions could offer a deeper understanding of the reasoning behind respondents' choices, capturing the nuances of their experiences.

To summarise, the data gathered through the access audit was methodically collected but is influenced by certain limitations that affect its broader applicability. The primary concern involves the use of a non-validated instrument. While this instrument was developed based on standardised guidelines, the absence of formal validation introduces a degree of uncertainty about its precision in measuring accessibility compliance as intended. Additionally, the study’s focus on Birmingham city-centre might not encapsulate the diverse urban layouts and infrastructure conditions present in other cities worldwide, which may limit the generalisability of the findings. Nevertheless, the data collected offers insightful observations about specific accessibility barriers within urban settings in the UK, providing a valuable localised snapshot that, while not universally applicable, contributes meaningfully to the discourse on urban accessibility within similar contexts.

In addition, the quality of the subjective data collected through the social survey is nuanced by certain design choices that could subtly influence the depth and breadth of the insights obtained. The use of unbalanced Likert scales, for instance, may inadvertently shape participant responses in a certain direction, possibly affecting the portrayal of the true sentiments of the MobAD community. Moreover, the survey's limitation that allowed respondents to select only one type of mobility aid may not fully capture the varied reality of many MobAD users who utilise different aids depending on specific situations, thus simplifying their diverse experiences. The exclusion of caregivers from the survey also omits valuable perspectives that could enhance understanding of the accessibility challenges faced by MobAD users, particularly those nuances that users themselves might not express. Additionally, the decision to omit open-ended questions, while understandable given resource constraints, does restrict opportunities to explore the complex motivations and detailed experiences of respondents. These factors may suggest that while the survey provides valuable preliminary insights into user perceptions of accessibility, enhancing the methodological approach in future studies could deepen and refine these insights, thereby enriching the data’s applicability and supporting more nuanced policy and practice interventions.

Despite the methodological limitations that might affect the generalisability of the findings, this study strengthens the idea that a considerable portion of the built environment has not been adequately designed to accommodate users of MobAD. In both investigations, transport physical infrastructure was found to be the least accessible area. This was almost exclusively attributed to physical gaps between transport boarding points and vehicles as well as boarding ramps. This combination of findings suggests that the interface between transport boarding points and vehicles is possibly one of the most problematic situations in urban environments for MobAD users. There is therefore a definite need for practitioners and researchers to explore different ways to bridge the precarious gap between public transport vehicles and set-off points. It is suggested that these interventions – which would act as an alternative to conventional boarding ramps – should be designed to efficiently accommodate MobAD users with diverse demographic and functioning characteristics.

B2. Bridge section: triangulating empirical evidence toward defining the design problem

This section synthesises findings from the systematic review, the accessibility audit, and the social survey to highlight the platform-train interface as the most critical issue for MobAD users. The triangulation of data from these diverse sources provides compelling evidence that the platform-train interface represents a significant barrier in the built environment for MobAD users.

The systematic review (Chapter 3) identified multiple accessibility challenges in public spaces, including train boarding ramps among others. The accessibility audit (Chapter 4.3.1) specifically singled out transport facilities in Birmingham city-centre, with boarding ramps highlighted as particularly problematic. Complementarily, the social survey (Chapter 4.3.2) pinpointed the gaps between trains and platforms as the most significant difficulty faced by MobAD users, further underscoring transport interfaces as key areas requiring attention.

The forthcoming section on defining the design problem will elaborate on the issues at platform-train interfaces. This will include an examination of existing solutions and their effectiveness, providing a foundation for evaluating their suitability and impact. This approach ensures a thorough understanding of the existing conditions and will reveal the significance for an alternative resolution of one of the most pressing barriers within the built environment.

5. Definition of design problem

This chapter delves into the "design problem" that emerged as the most pressing issue for MobAD users through the triangulation of evidence from the systematic review (Chapter 4) and the integrative accessibility assessment (i.e. accessibility audit and social survey – Chapter 5). The **platform-train interface (PTI)** has been identified as the most critical aspect of the built environment requiring attention and improvement to ensure a more accessible and inclusive experience for MobAD users. PTI is the gap that develops between train carriages and the platform edge in the macro-environment of a rail station as visualised inn Figure 5.1. By examining this design problem in detail, this chapter lays the foundation for proposing effective, targeted solutions that can be implemented to enhance the accessibility of PTIs.

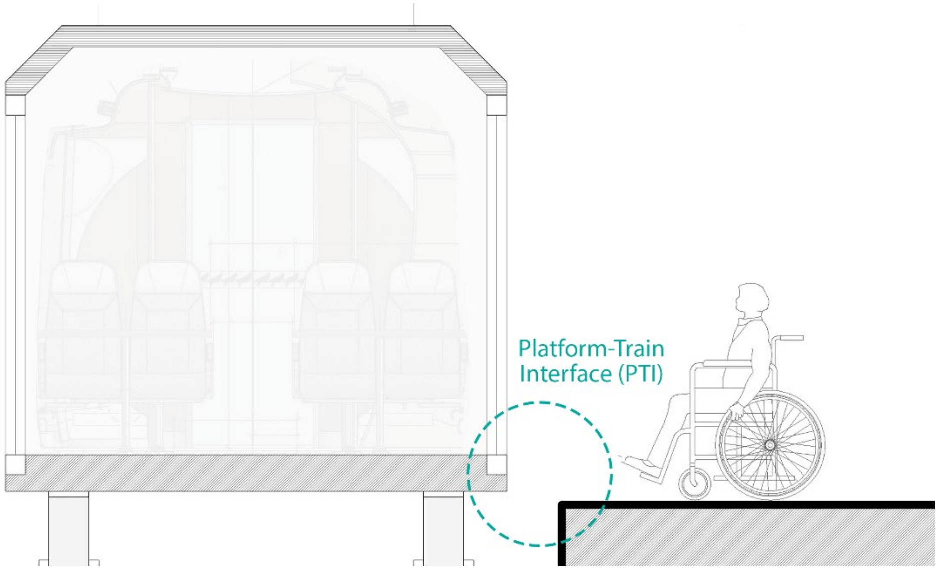


Figure 5.31: Platform-Train Interface

It should be emphasised that PTIs exhibit considerable variability across different parts of the world. This variability stems from several factors, including:

a) diverse *rail regulation and accessibility frameworks* that govern the design and operation of rail systems,
b) *train characteristics*, such as train types, floor heights, and door widths, which can differ substantially between regions and manufacturers,

c) *platform characteristics*, including height, width, and edge treatments, which are influenced by local construction standards and historical context.
d) *existing solutions*, which may vary in terms of their design, implementation, and effectiveness in addressing accessibility challenges.

Given this variability, it is crucial to adopt a context-specific approach when examining PTIs and their implications for MobAD users. As such, this thesis will focus on a UK context, which has its own unique set of rail regulations, train and platform characteristics, and accessibility solutions. By concentrating on the specific circumstances and challenges present in the UK, the thesis will be better positioned to develop targeted, effective interventions that can improve the platform-train interface and enhance the accessibility of the built environment for the universal MobAD user. It is therefore out of scope for this research to delve into solutions adopted in other countries to ensure the relevance and applicability of the findings as well as align closely with the particular needs of the UK's urban infrastructure.

5.1. PTI characteristics in a UK content

In essence, the most problematic feature of the PTI environment is the physical gap that develops between rail carriages and the platform edge. While the maximum acceptable gap that users of mobility assistive devices can negotiate themselves – without additional instruments – is 50x50 mm (Daamen et al. 2014; Grange-Faivre et al. 2017), most gaps present in much larger proportions. Specifically, the biggest horizontal gap can be up to 470 mm while the vertical gap can reach 460 mm, with distance measured from platform to floor (EU 2014; RSSB 2019). Figure 5.2 illustrates the design problem space.

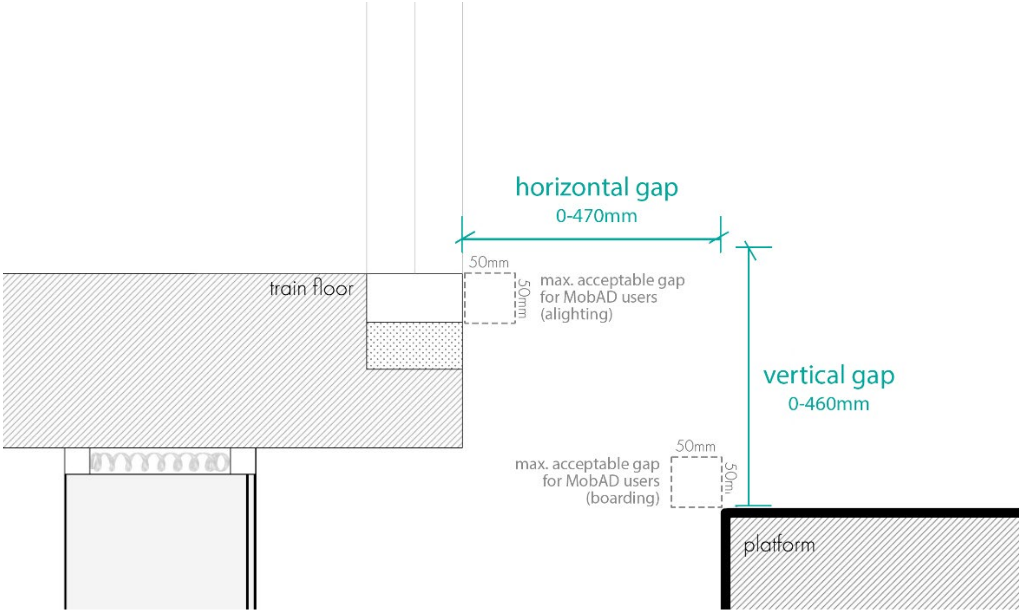


Figure 5.32: Design problem space

5.2. Existing solutions for PTIs in a UK context

In the UK, fewer than 2% of stations have level access between train and platform, meaning a platform-train ramp is required along with manual deployment by staff (DPTAC 2022). Several solutions have been designed to address the design problem over the years, including boarding ramps, on-board lifts, and gap fillers. There are two main categories of existing solutions for PTIs: (a) those *applied on platforms* and (b) those *applied on rail vehicles*. Platform-applied solutions include boarding ramps (Figure 5.3) and gap fillers (Figure 5.4). In a UK context, boarding ramps are the most widespread solution (RSSB 2020). Boarding ramps can be an attractive option for a number of reasons. First, they are relatively inexpensive compared to more permanent infrastructure modifications, making them an affordable option for transport operators. Second, they are transferable and can be easily moved between locations or different trains, providing flexibility in deployment. Additionally, ramps can be designed with adjustable lengths and heights, enabling them to accommodate a range of train and platform configurations.

However, there are also several disadvantages associated with boarding ramps that must be considered. Safety is a primary concern, as ramps with slippery surfaces can pose a significant risk to MobAD users, particularly in wet or icy conditions. Steep deployment angles and limited widths can also be problematic as they may lead to physical discomfort, difficulty in manoeuvring, or even accidents. Furthermore, the deployment of boarding ramps typically requires the assistance of trained staff, which can lead to delays and increased reliance on human intervention. This can result in inconsistent service quality and potential accessibility barriers if staff are unavailable or untrained. Lastly, the use of boarding ramps does not address the underlying issue of inadequate platform and train design, which may necessitate more comprehensive solutions for long-term improvements in accessibility. As an example, at 67% of stations in the UK, the platform(s) are too narrow in places to permit a compliant turning circle for wheelchair users at the base of a ramp (DPTAC 2022).

Figure 5.33: Boarding ramp. Source: Portaramp Co.

Figure 5.34: On-platform gap filler. Source: Wiki.

On-platform gap fillers present several advantages such as effectively filling the horizontal gap between the train and platform, which can be particularly beneficial for users of mobility assistive devices. They also offer a "plug-and-play" installation, allowing for quick and straightforward implementation without the need for extensive infrastructure modifications. Additionally, gap fillers typically require low maintenance, resulting in cost-effective long-term operation. Moreover, by providing a stable and continuous surface, gap fillers can enhance safety and confidence for all passengers, including those with reduced mobility, as they embark or disembark.

However, there are also some disadvantages associated with platform-applied gap fillers that must be considered. Firstly, they are not designed to bridge the vertical gap between the platform and train, which may still pose accessibility challenges for some MobAD users. This is a considerable drawback as at 33% of UK stations, the vertical gap is greater than 25 cm in places (DPTAC 2022). Secondly, gap fillers require knowledge of the gap dimensions for all types of vehicles in advance, which can be challenging, particularly in locations with a diverse range of train types and configurations. This necessitates careful planning and coordination between different stakeholders involved in rail operations. Additionally, wear and tear can occur if the gap fillers make contact with the train, potentially leading to reduced lifespan and increased maintenance requirements. Lastly, in cases where platforms serve multiple tracks or have curved alignments, the effectiveness of gap fillers may be compromised, requiring alternative or supplementary solutions to ensure comprehensive accessibility.

Vehicle-applied solutions include boarding lifts (Figure 5.5), gap fillers (Figure 5.6), and low-floor carriages (Figure 5.7). Boarding lifts present several advantages such as providing a significantly more secure and stable means of accessing trains compared to ramps, which can greatly benefit users of MobAD. In some cases, lifts can be designed to be self-operated, eliminating the need for conductors or other staff members to assist in the boarding process. This can lead to more consistent and reliable service quality for passengers. Additionally, lifts can accommodate both horizontal and vertical gaps between trains and platforms, making them a more versatile solution in comparison to other accessibility interventions.

Nevertheless, there are also some disadvantages associated with boarding lifts that must be considered. Firstly, they are typically much more expensive to install and maintain than other solutions such as ramps or gap fillers, which may present a financial barrier for some transport operators. Secondly, boarding lifts are generally vehicle-specific, meaning that they need to be designed and adapted for each train type, which can result in compatibility issues and further increase costs. Recent studies have shown that under 2% of the entire rail fleet in the UK has been equipped with lifts (DPTAC 2022). Furthermore, lifts may require additional space and structural support on both the train and platform, potentially impacting the available area for other passengers and posing challenges in retrofitting existing infrastructure. Lastly, lifts can be prone to mechanical failure, which may result in delays and reduced accessibility if not promptly addressed through regular maintenance and monitoring.

Figure 5.35: Boarding lift. Source: sj.se.

Low-floor carriages present several advantages such as being the most secure solution among all options as they provide a nearly level boarding experience that minimises the need for additional boarding equipment. They cater to a wide range of passengers regardless of their functional capabilities, making them a highly inclusive solution. In addition, low-floor carriages can contribute to a more efficient boarding and alighting process for all passengers, as they help reduce the dwell time at stations, ultimately leading to improved overall service performance.

Figure 5.36: Carriage-integrated gap fillers. Source: The Anonymous Widower.

Figure 5.37: Low-floor train. Source: wikimedia.

However, there are also some disadvantages associated with low-floor carriages that must be considered. Firstly, they are typically much more expensive to design, manufacture, and maintain than other accessibility solutions due to the complex engineering required to accommodate the low floor and associated systems. Secondly, low-floor carriages are a vehicle-specific feature, which can result in compatibility issues with existing rolling stock and infrastructure, further increasing costs and implementation challenges. Additionally, low-floor technology cannot be easily applied to British trains due to gauge restrictions, as the smaller vehicle size and limited clearance between the train and the track may not allow for the necessary structural modifications. In fact, statistics have shown that only 20% of UK stations could facilitate conducive conditions for low-floor/level access rail vehicles (DPTAC 2022). Lastly, integrating low-floor carriages into existing fleets can be logistically challenging, as it may require extensive modifications to platforms, train configurations, and operational procedures to ensure seamless integration and service continuity.

In summary, after triangulating results from the systematic review and the integrative accessibility assessment, this chapter pinpointed the design problem for this work. That is, the accessibility of the platform-train interface (PTI), where horizontal and vertical gaps are consistently identified as major barriers by MobAD users. Existing solutions such as boarding ramps, gap fillers, and lifts have been implemented in a UK context, each with its own merits and limitations. However, none of these have fully addressed the PTI challenges. Given these insights, it becomes clear that a novel intervention is necessary to improve PTI accessibility effectively. This solution must consider both the unique demands of UK rail systems and the specific needs of MobAD users, aiming for an innovative resolution that enhances user experience at PTIs. The subsequent sections of this thesis will explore potential new solutions tailored to these requirements.

B3. Bridge section: towards co-creating an inclusive solution to address the design problem

At this point, the thesis transitions from the definition of the design problem to the first stage of designing a new solution that addresses the PTI challenges faced by MobAD users. Given the limitations of existing solutions and the context-specific nature of the UK rail system, it is essential to engage with relevant stakeholders, including MobAD users, rail industry experts, and design professionals in the development of an innovative, targeted, and accessible intervention.

To ensure that the new solution is both user-centred and contextually appropriate, the thesis embarks on a collaborative design process. This approach involves working closely with MobAD users who provide valuable insights into their experiences and specific needs when navigating the PTI, as well as experts from the rail industry who contribute their technical knowledge and understanding of the constraints and opportunities within the UK rail system. Through this collaboration, the design process is enriched, enabling the development of a solution that addresses the issues identified in the previous chapters and accounts for the real-world experiences and perspectives of the people it aims to serve.

As the thesis progresses into developing an inclusive solution for MobAD users (research objective 3 – RO3), a collaborative approach will inform efforts to design an intervention that balances accessibility, safety, and usability for MobAD users with the operational demands of the UK rail system. By integrating insights from both MobAD users and industry experts, the research aims to innovate and refine a solution that enhances the PTI environment, creating a more inclusive experience for all passengers.

6. Collaborative ideation of a design solution with MobAD users and experts

In previous chapters (i.e., Chapters 3 and 4), it became evident that the platform-train interface (PTI) is one of the most challenging spatial situations that MobAD users can encounter in urban environments. This is due to the physical gap that develops between rail vehicles and station platforms. Also, Chapter 5 encompassed a brief description of existing solutions that aim to bridge this physical gap. Those solutions were classified as (a) platform-applied or (b) train-embedded bridging interventions.

6.1. Purpose

The following sections present a co-design approach for the ideation of design solutions to mitigate the physical gap between rail vehicles and platforms. The first objective is to solicit user experiences and professional insights regarding the design problem. The second objective is to ideate design solutions satisfying user requirements together with MobAD users and professionals. Both objectives align with Objective 2 – Engage with MobAD users (RO2) of this overall research, as defined in Chapter 1.3.

6.2. Methods

The initial plan was to collaboratively explore alternative solutions with MobAD users and experts in-person. This was disrupted by the COVID-19 pandemic, leading to a shift towards remote collaboration methods such as videoconferencing and online drawing tools. The pandemic-induced "stay-at-home" culture significantly affected research processes, fostering a rise in virtual meetings and distributed co-design workshops (Reith et al., 2021; Chen, 2021; Taylor et al., 2021; Losev et al., 2020), a trend likely to continue with projections showing only 25% of corporate meetings to be in-person by 2024 (Standaert et al., 2021). Therefore, the pandemic necessitated conducting the design workshops remotely using videoconference tools and online whiteboards.

The updated study design received ethical approval from the Engineering Ethics Committee of the University of Nottingham in November 2020. This process also covered aspects of data protection, data handling and retention, participants' anonymity and confidentiality, and participants' consent.

6.2.1. Participants

Study participants were sought through direct email communication with targeted user groups – i.e., national/regional groups and organisations of MobAD users – and interested participants from previous studies; email newsletters (i.e., via University of Nottingham email services); and social media adverts (i.e., on Twitter). The participant group (n = 35) consisted of users of diverse types of MobAD (n = 30) – i.e., users of manual wheelchairs (n = 7), powered wheelchairs (n = 15), scooters (n = 3), canes (n = 3), and walkers (n = 2) – and experts in relevant disciplines – namely human factors (n = 2), design engineering (n = 2), and architecture (n = 1). It is important to mention that three out of five participating experts were also users of MobAD (powered wheelchairs). The sample population (n = 35) was regarded as sufficient to produce credible evidence, as other studies using a similar methodology involved 20-50 participants in total (Vollenwyder et al., 2020; Bolster et al., 2021; Seita et al., 2022). Every participant of this workshop was offered a £15 shopping voucher as reimbursement for their time. Figure 6.1 illustrates human groups involved in this workshop. Table A.2 of the Appendix includes an anonymised list with information about the participants of this study.

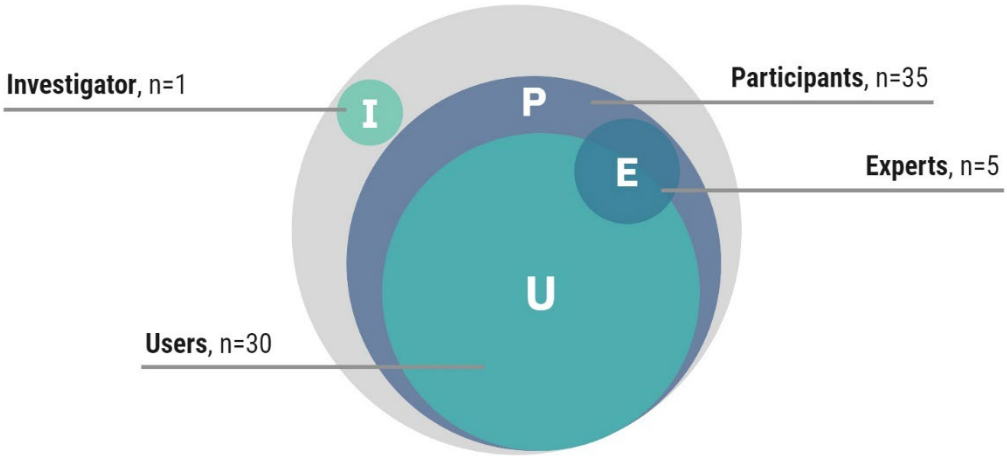


Figure 6.38: The human landscape of this workshop (in grey) and groups involved (in shades of blue).

6.2.2. Study design

To design and plan this facet of the design exploration, the "Experience-Based Co-Design" (EBCD) toolkit[3] (Bate & Robert, 2007) was adopted as a guide. EBCD has been applied in many studies as a method for working with groups of people who have experience accessing services and with professionals delivering services to make improvements or design new services together (Donetto et al., 2014). It draws on knowledge and ideas from design sciences and professions where the aim of making products, buildings, or environments better for the user is achieved by making the user integral to the design process itself (Bowen et al., 2013). A central part of EBCD is holding individual interviews with users to collect their experiences with respect to a specific issue and solicit their ideas on designing possible solutions (Bate & Robert, 2007). Users' experiences and ideas are then expected to stimulate a new round of conversations with professionals joining users to cooperatively develop solutions (Bate & Robert, 2007). Next, the co-design process culminates in a joint event or events in which users, professionals, and the research team participate in designing and implementing solutions to resolve the priority issues.

[3] The Experience-Based Co-Design toolkit is available online: https://www.pointofcarefoundation.org.uk/resource/experience-based-co-design-ebcd-toolkit/

A particular appeal of Experience-Based Co-Design (EBCD) is its adaptability to specific circumstances such as limited budgets. Consequently, some modifications were made to accommodate the project's restricted timeframe and resources as well as the constraints imposed by the pandemic. Drawing on the work of Ryanor et al. (2020), the EBCD process was adapted in several significant ways. The most notable changes included: (a) using digital platforms to host workshop events instead of conducting in-person meetings; (b) condensing the EBCD process by merging two or three steps into a single yet comprehensive activity; and (c) intensifying the EBCD process in terms of the duration and frequency of workshop events. Typically, studies employing the EBCD toolkit are completed over 12 months, whereas this study was completed in 6 months.

As explained in the previous section (i.e., Chapter 6.1), the COVID-19 pandemic significantly affected the organisation and implementation of the engagement events in this PhD project. The entirety of scheduled co-design workshops was realised through online platforms and digital tools. Pandemic-imposed limitations aside, an additional advantage of remote approaches is their high level of inclusivity. That is, remote access is likely to maximise participation of physically disabled people notwithstanding their location or mobility status. Many researchers have utilised a web-based methodology to convene meetings with disabled people and thereby facilitate their involvement (Bolster et al., 2021; Recke & Perna; 2021; Rotkonen et al., 2021; Sandoval et al., 2020; Schroeder & Lucas, 2021).

The adapted approach was hybrid in nature, as some of the included tasks required attendance of all participants while other tasks were individually run with or without the investigator's[4] attendance. Namely, the co-design process comprised of three stages: (1) the ***Induction Meeting*** (i.e., online group event), (2) the ***Experience + Design Exploration Duologues*** (i.e., one-to-one interaction, online sessions),

[4] The investigator of this study is the author of this thesis.

and (3) the ***Creative Canvas*** (i.e., many-to-many interaction, remote, asynchronous activity). The reasons for this procedural variability were (a) to expedite the design process without compromising its quality, (b) to experiment with novel techniques and explore new ways to collaborate with people remotely, and (c) to ensure that every voice would be explicitly heard while – at the same time – instil a team spirit and a sense of belongingness among the workshop participants.

6.2.3. Data collection

Initially, workshop participants were sent digital copies of the information sheet and the consent form of this study. Once the final workshop activity was completed, participants were provided with debriefing statements which included some additional information about the PhD project (i.e., objectives and hypothesis, primitive results, information on how participants could get informed about study outcomes, future studies, and contact information). As part of the study debriefing, participants were also asked to answer two open-ended questions to collect their feedback on the ideated outcomes and co-design process. The purpose of this was to retrieve participants' views on the methodological organisation and procedural aspects to refine or revise the study in a bid to enhance the generalisability of the research. This was implemented in a dedicated online form on Microsoft Forms.

The data collection process lasted six months (December 2020 – May 2021). The adapted process is illustrated in Figure 6.2, which provides a sequential flowchart of workshop stages and provides an outline of forms of conversation undertaken as well as respective group compositions. The following sections provide a detailed description of the different stages, in terms of process as well as techniques and methods used.

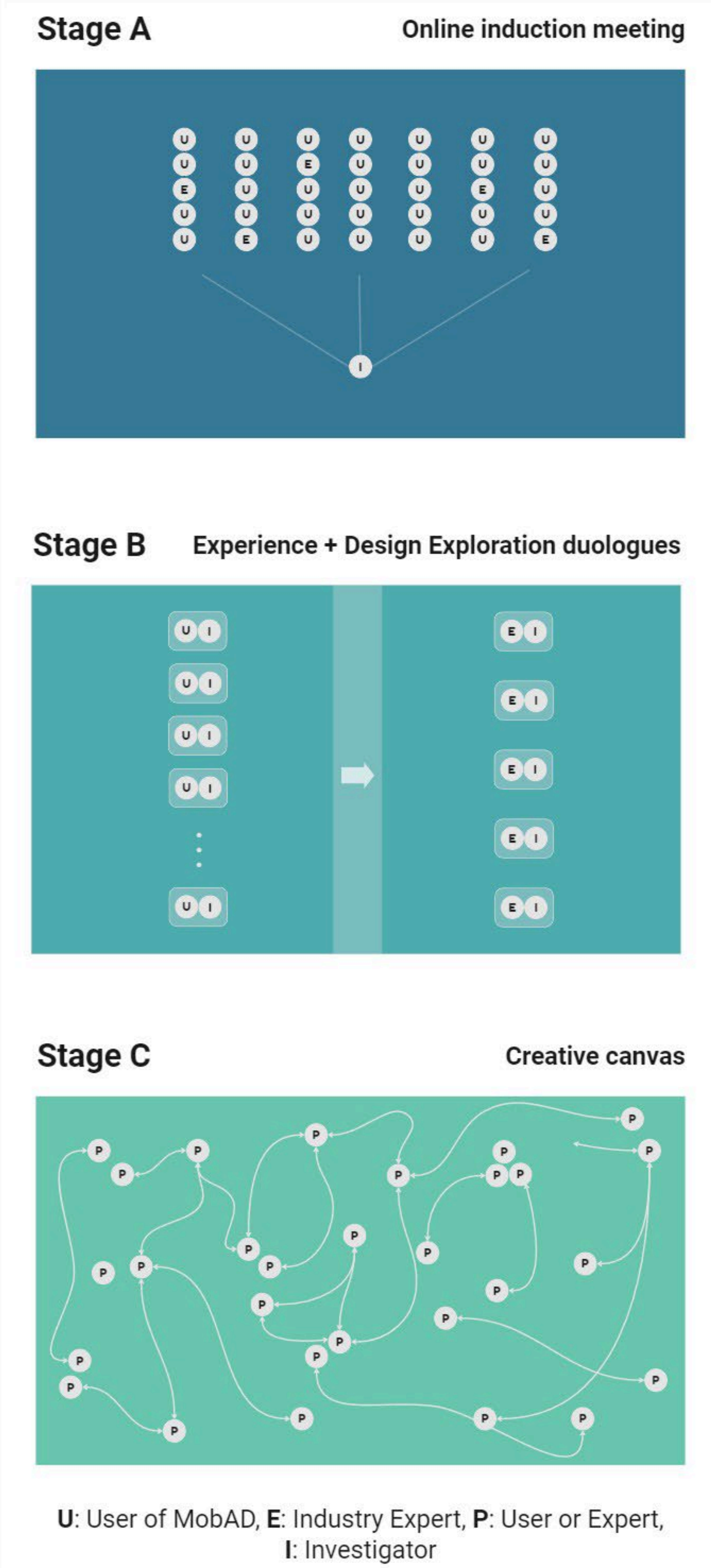


Figure 6.39: Flowchart of data collection process

6.2.3.1. Stage A – Induction meeting

In line with the EBCD toolkit, the research process involved an initial videoconference call with all participants, during which the research purpose and process were explained, including consent and anonymisation, the right to withdraw, and the analysis and reporting plans. The main focus of this meeting was on explaining the research problem and existing solutions in non-technical language. This was supported through the use of photos and diagrams. Figure 6.3 presents an example of the material used in this stage.

Figure 6.40: Use of visual material assisted with explaining the design environment to workshop participants. Copyright: BBC.

Furthermore, this meeting provided an informal training session to participants in the sense that they were presented with an overview of the workshop-related digital platforms (i.e., Microsoft Teams and Miro), their virtual environments, and their characteristics. The last part of this stage included a reflexive “Q-and-A” session during which participants could ask questions and leave their comments about the study as well as engage in a dialogue with the rest of the group. Figure 6.4 includes a list with all activities included in Stage A of the workshop.

Figure 6.41: List of activities in Stage A

The induction meeting was conducted to gain participants' trust and foster a sense of community. The intention was for participants to understand that the workshop outcomes would result from collaborative thinking and teamwork despite the physical remoteness of group members. Another objective was to emphasise the dimension of togetherness, particularly in the context of the prevailing conditions such as the global pandemic, travel restrictions, and lockdowns. Additionally, the meeting provided an opportunity to become acquainted with the participants and their communication styles, allowing them to become more comfortable with the investigator and fellow participants before engaging in the design tasks.

6.2.3.2. Stage B – Experience and design exploration duologues

The next stage of the workshops included individual conversations with MobAD users as well as experts from industry. Each meeting comprised of a semi-structured interview (experience) and a scenario-based ideation activity (design exploration). Figure 6.5 presents a roadmap of Stage B, including substages, forms of conversation, and participant groups involved. The following lines provide a comprehensive description of Stage B.

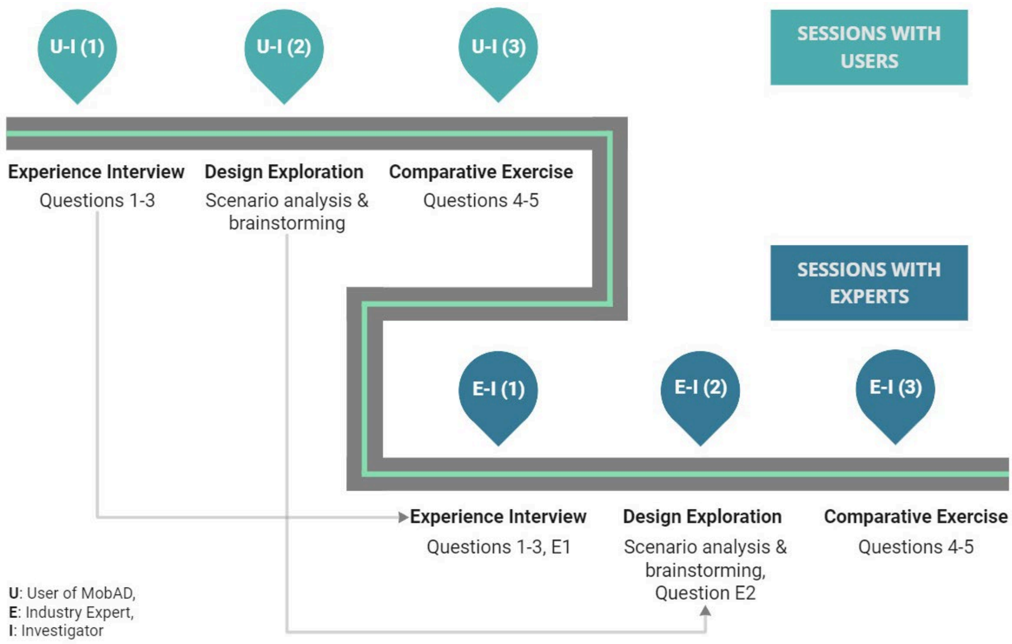


Figure 6.42: Roadmap of Stage B steps (1,2,3), forms of conversation (U-I, E-I), and activities (U-$I_{1\text{-}3}$, E- $I_{1\text{-}3}$)

According to the EBCD toolkit, the investigator engages with users and professionals in individual meetings during this stage of the process. Previous research has shown that individual interviews are highly effective at generating ideas in a brainstorming task (Guest et al., 2017). Also, user experience disclosures are more likely to occur in individual interviews than group discussion events (Aldag & Tinsley, 2008; Namey et al., 2016). Another advantage of interviews is that participants have more freedom to express themselves without being interrupted or distracted by others (Coenen et al., 2012). Meetings with users of MobAD preceded and provided the evidence basis for the subsequent meetings with industry experts. In these meetings, several types of visual media were utilised (i.e., images, diagrammatic illustrations, and drawings) as a means to spur the design conversation and elicit information from participants. Similar techniques of visual elicitation have been efficiently employed in design research (Rose, 2016; Adams et al., 2010; Schaeffer & Carlsson, 2014). In most cases, researchers asked study participants to take photos themselves of investigated situations or spaces to analyse participants' experiences with those (Adams et al., 2010; Schaeffer & Carlsson, 2014). The main limitation of this method is that it is a time-demanding activity. In conjunction with that, this particular study was conducted during the lockdown period (i.e., December 2020-May 2021), so it would be impossible to request participants to engage in fieldwork. Therefore, this study followed a more traditional approach, as seen in Cooper et al. (2012), which involved the use of previously-prepared visual resources to extract information on user experiences.

Meetings with workshop participants were conducted online through a videoconference application (i.e., Microsoft Teams) and a digital whiteboarding platform (i.e., Miro). Weblinks to meeting rooms and whiteboards were sent the evening before each meeting; every whiteboard was unique and accessible to participants till the last day of the workshop (i.e., 31 May 2021). The videoconference sessions were recorded and later transcribed using NVivo software for data analysis purposes. Participants' digital whiteboards were stored online and later used for data analysis.

At the beginning of every meeting, each participant was asked to give their verbal consent so that the session could be recorded. The investigator gave a short introduction (approximately 5-10 minutes) regarding the study background and objectives. In this step, the investigator once again explained the design problem and existing solutions (i.e., a platform-to-train ramp, a train-embedded lift, and elevated platform humps) using images and diagrammatic illustrations. The following part (Stage B1 – Experience) of the meeting comprised a semi-structured interview to understand participants' experiences with PTIs (i.e., the design problem). Interviews with MobAD users were slightly different from those with industry professionals regarding aspects of interrogation (i.e., personal functioning vs technical focus), terminology used (non-technical language vs scientific vocabulary), and number of questions. Table 6.1 includes three interview questions, which were addressed to both MobAD users and industry experts.

Question 1	How would you describe your experience with boarding/alighting trains?
Question 2	According to your opinion, what are the biggest challenges when accessing PTIs?
Question 3	Based on your experience, what are the biggest advantages and shortcomings of the previously presented solutions in terms of accommodating your functioning needs?

Table 6.16: Interview questions - Stage B1

It should be noted that the semi-structured interview did not follow a formal strict approach, as the intention was to make participants feel as comfortable as possible. For this reason, the phrasing of interview questions was often adapted according to the participant's background, expertise, and availability. For example, Questions 1 and 3 were adapted to "How would you describe your professional experience with PTIs?" and "According to your professional understanding, what are the most important advantages and disadvantages of the previously presented solutions with respect to accommodating MobAD users?" respectively. On top of these questions – and since meetings with experts took place after meetings with users were completed – an additional topic was explored together with industry professionals. This concerned users' functioning needs and preferences in a PTI context (Question E1) as originated from previous sessions with MobAD users.

On completion of the interview section, participants were presented with three design scenarios visualised in a drawing format (see Figures 6.6, 6.7, and 6.8). These scenarios referred to conceptual solutions which would potentially resolve the design problem (i.e., the physical gap between trains and platforms). Scenarios were created by the investigator based on patterns identified in different types of existing PTI bridging systems as described in Chapter 5.2. The scenarios represented different types of solutions. Specifically, Scenario 1 referred to extendable plates integrated onto platforms at predetermined positions. Scenario 2 presented a train-embedded ramp, which can be automatically deployed as part of the train and stored in a compact case under the door when not in use. Scenario 3 illustrated an extendable platform-to-train ramp, which could be moved along the platform either manually or by a type of automated system.

Figure 6.43: Scenario 1 platform extendable plates.

Figure 6.44: Scenario 2 - train-embedded ramps.

Figure 6.45: Scenario 3 - extendable and movable platform-to-train ramp.

The investigator then invited participants to transfer to a Miro whiteboard and discuss the qualities, shortcomings, or serviceability aspects of the given scenarios based on their functioning needs and personal preferences (Stage B2 – Design Exploration). For every presented scenario, Miro's digital workspace and interactive tools allowed participants and investigator to share a common board and make annotations or sketch over the scenario images in real-time. Figures 6.9, 6.10 ,6.11 contain screenshots of example whiteboards from this stage. As shown there, participants and investigator combined textual and sketch representations to discuss characteristics of each scenario as well as communicate their preferences, concerns, or possible improvements in a bid to co-ideate the most suitable solution. Since meetings with experts took place after meetings with users were completed, an additional topic was explored together with experts. This was about the applicability of the most discussed design concepts (Question E2), as those emerged from earlier sessions with users.

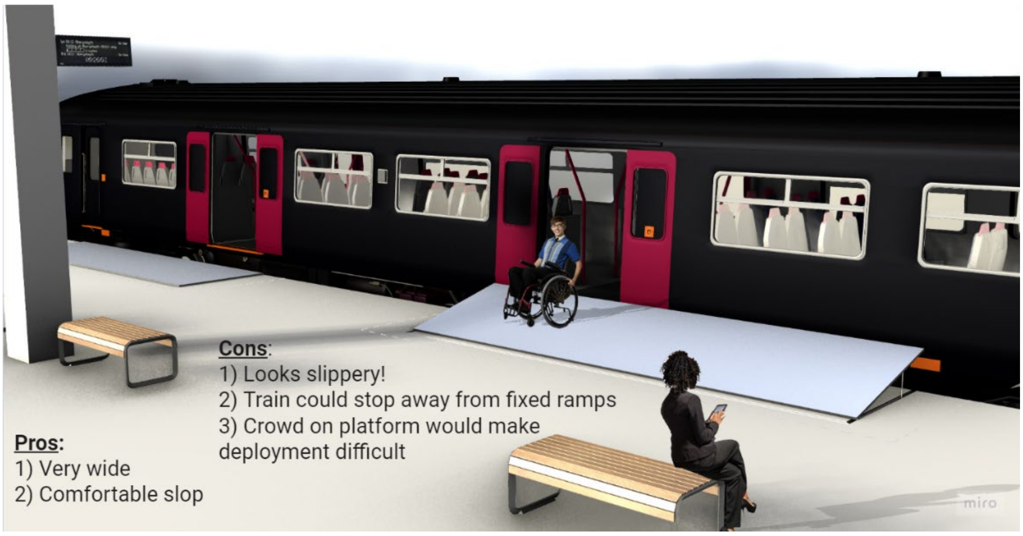


Figure 6.46: Scenario 1 - example Miro whiteboard from design exploration sessions

Figure 6.47: Scenario 2 – example Miro whiteboard from design exploration sessions

Figure 6.48: Scenario 3 – example Miro whiteboard from design exploration sessions

For the next step in the process (Stage B3 – Comparative Exercise), the Investigator asked participants to rank the conceptual scenarios (Question 4) from “most accommodating” to “least accommodating” solution and rate them against existing solutions (Question 5) as “more assistive” or “less assistive.” Once this comparative exercise was completed, a brief “Q-and-A” session followed in which participants could ask questions or share their reflections on the process and design concepts.

6.2.3.3. Stage C – Creative canvas

The final stages of the EBCD toolkit involve a series of group events where end-users and industry professionals meet up to co-create conceptual solutions (Bate & Robert, 2007). Due to pandemic-imposed restrictions, however, physical meetings were impossible during the time of investigation. Another limitation came from whiteboarding applications, as most of the then-available platforms would not support the desired combination of concurrent design activities, synchronous interaction between users, and video-chatting capabilities (Anderson et al., 2022).

Under these circumstances, it was decided to introduce a method for co-designing asynchronously. Many researchers have utilised asynchronous methods to conduct studies with human participants in various fields such as human-computer interaction (Walsh et al., 2012), education (Marbito, 2006; Winschiers-Theophilus et al., 2022), and engineering (Marques et al., 2021; Halvey et al., 2010). However, no similar examples have been identified in the design literature. Recent research has shown that asynchronous collaboration helps participants deeply engage in the development process mainly because they execute tasks at their own pace (Jorgensen, 2012). This major advantage of asynchronous methods aligned with the study intention to establish a comfortable-to-participants design process to bolster their creativity.

For this stage of the design workshop, a co-creation online canvas was set up using the Miro platform, which provided more open-source tools and a user-friendly design environment than other commercial whiteboarding applications. The canvas comprised all participants' whiteboards from Stage B (parent whiteboards), containing items generated during the individual brainstorming sessions, such as sticky notes, sketches over scenario images, and annotated drawings of new concepts. Figure 6.12 provides an overview of the co-creation canvas, including only content generated in Stage B – i.e., parent whiteboards.

Figure 6.49: Overview of creative canvas, including only parent whiteboards

For every included whiteboard, an individual frame was created whose owner's name appeared atop. All frames were "locked" by default – i.e., new items could be added in but initial content could not be edited – and only each frame's owner was able to unlock it. Figure 6.13 presents an example parent whiteboard.

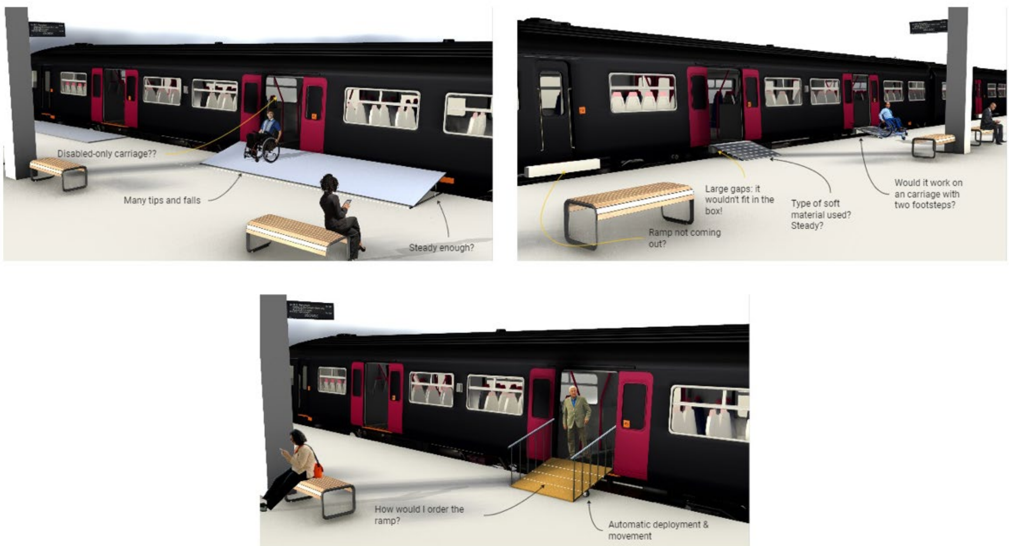


Figure 6.50: An example of a parent whiteboard

Immediately after the completion of Stage B, participants were provided with a link to the canvas. This task invited participants to explore the design landscape by visiting other participants' whiteboards and comment or a sketch) to initiate a creative conversation and further develop existing concepts (augmented whiteboards). Figure 6.14 presents an example augmented whiteboard.

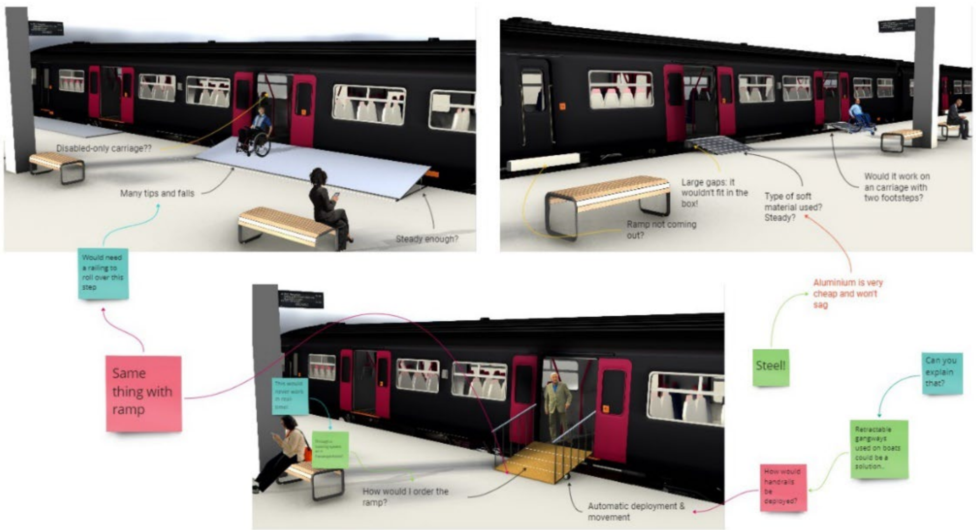


Figure 6.51: An example of an augmented whiteboard

Two or more participants who would like to engage in a design conversation had the option to generate a new whiteboard (child whiteboards) and collaboratively recreate given scenarios. Figure 6.15 illustrates an example child whiteboard.

Participants could communicate with each other via an integrated chat box. At the end of the design process, the canvas comprised a concoction of parent, augmented, and child whiteboards (Figure 6.16).

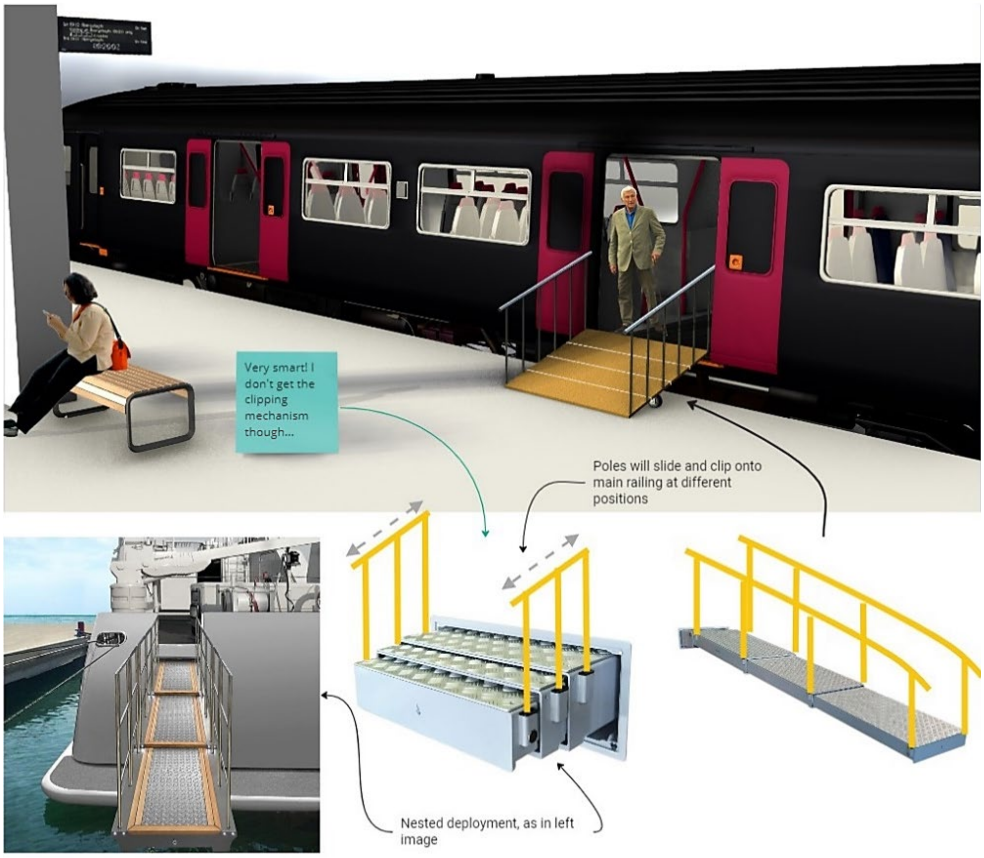


Figure 6.52: An example of a child whiteboard

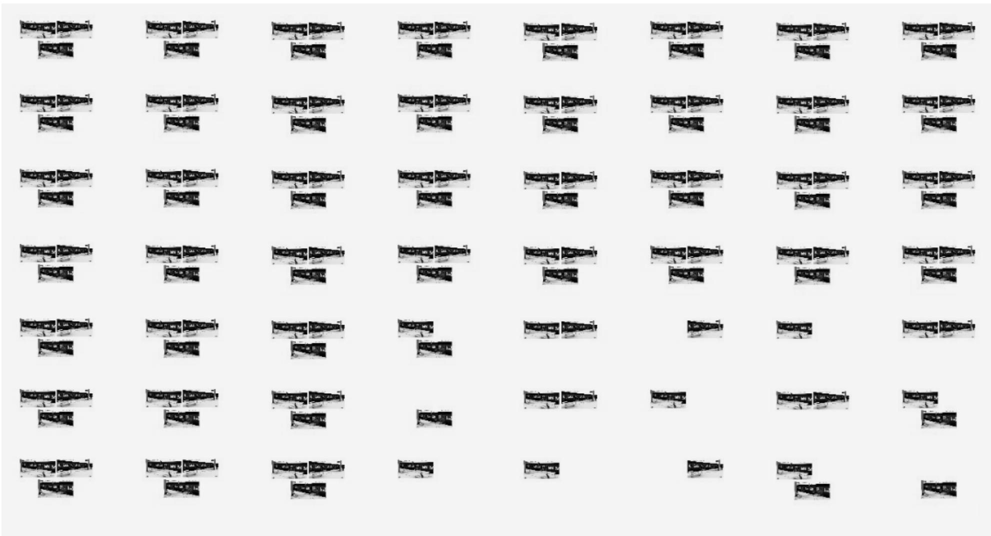


Figure 6.53: Overview of creative canvas at the end of Stage C

6.2.4. Data analysis

To interpret collected data from brainstorming sessions and creative canvas, a qualitative analysis was conducted. For the analysis part, a combination of techniques was used, namely thematic analysis (Burnard et al., 2008), content analysis (Elo & Kyngas, 2008), and a research-by-design interpretation. This combinatory approach was chosen because (a) different techniques were employed to collect data, (b) various types of data were generated (e.g., contents of 35 interviews and over 50 whiteboards), and (c) the study objectives could not be addressed through a singular analysis.

6.2.4.1. Analysis of experiences at PTIs

To analyse aspects of participants' experiences with PTIs (Stage B1 Questions 1-3) as well as expert opinions on experience-related insights (Stage B1 Question E1), thematic analysis was employed. This decision was based on the observation of recurring common themes within the interviews. The analysis process followed the approach suggested by Braun and Clarke (2021), which includes five steps: (a) familiarisation with data, (b) coding, (c) generation of themes, (d) review of themes, and (e) definition and naming of themes. Based on this approach, Figure 6.17 depicts a diagram of the thematic analysis process adopted for the first set of data (Stage B, Questions 1-3 and E1).

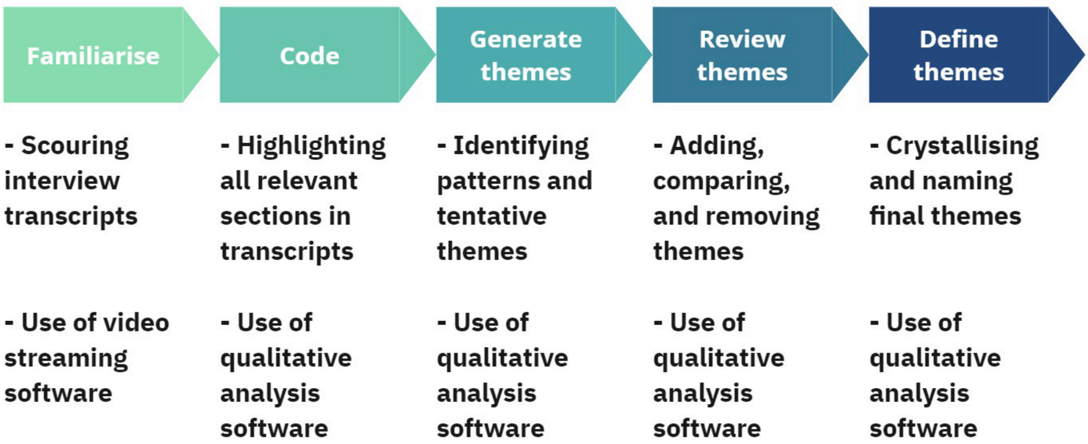


Figure 6.54: Thematic analysis - process diagram

Specifically, in the context of this study, familiarisation involved transcribing interview data. This process was conducted automatically using Microsoft Stream, an online video streaming application that auto-generated transcripts of all 35 recorded interviews. After obtaining all transcripts, they were imported into NVivo qualitative analysis software to complete the coding step, which involved highlighting relevant sections of text and assigning shorthand labels or “codes” to describe their content.

Once all codes were extracted, patterns among them were identified, leading to the development of tentative themes or subthemes. To ensure that the identified themes accurately represented the data, the dataset in NVivo was revisited, and the themes were compared against it. Table 6.2 presents an example of how thematic analysis was materialised in NVivo software. After a series of corrections, such as combining or discarding a few themes, the final set of themes was established and named succinctly to facilitate understanding of the data categorised beneath them.

Excerpt ID	Participant ID	Excerpt Text	Code	Theme
1	P02	"I often worry about accidents because sometimes the ramp is not deployed correctly."	Incorrect Ramp Deployment	Risk of Accidents
9	P04	"The steepness of some ramps makes it very difficult to board the train safely."	Steep Ramps	Risk of Accidents
14	P05	"I always need someone to help me with the platform-to-train ramp, which makes me feel less independent."	Reliance on Assistance	Loss of Autonomy
25	P09	"It's frustrating to rely on others just to use basic facilities like the ramp."	Third-Party Assistance	Loss of Autonomy
27	P10	"I often feel excluded because public transport isn't accessible, affecting my social life and daily activities."	Inaccessible PTIs	Social Exclusion
30	P11	"The lack of accessible public transport interfaces impacts my ability to develop personally and professionally."	Impact on Development	Social Exclusion

37	P14	"Different physical gaps and train designs cause a lot of anxiety when using public transport."	Varying Physical Gaps	Heterogeneity of PTIs
56	P18	"I get anxious not knowing what kind of gap or carriage design I'll encounter at each station."	Carriage Designs	Heterogeneity of PTIs

Table 6.17: Example thematic analysis table (Questions 1-3 & E1, NVivo)

6.2.4.2. Design analysis

To determine how design scenarios rank against each other (Question 4) and their acceptability compared to existing solutions (Question 5), content analysis was carried out. Content analysis provides an effective way to quantify qualitative data by counting instances of codes (Vaismoradi, 2013). The interview transcripts produced previously (see Chapter 6.2.4.2) were used for this analysis following the approach suggested by Elo and Kyngäs (2008).

In accordance with this approach, a categorisation matrix was first constructed by defining the units of analysis – specifically scenario ranking and acceptability compared to existing solutions – as well as the categories of analysis, i.e., [most accommodating, fairly accommodating, least accommodating] and [more assistive, less assistive] respectively. Table 6.3 presents the categorisation matrix constructed for this analysis.

Then the transcribed content was reviewed, relevant excerpts were selected, and these were coded for correspondence with or exemplification of the identified categories. For this step, the transcripts were imported and handled in NVivo analysis software. Table 6.4 presents an example of how content analysis was materialised in NVivo software. Finally, descriptive statistics (i.e., analysis of frequencies) were used to quantify the data coded under each category.

Scenario ranking			
	Scenario 1 (platform extension plates)	Scenario 2 (train-embedded ramp)	Scenario 3 (extendable & movable ramp)
Most accommodating			
Fairly accommodating			
Least accommodating			
Scenario acceptability over existing solutions			
More assistive			
Less assistive			

Table 6.18: Categorisation matrix - Content analysis (Questions 4-5)

Excerpt ID	Participant ID	Excerpt Text	Code	Frequency
1	P01	"I found Scenario C to be the most accommodating because it addressed all my needs."	Most Accommodating	1
7	P04	"Scenario B was fairly accommodating, but it missed a few key features."	Fairly Accommodating	1
31	P03	"Scenario A was the least accommodating. It lacked essential support."	Least Accommodating	1
43	P06	"Compared to existing solutions, Scenario C was much more assistive."	More Assistive	1
52	P12	"Scenario A was less assistive than what I currently use."	Less Assistive	1
82	P23	"I feel Scenario A is less assistive compared to current solutions."	Less Assistive	1

Table 6.19: Example content analysis table (Questions 4-5, NVivo)

To obtain analytical insight about the design scenarios, a combinatory approach was employed, which encompassed joint design knowledge from all different forms of conversation that occurred, namely *users* –

*investigator **(U-I)*** duologues (Stage B2), *experts – investigator **(E-I)*** duologues (Stage B2), as well as *group/mass interaction among all participants **(P-P)*** in canvas (Stage C). Figure 6.18 illustrates a diagram of the research-through-design analysis developed for the design-oriented data generated in the workshop (Stage B2 and Stage C). The following lines comprehensively describe the analysis process.

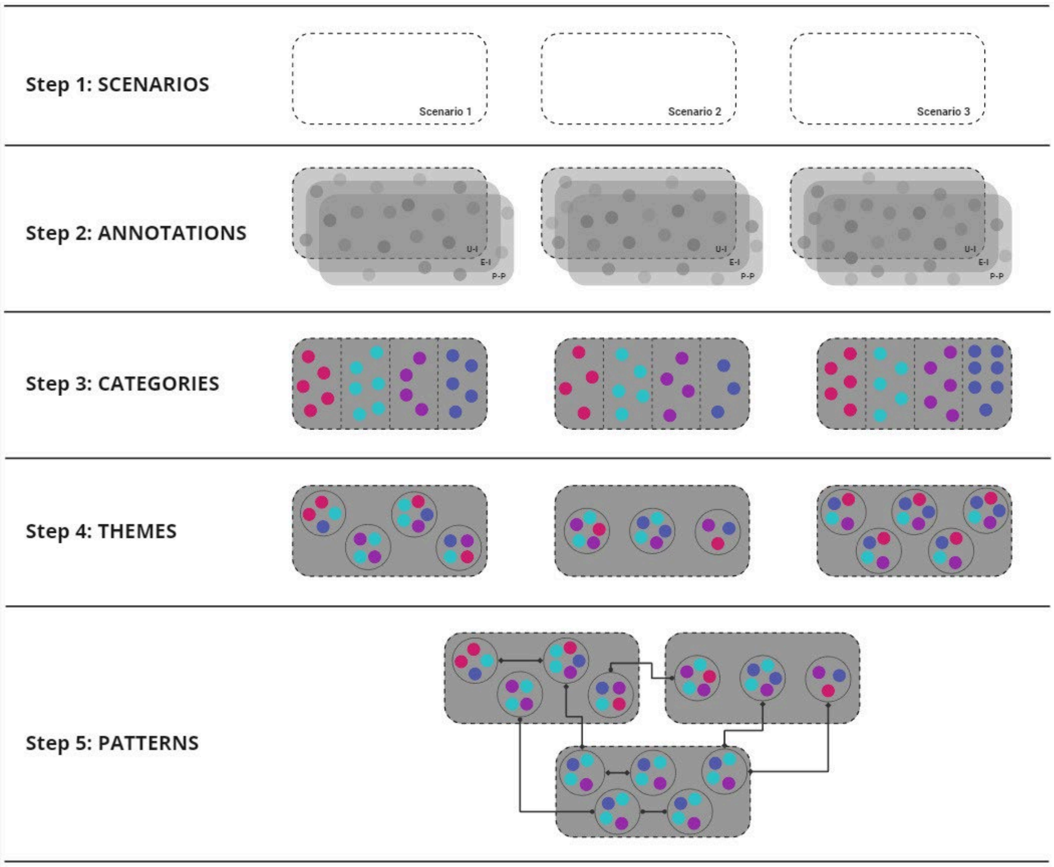


Figure 6.55: Research by design analysis sequence diagram

Analysis of observations was loosely based on the conceptual framework proposed by Drew & Guillemin (2014). This framework recognises three phases for the analysis process of data emerging from visual sources (Drew & Guillemin, 2014): (a) through user engagement, (b) through researcher-driven engagement, and (c) through re-contextualising. Similarly, design observations from U-I sessions were analysed to comprehend what is important for MobAD users. Subsequently, information from E-I sessions was scrutinised to investigate research and professional reflections on the applicability of design scenarios (Stage B, Question E2) as well as users' design input

(Stage B2). In this aspect, expert knowledge was considered to complement the investigator's research knowledge. Finally, observations from U-I and E-I duologues were juxtaposed with P-P interactions. This was essential to study how a heterogeneous audience (i.e., all participants) responded to observations from individual activities (U-I, E-I) and to identify possible conceptual connections or divisions between them.

As a first step, the interview transcripts were revisited, their content reviewed, and scenario-related excerpts selected (Step 1, Figure 6.18). Content from all created whiteboards on Miro was also collated. Next, experts' and whiteboard content were organised under different forms of conversations (i.e., U-I, E-I, P-P). Since the emerging dataset almost exclusively contained design-oriented information, annotated drawing-blocks were employed to support the coding process. A distinct advantage of annotations is that they can index both visible and invisible information about design artefacts (Gaver & Bowers, 2012). Using annotations to code the aggregated data – both visible (whiteboard content) and invisible (excerpts from interview transcripts) – low-level information on certain aspects of design scenarios was deduced.McCracken's (1988) five-step analysis approach was reinterpreted and connected to the annotated drawing-blocks. The five-step analysis provides a protocol for data processing, with each stage representing a greater degree of conceptual extrapolation. During the first two phases, observations are compiled. In the third and fourth steps, these observations are transformed into themes. The final phase involves searching for patterns among the different themes. Adobe Photoshop software was used to construct the coding scheme as follows:

- For each design scenario, three layers were created, containing observations retrieved from the respective forms of conversations between Users, Investigator, Experts, and Participants – i.e., U-I, E-I, and P-P (Step 2, Figure 6.18). In each layer, observations were illustrated on the design space as annotations directly linked to specific aspects or parts they were referring to (e.g., train or platform characteristics). When annotations referred to the concept as a whole, rather than particular parts or aspects of the design, connectors were visualised with a dashed line.

- With all three layers visible, the entirety of annotations attached to a scenario could be seen. Annotations with a similar focus were combined into respective categories (Step 3, Figure 6.18). Each category was assigned a colour, and these colours were used to categorically highlight the annotations. Each annotation could belong to one or more categories.
- Next, dotted lines were used to uncover themes at the level of the design scenario (Step 4, Figure 6.18). Superimposing all categories also assisted in determining the most prominent themes, establishing a hierarchy among the themes, and potentially eliminating redundant themes. The size of the dots was increased with an increasing number of connections between and within themes. This step was repeated for all three design scenarios.
- Finally, the categorically and thematically sorted annotated scenarios were brought together to identify possible patterns among them (Step 5, Figure 6.18). These patterns referred to predominant issues that would either unite or differentiate the three design scenarios. As such, patterns served as the conclusive layer of analysis, providing answers to the research questions, namely participants' most quintessential requirements for a new design solution. To summarise, Figure 6.19 provides an overview of the knowledge generation process, which has been followed to extract information from the co-design workshop. The flowchart refers to data collection and analysis tasks.

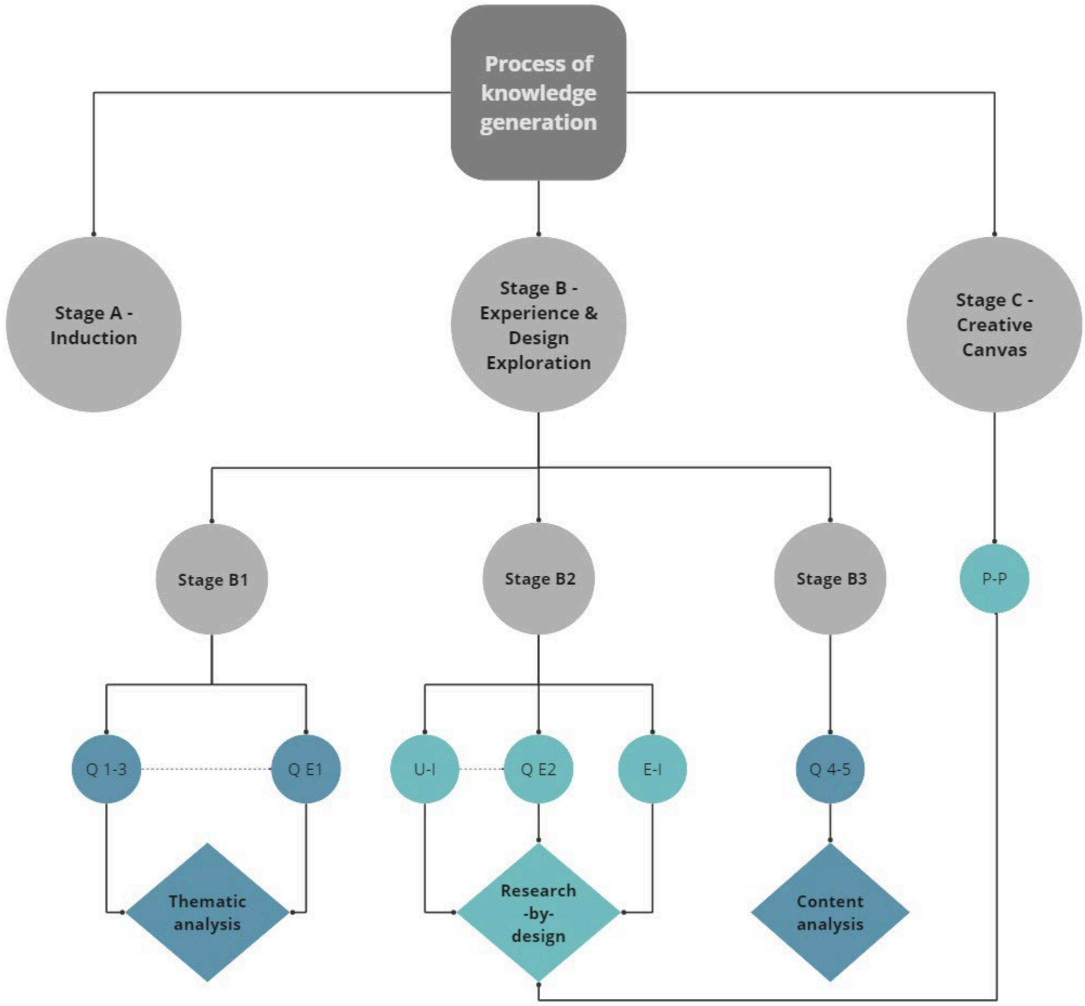


Figure 6.56: Process of knowledge generation

6.3. Results

The purpose of the co-design workshop was to explore user experiences with PTIs and collaboratively ideate design solutions, which could increase accessibility of PTIs. Following the analysis of data collected during the workshop, this section categorises study results in (a) experience-related and (b) scenario-related insights. This classification adds more clarity in addressing the two respective study objectives in a more informative and explicit way. This is also consistent with the underlying objectives of this whole research, which probes into MobAD users' experiences with problematic environments as well as the role of design in those. Furthermore, this grouping is also derivative of different methods employed for collection and analysis of data generated from the workshop sessions. Specifically, qualitative methods were adopted for the experiential part while mostly the use of design-led techniques has substantiated evidence for the co-ideation phase. The following subsections present the most significant insights from user experiences and findings from design conversations, respectively.

6.3.1. User experience findings

The first sets of questions (Questions 1-3 and E1) in Stage B of the workshop referred to experiences of participants with PTIs and existing solutions commonly used to mitigate the physical gap between trains and platforms - i.e., platform-to-train ramps, wheelchair lifts, and alternative platform arrangements or adaptations.

A general observation here is that the vast majority of workshop participants had little or no experience with negotiating gaps using any type of solution other than platform-to-train ramps. A possible explanation for this comes from the fact that all other types of solutions have been rarely applied in a UK context, which was the area of reference in this study. This has been corroborated by industry professionals in the subsequent conversations that were held with them.

Following the process described in Figure 6.17, four broad themes emerged from the analysis of collected data with respect to participant experience: *(a) risk of accidents, (b) loss of autonomy, (c) perceptions of social exclusion, and (d) heterogeneity of PTIs*.

6.3.1.1. Risk of accidents

Most participants expressed concerns regarding inadequacies in the usage of platform-to-train ramps that enable MobAD users to access trains, which might result in severe injuries to those using the ramps. In most cases, incorrect ramp deployment was accredited as the main cause of accidents, as station staff lacked the adequate knowledge to properly attach the ramp onto the train floor. Specifically, a frequently mentioned example included stability issues due to securement failures. Participant 12, a powered wheelchair user, reported:

> “When the ramp is deployed without the tabs being engaged, it means that it is sitting loosely on the doorplate and has the potential to simply come off and crash into the platform while in use; unfortunately, this has happened to me before. Luckily, I managed to escape with some minor injuries, but it could have turned out much worse for me.”

Steep ramps were often cited as a source of accidents at PTIs. Participant 4, a cane user, shared their experience:

> “I am disabled yet able to walk. However, I can no longer climb high gaps and cannot traverse a steep slope. Each time I've embarked on a trip, I've had to up an extremely steep ramp before boarding the train. On one occasion of late, this ended up with me losing my balance and falling to the ground. Because of that, I am still recovering from a high ankle sprain, you know… This was such a painful experience that I am seriously considering never to use trains again, as I now feel that using trains is fraught with difficulty and danger.”

Industry professionals brought a different angle into this topic, as many of them questioned quality of existing ramps as well as deployment skills of station staff. These two factors were also named as potential threats by both interviewed users of MobAD and industry experts. Participant 31, a wheelchair user who works as an accessibility consultant in rail transport industry, said:

> “The supply of unsafe, overused, or even damaged ramps by rail companies has placed the lives of wheelchair users in jeopardy for many years now, despite being notified of the problem. Let alone the

> negligent and dangerous deployment by staff working for some train operators… In London, it seems like a risk as to whether you will encounter a careful ramp wrangler or an unskilled person who avoids using the lugs or just cannot fit them into the holes and quits up. Due to these safety failures, wheelchair-bound passengers throughout the nation run the danger of falling down ramps into platforms or even onto the tracks between carriages and platforms, which might result in devastating injuries."

6.3.1.2. Loss of autonomy

Loss of autonomy at PTIs was a highly discussed subject among workshop participants. The very fact that existing solutions – mainly platform-to-train ramps – require deployment by a third party (e.g., a train conductor or a member of station staff) was considered to diminish MobAD users' independence. Given the operational nature of existing solutions, the loss of autonomy is even more apparent at situations where no third party is available. Participant 27, a powered wheelchair user, shared:

> "The worst scenario is arriving at an unmanned station on a wheelchair, with no one there to help you board the train. This is very much the case where I am coming from as I live in a small town outside London. It has happened many, many times: the ramps were there, I could see them, but to no avail. Sometimes I ask train conductors to assist with boarding but other times I cannot reach them due to presence of many people on platform. My journey was over before it had begun."

Assisted travel[5] offers support to train passengers so they can travel by rail. A variety of services, including provision of a ramp to board and alight trains, are parts of the assistance that may be booked in advance. Passengers may request help up to 24 hours in advance, but they can also raise last-minute request without making a reservation, subject to staff availability. In a PTI context, participants had mixed opinions on assisted travel services, with users' independence having a leading role in the debate. Participant 22, a powered wheelchair user, had a negative experience to recite:

> "I have a 15-year-old son who is also mobility disabled. Last January, he was put on a train at Birmingham going to Bridlington changing at Sheffield, but nobody was there to help him off despite having made a booking with the Passenger Assist. So, he had to stay on until he could get help from the train crew who put him off at Darlington, station staff there put him on a train for Doncaster where he was taken of and put on the Bridlington train. This was ok until the conductor said he would have to change at Gilberdyke so he got off but there was no one there to help him. The result was that his father had to drive all the way to Gilberdyke to pick him up. My son was in a terrible psychological state after this experience, being left helpless at the platform and bereft of the ability to travel independently".

Participants 3 and 17, who both used mobility scooters, were critical of assisted travel:

> "The most negative part [of the PTI experience] has to do with Passenger Assist. I used to make bookings

[5] UK National Rail have developed Passenger Assist, a type of assisted travel. More info can be found on their website: https://www.nationalrail.co.uk/stations_destinations/plan-assistance.aspx

> there, but no one would turn up to help me get on the train – maybe the station is too busy, I don't know. How come this is independence? This is a deception of independence if nothing else."

> "There is no way I am ever going to use it [assisted travel system]. I hate when people make a fuss over me and my disability … I stick to the traditional way and would only ask for help with boarding once I arrive on the platform … In fact, I don't want to rely on anybody to jump on or off the train, I just want to be independent… [Necessity of assisted travel systems] is the biggest shortcoming of these situations [PTIs]; that is where you should focus on."

On the other hand, Participant 34, a non-disabled industry professional who works as accessibility manager in a national rail service, defended assisted travel systems:

> "Assisted travel systems are provided by station facility operators and reservations are overseen by the Rail Deliver Group. In most cases, systems work well and increase people's confidence and capacity to travel by rail alone. It surprises me to hear that other participants had reservations about the system or conductors, as staff has been very helpful and provided an excellent service on the whole. Last year, there were over 1.5 million passenger assists throughout the UK rail network. This translates to 3.2 assists per booking, meaning that operators helped passengers accomplish more than 3 tasks throughout their journeys on average. It's actually a huge step towards users' independence."

6.3.1.3. Social exclusion

Another dimension outlined through the collected data referred to participants' experiences of being socially isolated as a result of inaccessible PTI environments. Specifically, interpersonal relationships and daily activities (e.g., shopping) were cited as the most affected areas by MobAD users. Participant 32, a wheelchair user who works as an accessibility consultant in an architectural firm, said:

> "I don't drive so I depend on public transport. In all honesty, I prefer taking the bus to work and elsewhere. [Accessing trains] can be incredibly challenging mainly because of access ramps often being narrow, slippery, or even unlawfully steep… When no buses are available, I avoid visiting friends or relatives if taking the train is the only option. Seclusion is the right word, I reckon…"

In a similar vein, Participant 3, a user of mobility scooter, has described their experience with boarding trains:

> "My daughter-in-law does the shopping for me, as I can't go to the city-centre by train. I like to have my mobility scooter with me when I go on outings. But there's always, "Oh you can't take that on here, we haven't got the right ramp for you to board" even though I did it last week, so I know you can. Since I can't walk or stand up for the whole day, I must have a chair with me. But I couldn't carry my chair in the shopping mall, could I (laughter)?"

Moreover, aspects of personal development (i.e., employment and education) were also impacted by problematic PTIs. Participant 19, a cane user, mentioned:

> "I was born and brought up in a country of the Global South… Due to my condition, I couldn't commute to

university easily as platform infrastructure was very poor and therefore I did not complete my studies there… I moved to the UK fifteen years ago and hoped that things would be different here… I had to change three jobs as stations at different areas around London do not support level boarding, as I find it very demanding to use a ramp with no handheld support… My ability to take up a job of my choice is diminished let alone my income."

6.3.1.4. PTI heterogeneity

Issues related to heterogeneity of PTIs were particularly prominent in the interview data. Physical gaps between trains and platforms develop in various dimensions (i.e., height x width) across UK rail stations. Differences among carriages were frequently mentioned as a source of anxiety, too. In general, concerns regarding PTI variability were widespread among interviewees. For example, Participant 23, a scooter user, stated:

> "Portable ramps for wheelchairs definitely help. Wheelchair lifts are an even better solution – I had the chance to use one of those during a trip overseas. But I am asking you this: Let's assume for a moment that I boarded a train equipped with a lift. Many journeys involve two even three train changes. How would I know if connecting trains included wheelchair lifts as well? What if they didn't? Would then I be able to call for assistance so that I could resume my journey? And what happens if there is no level access? Would that station be equipped with a ramp, wide enough to accommodate my scooter? Would station staff have adequate knowledge to deploy it?"

Participant 34, who works as an accessibility manager in a national rail service, offered an explanation for the reported platform heterogeneity:

> "… Regarding UK stations, the average platform height is 915mm and [average] offset is 730mm above rail level. Most platforms were built according to those standards but there are still many platforms of lower heights or larger offsets. This is because some existing stations have platforms where the original infrastructure has been unchanged since the lines were built with what was a different standard… The degree of curvature permitted is another fundamental obstacle to universal step-free, gap-free access on the traditional train network. Two thirds of Britain's platforms are on curves. Where these curves are particularly tight, the gap between the train and the platform must be increased to make sure that trains can pass safely."

In conjunction with variability in platforms, train carriage designs can vary, as different models rarely have similar characteristics. Participant 35, a principal design engineer in the rail industry,commented:

> "… By and large, classic trains have their floor at a 1100mm height internally. In two of our models, we had to go up by 50 and 100mm, respectively, as it was necessary to accommodate underfloor equipment. Result is, bigger gaps develop. If you also take into account models with an additional footstep included, then this gap increases in two dimensions! This means that a range of 20-25 ramps of different sizes would be required to accommodate a single station – if we wanted to respect accessibility regulations."

In summary, the analysis of participant experiences in the study revealed four key issues: (a) risk of accidents, primarily due to incorrect ramp deployment and steep ramps, (b) loss of autonomy, as MobAD users rely on third-party assistance to use facilities such as platform-to-train ramps, (c) social exclusion resulting from inaccessible public transport interfaces (PTIs), impacting personal relationships, daily activities, and personal development, and (d) the heterogeneity of PTIs, with varying physical gaps and carriage designs causing anxiety among users.

6.3.2. Design findings

This section presents findings that emerged from the design conversation with workshop participants. It concerns aspects of the conceptualisation of new solutions, which would improve MobAD users' experiences with PTIs. The first part (Scenario Benchmarking) of this section sets out how workshop participants valued the presented design scenarios among each other and against existing solutions. The second part (Design Preferences) encapsulates knowledge generated in the design activities of the workshop.

6.3.2.1. Scenario benchmarking

In Stage B2, workshop participants were presented with three design scenarios of possible solutions. After having a comprehensive discussion about design aspects of each scenario, participants were asked to rank the three design scenarios (Question 4) and rate them against existing solutions (Question 5). Content analysis was used to generate knowledge from collected data; a categorisation matrix was developed to help with coding the data under respective units and categories. *Table 6.5* presents the quantified results in the categorisation matrix, as emerged from the content analysis.

Scenario ranking			
	Scenario 1 (platform extension plates, Figure 6.6)	Scenario 2 (train-embedded ramp, Figure 6.7)	Scenario 3 (extendable & movable ramp, Figure 6.8)
Most accommodating	7	2	26

Fairly accommodating	17	12	6
Least accommodating	11	21	3
Scenario acceptability over existing solutions			
More assistive	23	18	31
Less assistive	12	17	4

Table 6.20: Categorisation matrix – results from content analysis

What stands out in Table 3 is the dominance of Scenario 3 (extendable and movable platform-to-train ramp) among participants' preferences. More than three quarters of participants ranked the ramp as the most accommodating scenario. This trend had emerged even from the design exploration stage, as participants addressed Scenario 3 with great optimism. Integration of handrails was perhaps the most important advantage of Scenario 3 over the other two scenarios, as it was frequently mentioned by participants. For example, Participant 29, a cane user, stated:

> "[Integrating handrails] is a fantastic idea! I wonder why no operator has implemented that before…I can no longer climb gaps or traverse a steep slope without support. Handrails are my support… [Most accommodating solution would be] Scenario 3, no doubt about it."

This view was also echoed by Participant 33, who works as an accessibility consultant, and commented:

> "I would definitely go with option 3 [Scenario 3]. Look, personally, I don't mind negotiating the classic train ramps on my electric wheelchair. But I know very many people that cannot do without access railings. For instance, I keep asking myself many a time is it safe for vision-disabled people with canes to use the classic ramps? Not only should handrails be built on access ramps, but they must also become a legal requirement"

Most participants all but dismissed Scenario 2 (train-embedded ramp) as a possible solution, as only 2 out of a total 35 participants considered Scenario 2 to be the most accommodating solution. A significant reason was the fact that Scenario 2 referred to a vehicle-specific and operator-specific solution, which would not ensure accessibility across the entire rail network. As Participant 15, a powered wheelchair user, said:

> "[Scenario 2] is similar to wheelchair lifts. One train has it, next train doesn't… What disabled people need the most from train infrastructure is reliability. Bringing some more inconsistent systems into play, like this ramp here [user pointed to Scenario 2 using their cursor in Miro whiteboard], will clearly not help."

An inspection of the data in Table 3 reveals that participants' opinions on Scenario 1 were mixed, as almost half of the participants regarded platform movable extensions as a fairly accommodating solution. Some interviewees found Scenario 1 to be the most accessible solution because it would be able to accommodate any type of PTI variation, as a result of the extensions being structurally adaptable. As Participant 23, a mobility scooter user, put it:

> "It's interesting that this [concept] would use both vertical and horizontal movements to address all types of gaps. It could also cater for both high trains and low-level platforms".

On the other hand, the fact that the extensions would only be installed in some locations on platform sparked some debate. This was in conjunction with the fact that trains should stop at predetermined spots and MobAD users would have to board at designated carriages. For example, Participant 35, a design engineer in the rail industry, commented:

> "We have trialled this idea with disability-designated carriages before and it just didn't work with disabled people, as many were adamant it would be discriminatory to stipulate where they should and shouldn't be… Then, this scenario has been labelled as a flexible one, and I am sure that the design intention was such, but in fact it describes a very static system where those extensions are affixed on set locations on platform…I have my reservations that drivers would be able to park by the stops, and even if they did, it would be increasingly difficult to align every train door with the extensions...One should also take into consideration that there are different types of train, with different dooring systems and arrangements…"

Turning now to acceptability of the three design scenarios in relation to existing solutions, data from Table 3 indicated that the majority of participants would select all three scenarios over existing solutions. This is particularly true for Scenario 3, as participants were almost unanimous in the view that it would be more assistive than any of the existing solutions. Participant 9, who frequently uses a rollator, stated:

> "[Scenario 3] would be the ideal solution. It would just make me feel so comfortable and independent compared to the yellow ramps [conventional platform-to-train ramps]."

Participant 32, a powered wheelchair user who works as an accessibility manager in a national rail service, added:

> "It's very probable that such a system [referring to Scenario 3] would outclass the commonly used ramps we see on stations in terms of usability as well as accessibility… The way I see it, this movable ramp would be suitable for both straight and curved platforms, providing independent access for disabled

> people… It could easily bridge gaps in two directions plus no rolling stock modifications would be required."

In summary, the benchmarking analysis revealed a clear preference among participants for Scenario 3 – an extendable and movable platform-to-train ramp – which stood out due to the inclusion of handrails and was ranked as the most accommodating scenario by over three-quarters of participants. Additionally, the data shows that all three proposed scenarios were deemed superior to existing solutions, with near unanimity in favour of Scenario 3 as the most assistive option.

6.3.2.2. Synthesis of design information

To interpret data from individual design exploration sessions (Stage B1 – Question E2, Stage B2) as well as the creative canvas (Stage C), a research-by-design approach was employed as described in the previous section of this chapter (i.e., 6.2.4.2 – Design Analysis). The use of visuals was elemental in undertaking the analysis, which recognised four levels of coding data into information. At first, only annotations were assigned to the individual design scenarios. Next, meaning was given to these annotations via categorical and thematic sorting. Finally, all design scenarios were superimposed to identify patterns and extract meaningful knowledge for the next stage of the design process.

Table 6.6 describes the lower two levels of coded data (i.e., annotations and categories) in this analysis. Due to an abundance of information, only the most cited annotations are included below.

CATEGORIES	MOST CITED ANNOTATIONS
Cost	Equipment/Parts, Construction, Operation, Maintenance
Implementation	Production time, Labour & Technology

Applicability	Platform type (straight/curved), Gap coverage (horizontal, vertical, both), Train Types (low/high deck), Accessibility
Operation	Delay in boarding, Ease of operation, Safety

Table 6.21: Most cited annotations and identified categories - results from research-by-design analysis

Figures 6.20-6.22- illustrate themes identified in the respective design scenarios.

A quintessential part of the annotation-based analysis process was the identification of patterns. These patterns encompassed convergent or divergent themes among scenarios which referred to participants' design preferences based on their personal needs or experiences. The following section presents six patterns extracted from the analysis which encapsulate the entirety of generated knowledge during the design exploration sessions as well as the creative canvas. Figure 6.23 illustrates the identified patterns among the three design scenarios, which are described in the following lines.

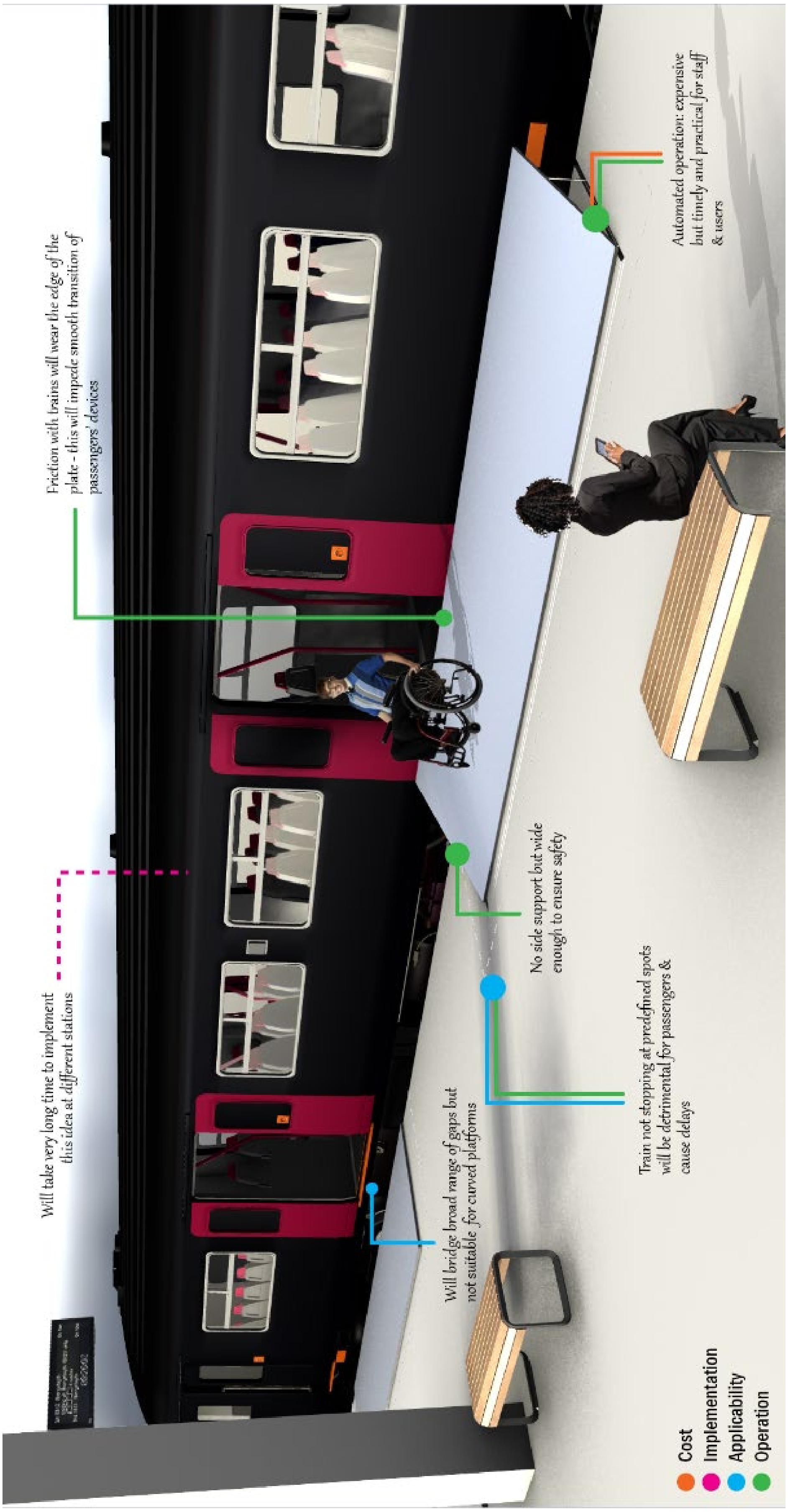


Figure 6.57: Themes identified after analysis of annotations regarding Scenario 1

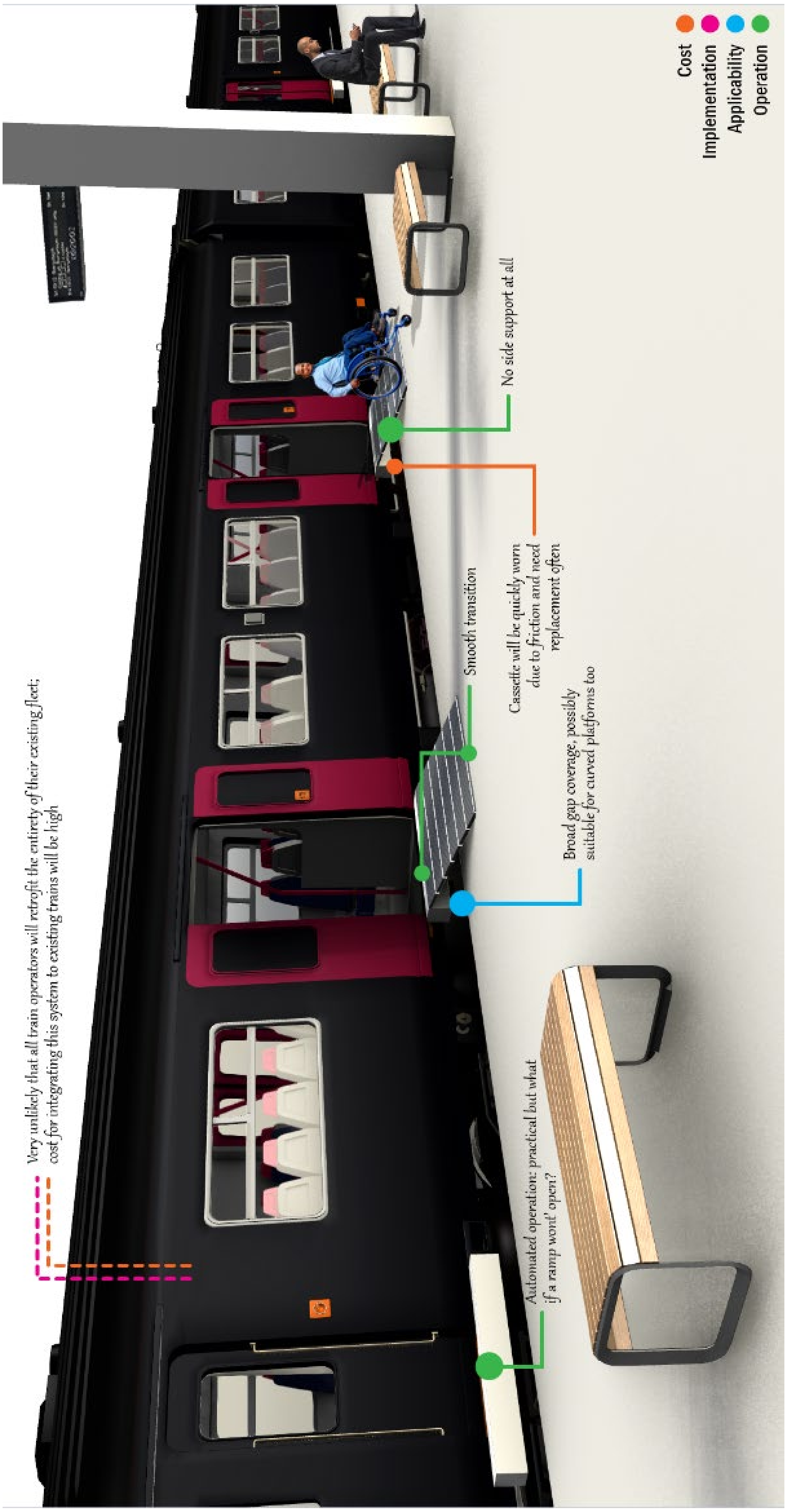


Figure 6.58: Themes identified after analysis of annotations regarding Scenario 2

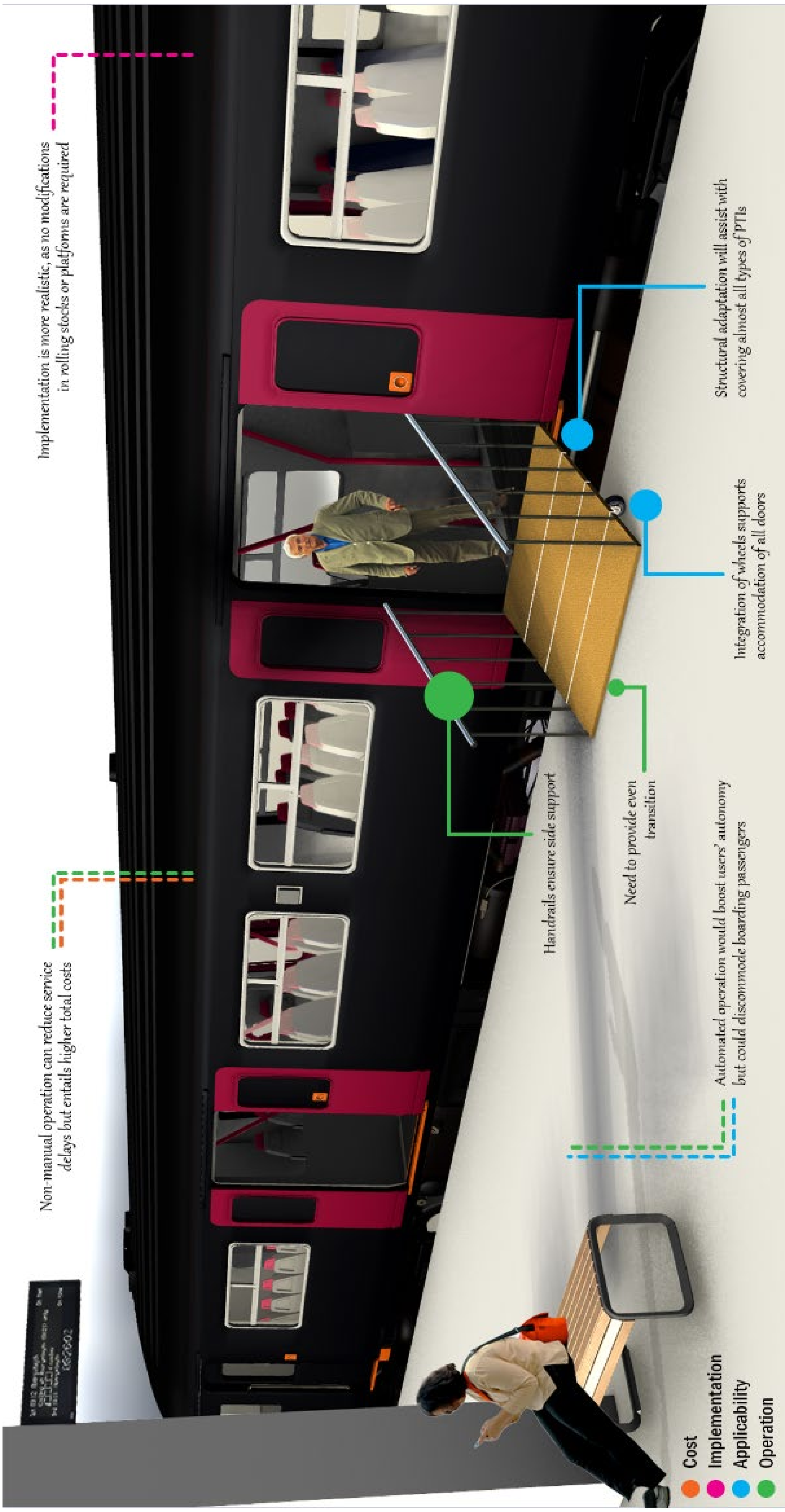


Figure 6.59: Themes identified after analysis of annotations regarding Scenario 3

Figure 6.60: Patterns identified after analysis of themes across all three scenarios

6.3.2.2.1. Ability to function with minimal human intervention

One of the most important findings that emerged from the analysis of whiteboards is that the majority of participants favoured a solution that would have the ability to function with minimal human intervention. Unlike the traditional platform-to-train ramps, all three scenarios referred to solutions that could be set in motion through networks of sensors and actuators. Many participants claimed that automated or semi-automated solutions would boost their functioning independence and feelings of autonomy. On the other hand, it was reported that integration and maintenance of powered systems would increase related costs – i.e., regarding production and operation.

6.3.2.2.2. Ability to accommodate different access points

Accommodation of different access points – namely train doors – was another crucial topic identified in the patterns. The ability to accommodate all or many doors of a parked train was a common feature in Scenarios 2 and 3. This received very positive reviews from workshop participants. Especially in the case of Scenario 3 (i.e., extendable and movable ramp), some participants underlined the role of wheels as an enabler of servicing different access points in a timely manner. However, many MobAD users expressed doubts regarding the applicability of Scenario 1 (i.e., extension plates). Their main concern was potential misalignments of stopping trains to extension plates as well as trains not stopping at the predefined spots. Figure 6.24 presents a participant's whiteboard, where their design questions refer to servicing of different train doors.

Figure 6.61: Emerging patterns - example from participants' boards (1)

6.3.2.2.3. Broad serviceability

All three scenarios referred to solutions that could potentially cover a wide range of PTIs in terms of platforms (i.e., straight and curved), trains (i.e., high- and low-deck), and physical gaps (i.e., vertical and horizontal). For workshop participants, broad serviceability was also a key prerequisite with a view to outlining an applicable solution for bridging PTIs in their whiteboards. Participants' design observations overall indicated that Scenario 3 would cover the broadest range of PTIs while Scenario 1 was found to be rather ineffective with respect to curved platforms. Figure 6.25 depicts a participant's annotated whiteboard, in which they compared Scenarios 2 and 3 in terms of applicability.

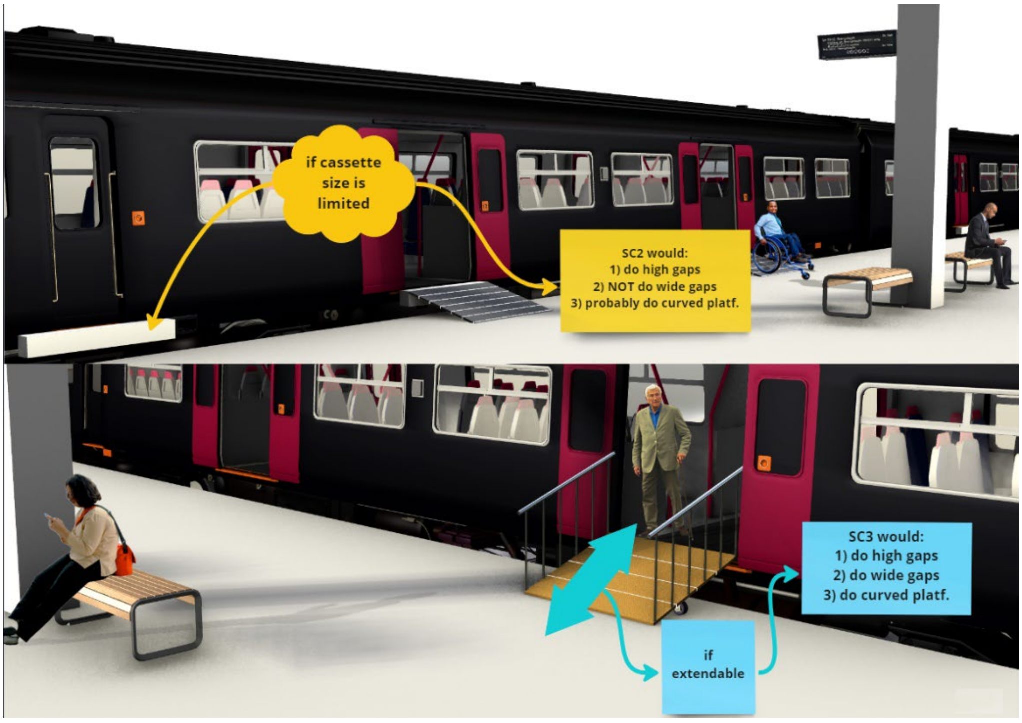


Figure 6.62: Emerging patterns - example from participants' boards (2)

6.3.2.2.4. Side support

Integration of elements to provide side support was of utmost importance to workshop participants. This became particularly noticeable from the subsequent analysis of the co-created whiteboards as participants discussed in groups and collaboratively sketched ideas in a bid to integrate types of side support in Scenarios 1 and 2. An example whiteboard is illustrated in Figure 6.26 below. In this whiteboard, users communicated their ideas on handrail integration in platform extension plates through drawings and text.

6.3.2.2.5. Even transition

In all forms of conversations, even transition from upper- to lower-level surfaces (and vice-versa) was a recurrent topic. Specifically, many participants suggested that all three scenarios were short of elements which could facilitate smooth transition among different levels at PTIs (i.e., platform – bridging solution – train floor). For instance, one participant claimed that it would be very challenging for a certain cohort of MobAD users to negotiate even the slightest of height differences. Taking this into account, they proposed that a transition element (i.e., a threshold plate) should be integrated into the edge of the conceptual platform-to-train ramp (Scenario 3). This proposition is shown in Figure 6.27, which includes an instance of participant's whiteboard.

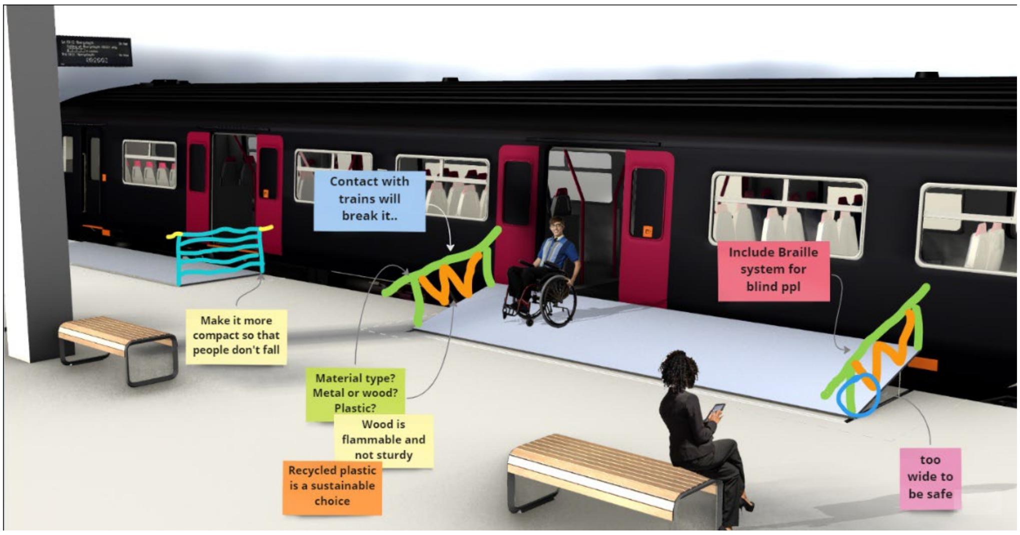


Figure 6.63: Emerging patterns - example from participants' boards (3)

Figure 6.64: Emerging patterns - example from participants' boards (4)

6.3.2.2.6. Stand-alone solution

Lastly, it became evident through the analysis of whiteboards that participants were more inclined to a stand-alone type of solution rather than integrated ones. Concerns regarding integrated solutions, such as platform-fixed and train-embedded bridging systems as visualised in Scenarios 1 and 2 respectively, were more widespread among industry professionals. Modifications of current railway infrastructure or rolling stock were one of the most communicated factors as it would entail excessive amounts of time, cost, and labour to retrofit existing platforms and trains across the UK rail network. Following from this, other participants stated that it would be more advantageous for the PTI solutions to be produced and assembled off-site so that train traffic did not get distorted. As such, MobAD users and industry professionals agreed that a stand-alone solution similar to the one proposed in Scenario 3 would better meet their expectations.

6.4. Discussion

This study set out to explore user experiences and expert insights regarding the design problem (i.e., PTIs). A second objective was to ideate design solutions which would satisfy user requirements together with MobAD users and professionals. Both study objectives were designed to concur with Objective 2 – Engage with MobAD users (RO2) of this overall research, as defined in Chapter 1.3. To address the study objectives and realise RO2, a mix of previously employed as well as newly introduced methods for data collection and analysis was utilised. The core part of this study was materialised through a series of co-design workshop sessions. The current study found that conventional platform-to-door ramps cause a great deal of difficulty to workshop participants who would prefer to use a ramp with different design characteristics and operation arrangements.

6.4.1. Results-based insights

A significant finding of this study is that physical gaps between train and platforms as well as conventional ramps impacted different quality-of-life aspects of MobAD users – namely autonomy, safety, and social participation. This finding corroborates conclusions of the systematic review which was analysed in Chapter 3 in the sense that non-accessible conditions in a PTI context are likely to increase inequalities and social exclusion of MobAD users.

A strong relationship between physical accessibility and MobAD users' quality of life has also been reported in the literature. Steinfeld et al. (2010) indicated that several physical elements within allowable accessibility standards impede the independent functioning of a large percentage of MobAD users. Findings from Bastiaanssen et al. (2020) and El-Geneidy et al. (2016) suggested that inaccessible transport infrastructure could prompt a deficit in education and employment opportunities for MobAD users when compared to non-disabled individuals. Evidence from other studies has shown that access barriers in the built environment propel health inequalities for MobAD users (Edwards et al., 2020; Iezzoni et al., 2015). In general, the results from this study align with a substantial body of research indicating that inaccessible environments diminish the quality of life for disabled individuals. Given that physical gaps between trains and platforms as well as traditional bridging solutions – for instance, conventional ramps – were found to be inaccessible and not preferred by MobAD users, it is imperative that transport planners and urban designers acknowledge these findings and implement more effective solutions.

Another important topic that emerged from the analysis of interview data is the heterogeneity of PTIs that exist across the UK. This is consistent with previous findings (see Chapter 5 – Design Problem) which indicated a wide variation in physical gaps between trains and platforms nationwide. The reported differences in existing train and platform characteristics probably explain participants' inclination for a standalone solution as described in Scenario 3, which would adapt to a wide range of PTIs and service more access points.

Perhaps the most compelling outcome of this study is the participant-led identification of six design qualities which could delineate an efficient solution to satisfy MobAD users' needs at PTIs. These characteristics were mentioned by a vast majority of workshop participants and will guide subsequent stages of the design process as those are described in the next chapters. Table 6.7 includes a list with the most critical design qualities, according to workshop participants. These findings will be of interest to human factors and railway infrastructure engineers, rolling stock and spatial designers, and policymakers at Rail Safety and Standards Board (RSSB) or National Rail.

Ability to function with minimal human intervention
Ability to accommodate different access points
Broad serviceability
Side support
Even transition
Standalone solution

Table 6.22: Preferred design qualities, according to workshop participants

6.4.2. Methodological strengths

To collect participant data, an integrative approach was employed which combined interviews and digital whiteboarding techniques. While this combination is quite common within the field of design studies – see for example the work by Winschiers-Theophilus et al. (2021) – there is a notable paucity of empirical research utilising asynchronous methods to garner design data. A key advantage of asynchronous group activities is that group members are flexible to access activity materials from any Internet-connected place at a time of their convenience (Mayadas, 2019). In the case of MobAD users, this was of particular value as it allowed mobility-impaired individuals from different contexts to participate in the study without requiring any transfers. Many of the workshop participants claimed that the ability to access the canvas and add design input at any time increased their creativity and eagerness to participate. It was also reported that this procedural flexibility allowed workshop participants to spend more time brainstorming and analysing design aspects within different scenarios. Considering that the creative canvas was essentially a reciprocal interface, participants had more time to reflect upon co-participants' whiteboards and respond to their comments without any interruptions. Consequently, this study has shown that the innate flexibility of asynchronous methods is likely to stimulate community engagement and facilitate the co-design process.

Further benefits of using asynchronous methods in co-design processes derive from their highly interactive nature (Shea et al., 2019). Relevant literature has claimed that using interactive techniques in design is very likely to promote democratic values (de la Pena et al., 2017). As participants engaged in different forms of design conversations (i.e., one-to-one, one-to-many, and many-to-many) over the canvas contents, they established impromptu systems to communicate with each other and further the design dialogue in a civilised frame. For example, some participants created an informal set of rules to ensure that the design conversation would be conducted in an egalitarian and well-organised manner. Figure 6.28 illustrates this set of rules, as those were introduced and later updated by some workshop participants in the Miro whiteboarding environment. These participant-oriented initiatives may be taken as representative examples of a democratic design process, which has been structured from the bottom up.

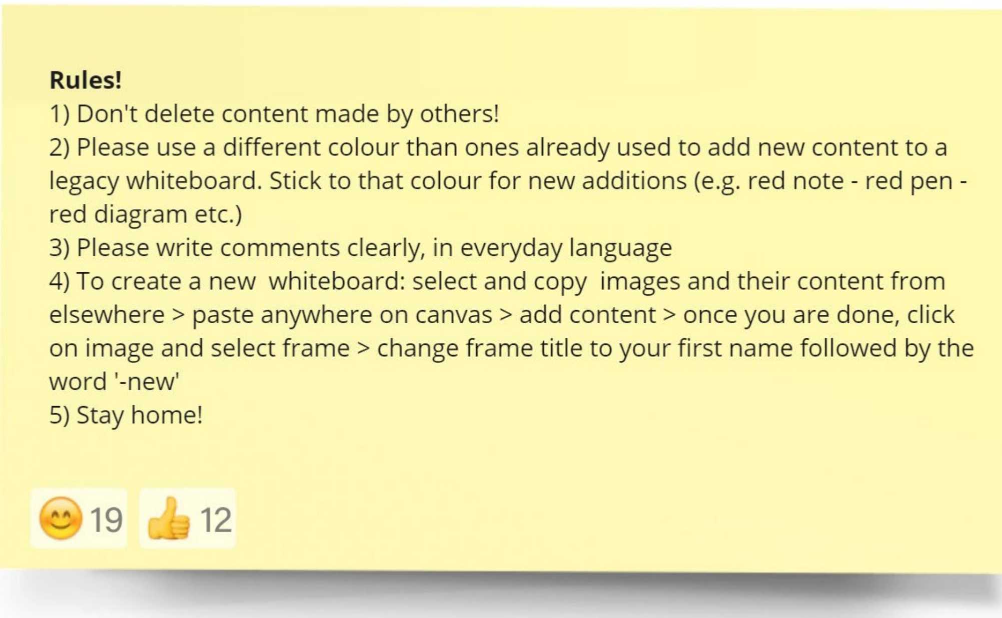


Figure 6.65: Participant-established list of rules for co-creation

The novel approach followed in Stage 3 may have methodological implications for the emerging field of design crowdsourcing, which involves a large group of distributed participants contributing or producing ideas about certain design problems (Grace et al., 2015). Recent advancements in digital infrastructure, such as whiteboarding applications and cloud computing, have facilitated online crowdsourcing platforms such as CadCrowd. Likewise, the Miro online whiteboard tool was utilised to set up a rough platform for design crowdsourcing to retrieve ideas from MobAD users and professionals. A possible advantage of this method is that design researchers would be able to collect a wide variety of new ideas over a certain design problem, notwithstanding time and space limitations. At this point, it is important to underline that the investigator of this study did not participate in the activities of the creative canvas (Stage 3). It is generally acknowledged that this practice should eliminate bias in the data collection stage of similar research efforts (Pannucci & Wilkins, 2010).

Most importantly, the approach followed in Stage 3 is one of the first examples of a citizen-moderated co-design process with respect to the fields of industrial and spatial design (Vlachaki, 2020). Workshop participants were given almost absolute control over the design process for a cumulative period of three months. That said, the design conversation remarkably evolved as the participant-led interactions that took place in canvas engendered more than 50 augmented or child whiteboards (see Figure 6.16), which comprised valuable feedback on presented scenarios or new design ideas. In many cases, participants' knowledge steered the design process as most of the workshop participants were experienced users of MobAD or trained professionals. Specifically, participants handled complex design characteristics and contributed multi-faceted proposals in a bid to resolve the given problem, thus acting as research partners. This might resonate with the notion of citizen science which suggests that members of the community can engage in scientific studies in collaboration with or under the guidance of researchers to assist with various research activities (Gura, 2013; Kullenberg & Kasperowski, 2016; Vohland et al., 2021). Considering all the above, the creative canvas can serve as an example case for future studies that intend to adopt bottom-up strategies to crowdsource design ideas.

This work presented a model for visual analysis of whiteboard contents, offering a novel understanding of utilising annotations for data analysis. The adopted approach structured the development of visuals from the outset, linking the analysis to specific design elements and utilising graphic design software (e.g., Adobe Photoshop) to clarify data through layered annotations. This method produced comprehensive and interactive results by categorising similar annotations and identifying patterns. Unlike Sauerwein et al. (2018), who based their analysis on interview transcripts, this study primarily relied on participant-generated visual input from creative canvases, minimising interpretation bias. Consequently, annotated drawing-blocks provide a robust foundation for future studies involving visual data analysis, particularly when data is directly created by participants, thereby reducing the risk of misinterpretation and researcher bias.

6.4.3. Study limitations and critical appraisal

Despite the methodological strengths and novelties described above, the study is characterised by several limitations, particularly concerning Stage C – Creative Canvas. A significant limitation of this stage is the potential for dominant voices to overshadow the contributions of other participants, exacerbated by the on-demand nature of the board and the lack of tracking participant contributions. This can lead to biased outcomes, with more vocal individuals disproportionately influencing the co-creation process, while quieter participants may feel sidelined. Additionally, without a system to attribute ideas accurately, it becomes challenging to ensure a diverse and balanced representation of perspectives. To mitigate these issues, future co-creation sessions could implement structured turn-taking and moderated discussions, ensuring all participants have equal opportunities to contribute.

Furthermore, integrating a system that logs edits and comments would help track participant engagement and maintain a fair representation of ideas. This approach would promote inclusivity and balance, reducing the risk of bias and ensuring that the final outcomes reflect a broad spectrum of contributions.

The asynchronous nature of Stage C's co-creation activity presents limitations in fostering real-time interaction and dynamic idea development. Participants may miss out on the benefits of immediate feedback and collaborative brainstorming, which are crucial for developing and refining concepts effectively. This lack of synchronous engagement can result in a fragmented and less cohesive design process. To enhance the quality of co-creation, future studies should consider incorporating synchronous sessions alongside asynchronous activities. Scheduled real-time workshops or virtual meetings can facilitate direct interaction, enabling participants to engage in more dynamic and responsive collaboration. This hybrid approach would combine the flexibility of asynchronous participation with the immediacy and depth of synchronous co-creation, leading to richer and more integrated design outcomes.

The absence of predefined rules or topic guides in Stage C can lead to a lack of focus and consistency in the co-design activity. Without clear guidelines, participants might diverge from the intended objectives, resulting in varied and potentially unfocused contributions. This open-ended approach can also hinder the alignment of efforts towards common goals, reducing the effectiveness of the co-design process. Establishing clear guidelines and objectives at the outset is crucial for providing structure and direction. Future co-creation sessions should implement a well-defined framework that outlines the scope, goals, and expectations of the activity. Providing participants with a topic guide and structured tasks can help maintain focus, ensure alignment with research objectives, and facilitate more cohesive and relevant contributions.

Relying on a digital platform like Miro for co-creation activity may inadvertently exclude individuals who are less familiar with technology or lack access to the necessary devices and internet connectivity. This digital divide can limit the diversity of participants, skewing the findings and reducing the inclusivity of the study. Participants who face technological barriers might struggle to engage fully with the platform, leading to underrepresented perspectives. To address this limitation, future studies should provide alternative methods of participation, such as offline workshops or hybrid models that combine digital and in-person engagement. Additionally, offering training sessions and technical support can help participants navigate the digital tools more effectively. Ensuring that all participants have access to the necessary resources and support will promote inclusivity, broaden the range of contributions, and enhance the overall quality of the co-creation process.

B4. Bridge section: transitioning from collaborative ideation to data-driven design development

The findings from Chapter 6 highlight the importance of user-centred design in addressing the challenges faced by MobAD users at PTIs. The co-design workshops revealed significant difficulties associated with conventional platform-to-door ramps, underscoring the need for innovative design solutions that align with the preferences and requirements of the users. A key outcome from these workshops was the identification of six essential design qualities, which have been deemed critical by the participants. These qualities serve as a foundation for the next phase of the design process, providing clear guidelines to ensure that the final design solutions are both practical and user-friendly.

Chapter 7 builds directly on the insights and participant feedback from the co-design workshops. With a focus on developing an adaptable and movable ramp, as indicated by MobAD users' preferences, this chapter delves into the use of computational design methods to enhance the design process. By drawing inspiration from precedent projects and utilising advanced technologies, the aim is to create solutions that not only meet the functional requirements identified in Chapter 6 but also incorporate the innovative characteristics desired by the users. This approach ensures that the design development remains grounded in user experience while leveraging modern tools to optimise results.

The comprehensive approach in Chapter 7 integrates AI techniques to gather inspiration from existing projects, providing a rich source of innovative and user-centric design ideas. These design ideas are then optimised through advanced computational methodologies, ensuring that the final solutions are refined to meet the specific needs and preferences of MobAD users. This process aligns with the research objective of enhancing accessibility at PTIs and integrates the practical insights gained from user engagement, thereby ensuring that the resulting designs are both effective and user-approved.

7. Development of possible design solutions through utilising advanced computational methods

As described in Chapter 6, the unanimous decision of the MobAD users and experts was to develop an adaptable and movable type of ramp as the most suitable solution to bridge physical gaps between trains and platforms. This chapter explores how adopting a mix of computational design methods can streamline the design process by drawing inspiration from precedents as well as better align design outcomes with users' needs and preferences collected previously.

7.1. Purpose

The purpose of this section of work is dual. Firstly, the chapter focuses on gathering inspiration from precedent projects to inform the creation process (Stage A). Next, the chapter explores the design optimisation of possible solutions for addressing the physical gap between trains and platforms (Stage B). The current chapter looks to address research objective 3 (RO3) with respect to developing solutions to enhance accessibility at critical points within the built environment using modern design techniques and advanced technologies.

7.2. Methods

In alignment with the dual objectives of this chapter, the design development process is divided into two consecutive stages: Stage A and Stage B. Stage A employs machine learning techniques and evolutionary algorithms to derive design inspiration from precedent projects. Building upon the insights gained in Stage A, Stage B leverages advanced computational design methodologies to optimise potential PTI solutions, as those retrieved from precedent projects in Stage A.

To gather design inspiration from similar objects or patents, various resources and databases were explored in Stage A. This process was challenging due to the lack of labels on most drawings, which hindered keyword filtering for relevant selections. Additionally, these drawings were indexed by categories such as area (e.g. open spaces, streets, interiors) or type (e.g. chairs, ramps, pavilions), which facilitated quick searches and marketing but did not support identifying projects based on design parameters like geometries or topologies. For example, using text queries such as “a ramp with handrails” or “a portable ramp” in design and patent databases yielded limited results. It proved difficult to find relevant projects based on attributes or schematic representations using textual prompts.

Given the ineffectiveness of text-based searches, a visual-based search strategy was considered, specifically an AI-mediated content-based image retrieval (CBIR) system. This system would accelerate the information-gathering process by using concept drawings of possible solutions for PTIs created by the author to find similar drawings in large databases based on visual similarity rather than text-based queries. Consequently, a CBIR system was developed (Figure 7.1) to: (a) receive input drawings of ramps, (b) search extensive design drawing databases, (c) compare input drawings with database drawings without requiring textual information, and (d) return the most visually similar database drawings. The following section outlines the novel CBIR approach, which employs AI tools to enhance the design inspiration process.

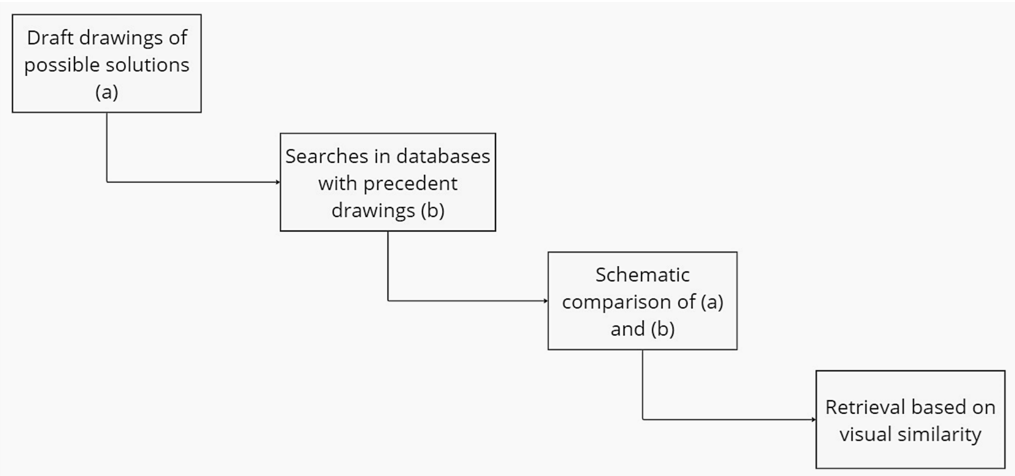


Figure 7.66: Workflow for retrieval of drawings

Stage B builds on the findings of Stage A. Specifically, the retrieved drawings from Stage A are transformed into a suitable format for further analysis and manipulation. A filtering process then occurs to ensure that the selected models meet the required spatial accessibility and functionality criteria based on Universal Design guidelines and standards (Chapter 2), the design problem environment (Chapter 5), and MobAD users' preferences (Chapter 6). This warrants that only suitable designs are carried forward into the final stages of the design development process. The fittest design matching as much as possible the established criteria will be qualified as the final solution to the PTI problem. The following lines describe Stages A and B in a more detailed way.

7.2.1. Stage A – content-based image retrieval (CBIR): system description

Drawings from an external database were analysed using a custom-made deep convolutional autoencoder (CAE), a type of AI model that extracts important features (i.e., image characteristics like colour, patterns, and spatial relationships) from each drawing. These extracted features were stored as vectors or sets of numbered patterns in a reference library.

Next, interactive evolutionary algorithms (IEA), which are a subset of evolutionary algorithms, generated another set of drawings. These drawings represented a variety of basic ramp-type solutions forms as prospective solutions for PTIs. The generation process of these new drawings was regulated by the author and based on geometric and design characteristics of existing PTI solutions as well as conceptual ones – i.e. Scenario 3 from co-design workshops as the most preferred solution among workshop participants (Chapter 6.3.2.1). This step was implemented in a CAD environment using the Rhino3D software and Grasshopper 3D, which functions as Rhino's visual programming interface. Namely, the Biomorpher tool (Harding 2018) was utilised. Biomorpher employs IEA to allow users to create and evolve numerous designs based on performance parameters (e.g. structural, functional, or geometric criteria) and interactively explore previous or new solutions until they select the most suitable one.

The new drawings generated through Biomorpher were submitted as queries to the CAE, which extracted their feature vectors. A similarity metric called k-Nearest Neighbours (kNN), an AI method for finding similar items, was then used to compare the feature vectors of the query drawings with those in the reference library. The vectors in the reference library that most closely match the query drawing vectors were identified. The corresponding reference drawings were then retrieved and displayed. This process was repeated for all the query drawings. In the end, the reference drawings with the highest similarity scores were selected for the optimisation stage. Figure 7.2 visualises the process described above.

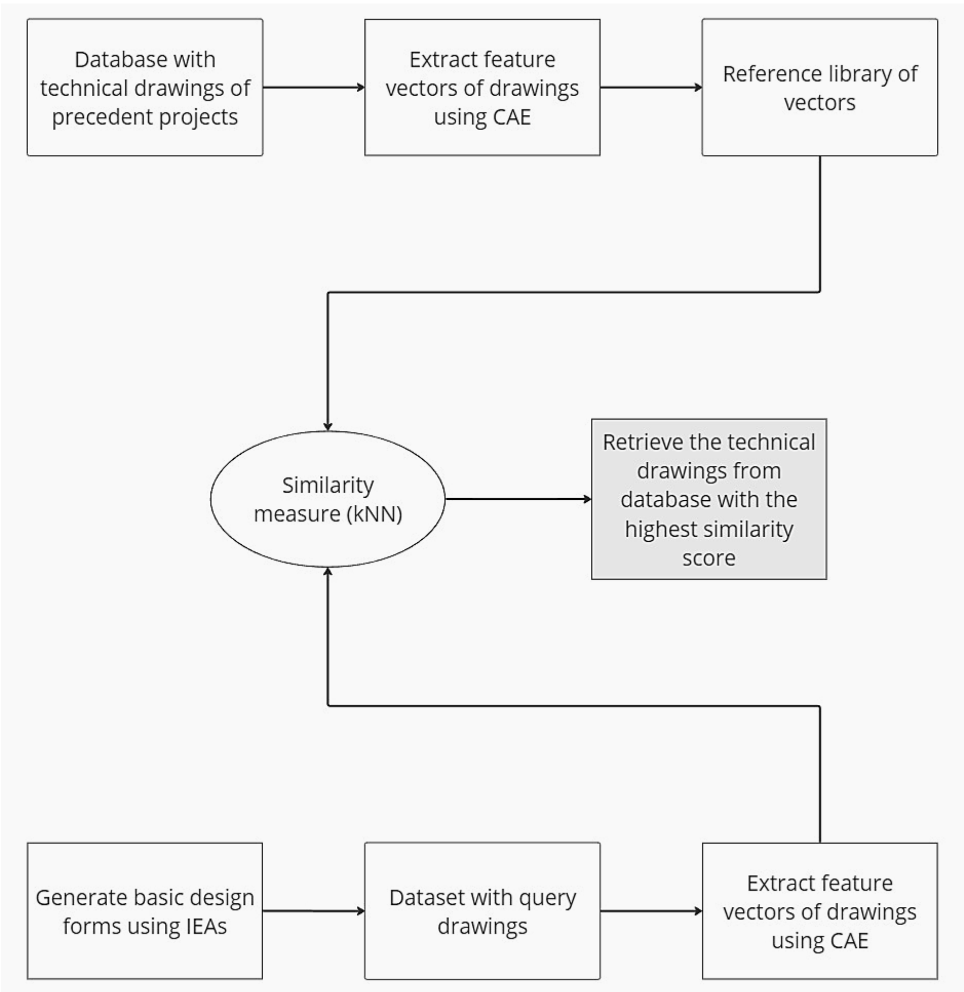


Figure 7.67: Design of the CBIR system

This work includes a comprehensive description of the CAE and IEA/Biomorpher architectures as well as other components of the workflow presented in Figure 7.2. Due to the highly technical nature of it, this part has moved to the Appendix (A.4) section of this thesis, in an effort to maintain cohesion of the research narrative.

7.2.2. Stage B – design optimisation: workflow description

To arrive at an optimised solution that integrates spatial constraints, functional characteristics of the universal MobAD user, and user design preferences, a workflow consisting of three main parts has been developed: (a) conversion of the reference drawings with the highest similarity scores as emerged from Stage A – CBIR into 3D models, (b) contextualisation of reference models into a digital design environment, and (c) evolutionary optimisation of the reference models based on functional, spatial, and aesthetic criteria. Figure 7.3 illustrates the developed workflow and main tools used. The following lines describe the various steps depicted in Figure 7.3 in greater detail.

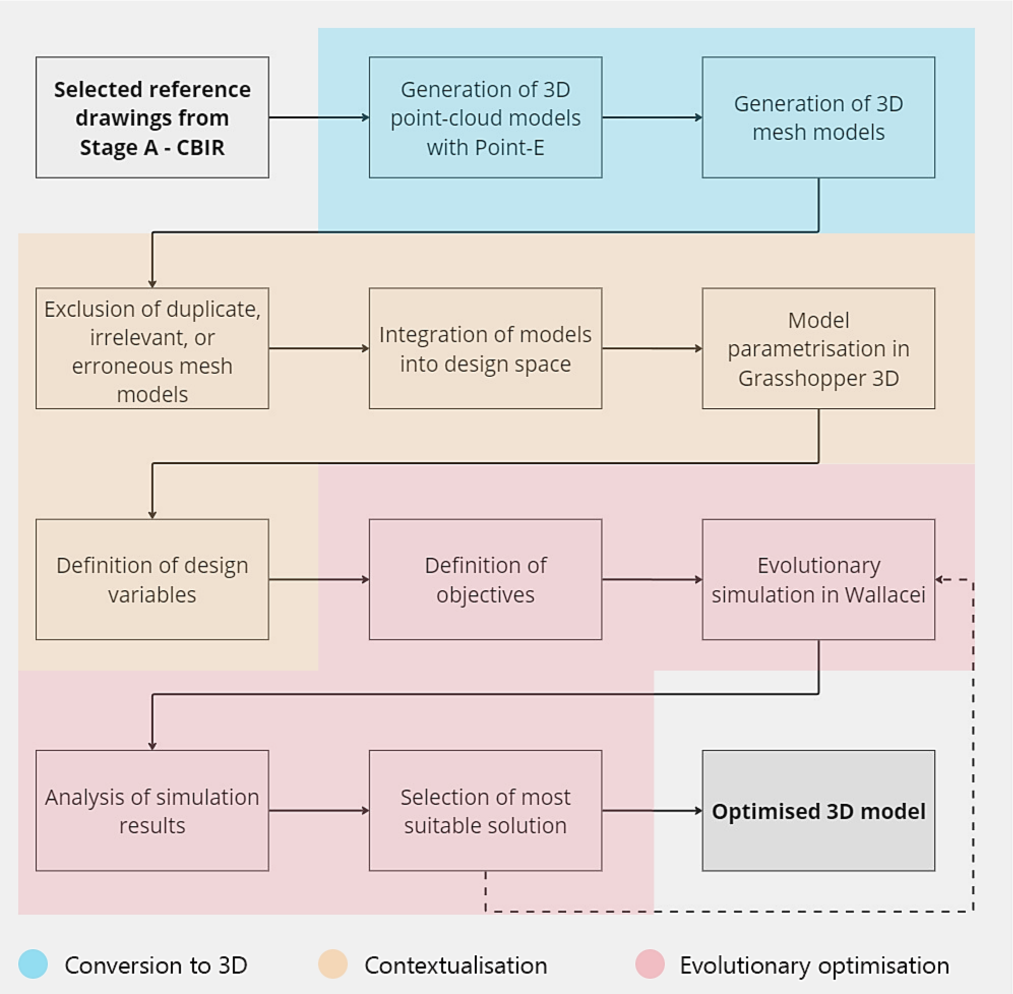


Figure 7.68: Design optimisation workflow

a) Conversion of reference drawings into 3D models

The initial step involved vectorising multiple two-dimensional (2D) raster representations into three-dimensional (3D) forms. Given the taxing and time-consuming nature of this task, a pre-trained deep learning system Point-E (Nichol et al. 2022) was employed to synthesise 3D models from 2D images. This system processed 2D images through multiple deep neural networks and returned a “point-cloud” form which was then converted into a 3D mesh model of the imported image. The developed code for this implementation is available on GitHub, and this process was repeated for all reference drawings with high similarity scores, as derived from Stage A – CBIR.

b) Contextualisation of reference models

The second step involved the integration of the reference models into the investigated design environment in a BIM/CAD software. Here, both the design problem space (i.e. platform-train interface) and the reference models were simulated in 3D forms. Duplicates and erroneous interpretations of the input forms were removed, retaining only the 3D models that most accurately reconstructed the input form according to the users’ feedback of the design ideation stage (Chapter 6.4.1). Specifically, ramp or ramp-type models lacking handrails or non-flexible objects were excluded as these were identified as desirable design features based on MobAD users and experts.

To accurately translate the design environment (i.e. spatial constraints and user functioning requirements) into manipulable 3D forms, a programming script was developed to determine optimal ramp width and length based on various design criteria. These criteria include platform characteristics (width, length, vertical and horizontal distance from rail tracks), train footstep characteristics (vertical and horizontal distance from the platform edge), and user requirements (slope negotiation and clear width). Rhino 3D

(McNeel 2023) and its integrated Grasshopper 3D visual-scripting tool, as well as the Python programming language, were utilised for this process.

For integrating platform and train characteristics, UK Rail Safety Standards Board (RSSB 2019; RSSB 2020) and EU (EU 2014) regulations were consulted as detailed in Chapter 6. Functional characteristics of different MobAD users were incorporated using IDeA design resources for creating universal environments (D'Souza et al. 2011; D'Souza et al. 2020; Lenker et al. 2016) as introduced in Chapter 2.1.1. Table 7.1 summarises the script variables based on these resources. The developed Grasshopper script is available on GitHub.

This script dynamically generated and visualised various possible PTI arrangements, accommodating spatial constraints, user requirements, and design criteria, thus enabling comprehensive exploration of potential solutions and identification of the most effective designs tailored to MobAD users.

The remaining reference models were also imported into a CAD/BIM environment (i.e. Rhino 3D) for further refinement and parametrisation within a Grasshopper environment. This entailed translating the topological properties of the modelled objects (e.g. dimensions, compactness, connectedness) into mathematical variables that can be adjusted via number sliders or Boolean toggles to control the object's behaviour or appearance. This parametrisation allowed the models to respond to changing requirements or constraints and facilitated easy iteration and exploration of design options. This step was crucial for integrating the 3D model into the design space and aligning it with design variables (i.e. MobAD users' functioning requirements and spatial constraints) as seen in Table 7.1, upon which the optimisation process will be implemented.

DESIGN VARIABLE	VALUE RANGE	SOURCE
Platform		
Width	≥ 2.5m	(RSSB, 2020)
Length	4 – 6m	(RSSB, 2020)
Vertical distance (height) from rail track	890 – 915mm	(RSSB, 2020)
Horizontal distance (offset) from rail track	730 – 745mm	(RSSB, 2020)
Train footstep		
Vertical distance from platform edge (height gap)	≤ 460mm	(RSSB, 2019); (EU, 2014)
Horizontal distance from platform edge (width gap)	≤ 470mm	(RSSB, 2019); (EU, 2014)
Universal MobAD user		
Functional side reach (for handrails)	650 – 1250mm	(D'Souza et al., 2011)
Clear ramp width	≥ 837mm	(D'Souza et al., 2011)
Negotiable slope	≤ 7.5°	(D'Souza et al., 2011); (Lenker et al., 2016)

Table 7.23: Variables used in developed script according to literature guidelines and regulations. For the universal MobAD user, the given thresholds represent the most extreme functioning limitations to cover a wide range of users' abilities.

c) <u>Evolutionary optimisation</u>

Once the design variables were defined, the next step involved establishing clear objectives for the optimisation. Objectives could include criteria such as minimising width between train and platform or maximising access slope. These objectives were the criteria for guiding the optimisation process and provided a basis for evaluating the effectiveness of different design solutions.

Reference models and objectives were then inputted into Wallacei (Makki et al. 2022), an evolutionary simulation engine integrated within the Grasshopper environment. Wallacei uses evolutionary algorithms to explore a wide range of possible design solutions. By iteratively adjusting the design variables, the simulation seeks to identify solutions that best meet the defined objectives. This process involved generating multiple design iterations, each evaluated against the objectives to determine its fitness.

After the evolutionary simulation is completed, the results were analysed to assess how well each design solution meets the objectives. This analysis involved comparing the performance of different iterations based on the defined criteria. The goal was to identify the most promising solutions that achieve a balance between competing objectives.

Based on the analysis of simulation results, the most suitable solution was selected. This involved choosing the design iteration that best met the objectives. The selection process might consider trade-offs between different objectives to ensure the chosen solution is optimal in the context of the overall project goals. This process could loop back to the evolutionary simulation stage for further iterations. This was to refine and improve the design until the most suitable and optimised 3D model was achieved – a design that would be systematically enhanced to meet the users' needs and spatial constraints effectively.

This work includes a comprehensive description of the Point-E and Wallacei tools as well as other components of the workflow presented in Figure 7.3. Due to the highly technical nature of it, this part has moved to the Appendix (A.5) section of this thesis, in an effort to maintain cohesion of the research narrative.

7.3. Results

This section is divided into two parts. The first part presents results in relation to drawing inspiration from precedent projects using the content-based image system (Stage A). The second part analyses the design optimisation process (Stage B).

7.3.1. Getting design inspiration from precedents using a CBIR system

Upon developing the CBIR system, it was utilised to identify similar drawings of precedent projects to garner inspiration prior to the design formation stage. Initially, the Biomorpher plug-in was employed to generate multiple alternative forms of a preliminary design (i.e. a generic ramp object) that had been previously created. This approach enabled the CBIR system to recognise different variations of ramp patterns and subsequently identify numerous precedent drawings across various databases. Ultimately, the CBIR system returned schematically similar drawings of precedent projects.

7.3.1.1. Building the data sources

To construct the reference database, precedent projects were compiled from the following public collections: Archello, Architectural Drawing Guide, Architizer Library, RIBApix Collection, and USPTO Patent Database. An initial screening was applied to include only items referring to architectural or industrial drawings in greyscale. The included drawings presented objects in plan, elevation, cross-section, and axonometric views. In total, over 100,000 drawings were included.

For the query dataset, a basic ramp-type form was initially created in Rhinoceros 3D. It was then parametrised in Grasshopper 3D and a visual script was developed to express and manipulate its topological parameters. The analysed parameters were: (a) ramp width, (b) ramp length, (c) count of ramp sections, (d) arrangement of ramp sections (vertical/horizontal), (e) height of handrails, and (f) shape of handrails. The visual script and initial design form (phenotype) are illustrated in Figure 7.4 and Figure 7.5.

The next step involved the evolutionary exploration of various design alternatives in Biomorpher. Using Biomorpher, multiple forms were generated, allowing for interactive selection and further evolution of the most suitable genotypes.

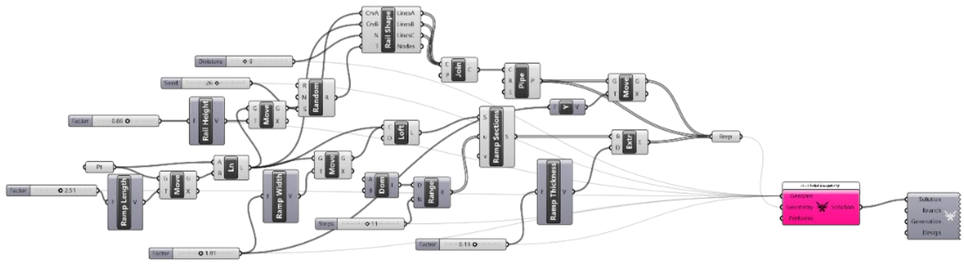


Figure 7.69: Design algorithm for generation of query dataset

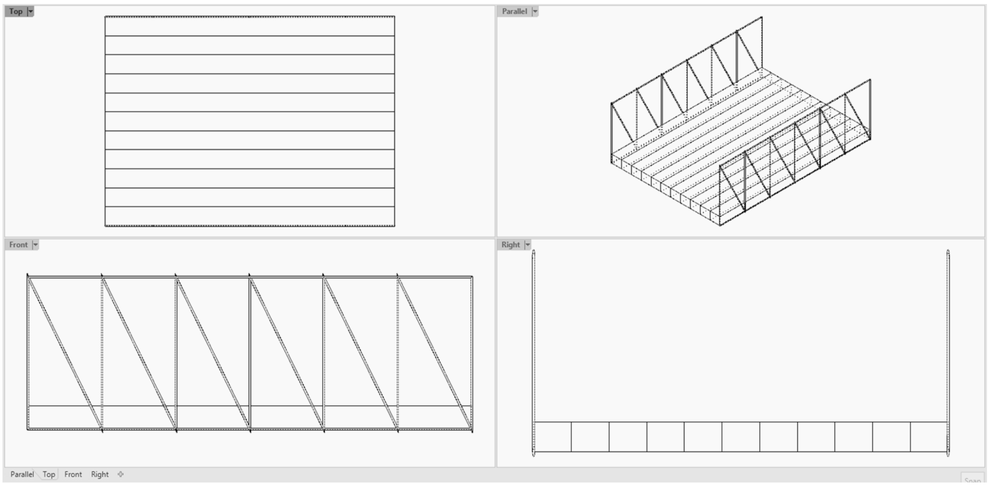


Figure 7.70: Initial design form (phenotype) for generation of query drawings

Beginning with the phenotype illustrated in Figure 7.5 above, hundreds of query drawings were generated. Biomorpher automatically adjusted the given genomes, combined them, and returned numerous genotype designs. Figure 7.6 below presents initial settings and K-means clusters of the first generation (Generation 0). The clusters tab visualises the entire population and how it has been grouped into 12 different clusters. Each design is displayed as a dot, and since it would become overwhelming to show the actual geometry of each, the total number of dots corresponds to the population size. Each cluster contains at least one dot, but the number varies from cluster to cluster (depending on how closely related the designs are). The ordering of the clusters i.e., the relation between, them has no meaning. However, within each cluster it is possible to determine the dot (design) that is closest to the centroid, and this is referred to as the representative design. In other words, this is the design that best represents all the designs within its cluster. The representative design is the dot at the centre and the distances to the other dots represent the normalised euclidean distances between them. Representative designs of all twelve clusters are shown in Figure 7.7.

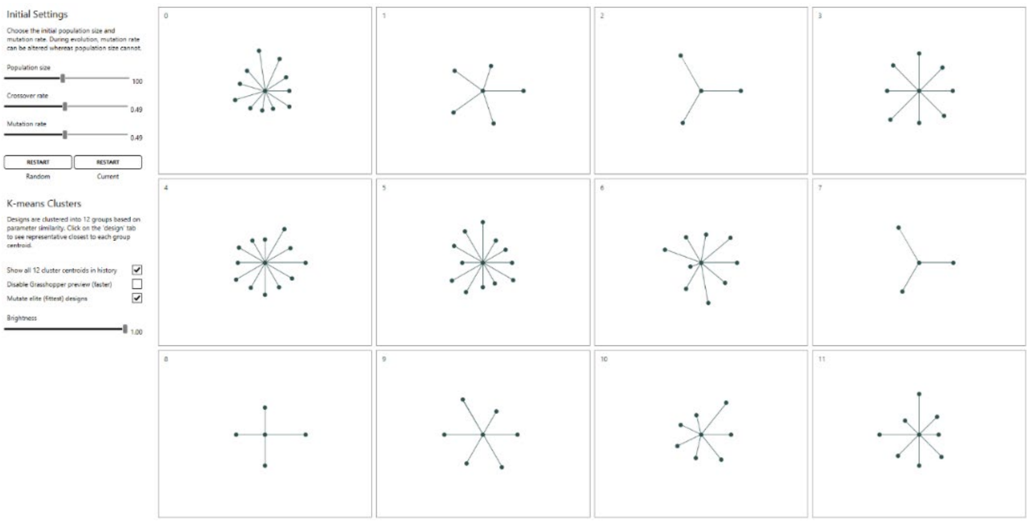


Figure 7.71: Query dataset - Generation 0, K-means clusters

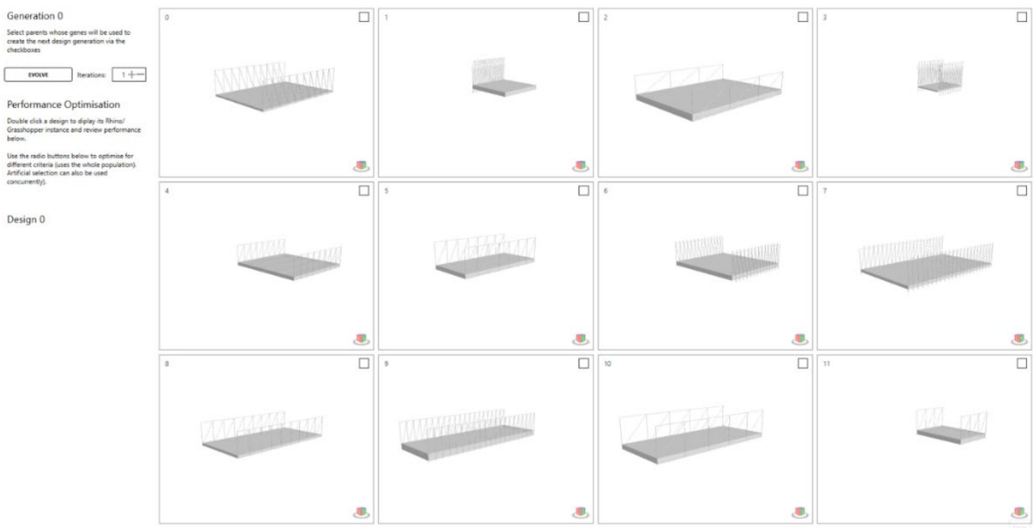


Figure 7.72: Query dataset - Generation 0, representative design forms

Since the research focus of this effort has been on exploring design alternatives rather than optimising those, the evolutionary process was driven by visual/aesthetic criteria instead of performance measurements. For this reason, performance criteria (such as minimum-maximum genome values) were omitted in the analysis, and the evolutionary process would continue until a satisfactory design was selected. In many cases, this was achieved by further evolving one or more of the previously generated designs. Taking on from the example presented in Figure 7.7, four designs from the initial generation were selected, as illustrated in Figure 7.8, and further evolved those. Figure 7.9 presents the design outcomes of the new generation (Generation 1).

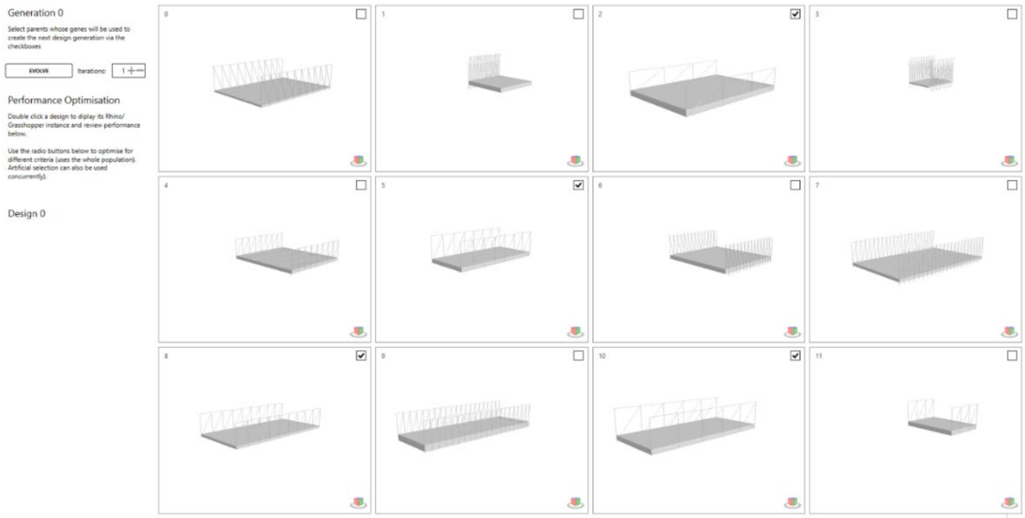


Figure 7.73: Query dataset - Generation 0, selected designs for further exploration

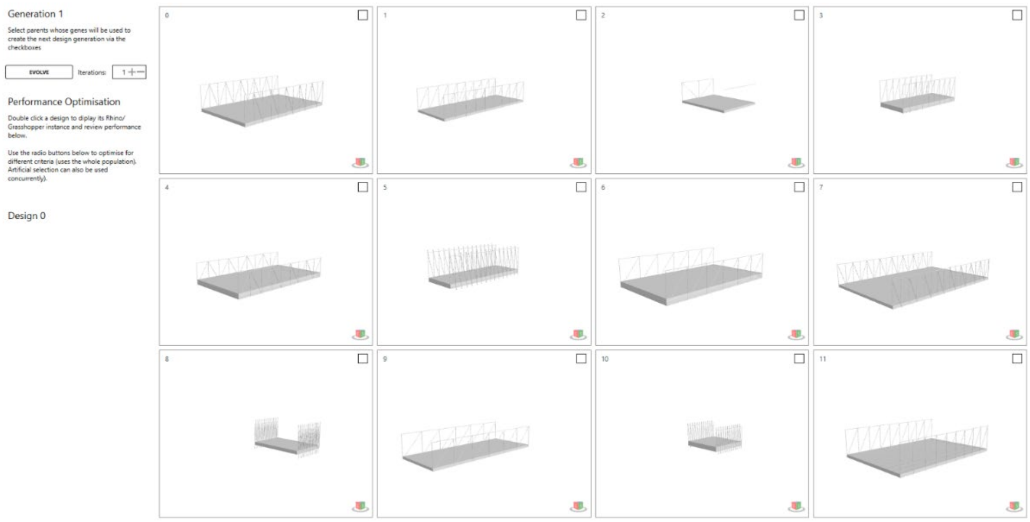


Figure 7.74: Query dataset - Generation 1, representative design forms

Next, different views of the selected designs were exported – namely, top, left, right, and isometric views – to black-and-white drawings. Each drawing was formatted to 512*512 pixels (width*length) in terms of resolution. Figure 7.10 presents an example of different views for a selected design.

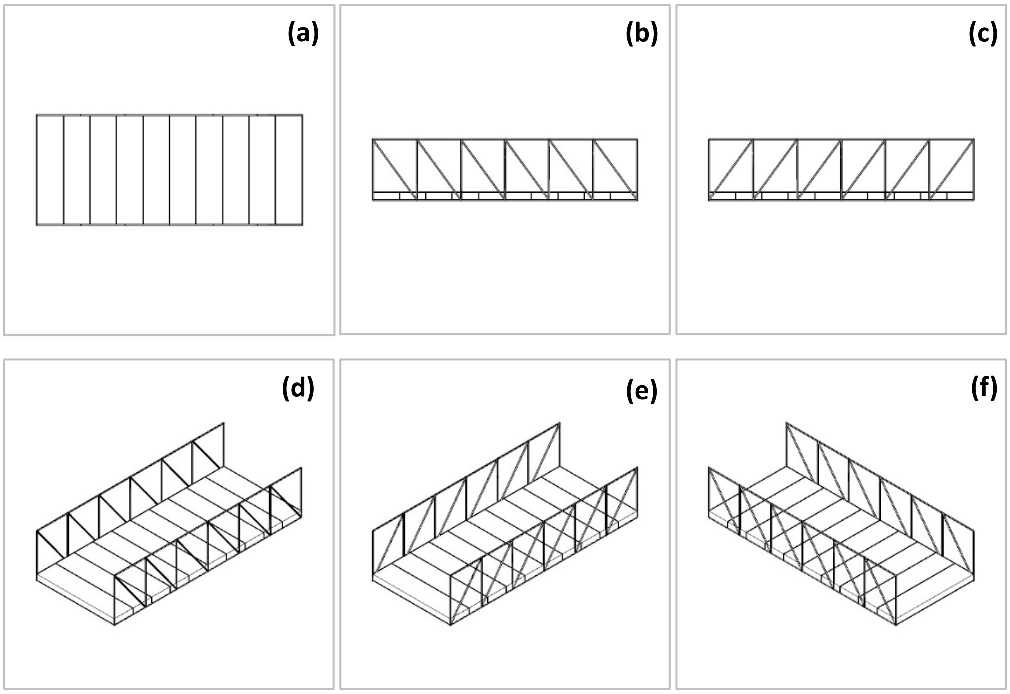


Figure 7.75: Query dataset, an example drawing in different views

Overall, 20 generations were performed, which returned a total of 1356 drawings. In every generation, genotype solutions that did not represent ramp-type objects were omitted. This filtering process dropped the number drawings to 1125. Those drawings comprised the ***query dataset***, against which drawings from the reference databases were sought.

7.3.1.2. Image retrieval

As the next step, all the drawings from the reference databases (i.e., over 100,000 images) were imported into the CAE. This process enabled the extraction of vectors of latent features for every image included in the reference databases, thus building the ***reference library***.

Next, all 1125 generated images from the query dataset were imported into the constructed CBIR system. The system browsed over 100,000 drawings from the reference database. For each image in the query dataset, the system returned the 2, 3, 5, or 7 most similar drawings (i.e., k=2, k=3, k=5, or k=7 closest cases, using the KNN algorithm) from the reference database. After filtering all 7875 retrieved drawings, 7839 cases were omitted as irrelevant for the purposes of this research, according to specific exclusion criteria. These cases were excluded because they referred to (a) duplicate drawings (n=6013), (b) non-ramp type objects (n=1162), or (c) representations from which no meaningful analogies could be drawn to a prospective solution (n=664).In the end 36 drawings were selected for further topological and functional exploration in advance of the design formation stage, a sample of which are presented in Figure 7.11. All 36 drawings are publicly accessible at GitHub.

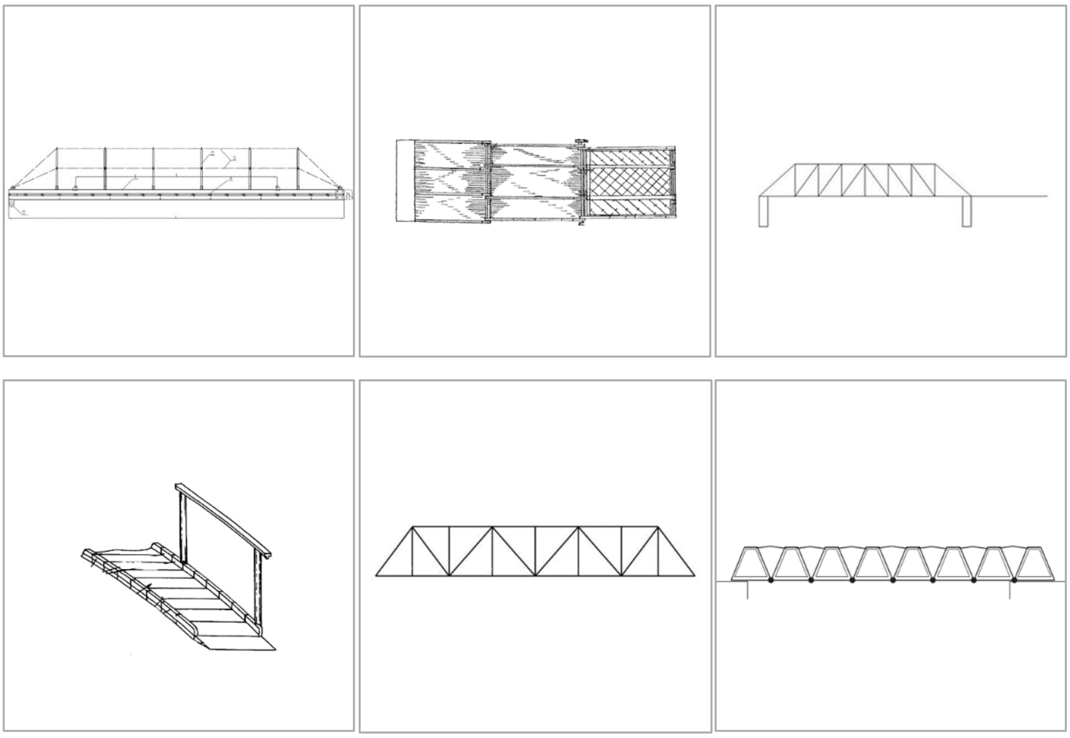


Figure 7.76: A sample of the drawings selected for further design exploration.

7.3.2. Multi-objective design optimisation of selected solutions

In the previous section (Chapter 7.3.1), thirty-six drawings of precedent projects were identified, which could serve as inspiring references for a potential design solution to the research problem. Chapter 7.2.2 presented a data-driven workflow, which is capable of integrating user data and precedent design knowledge with a view to arriving at an optimised solution. The following lines present outcomes of the application of this workflow with a view to developing a design solution that matches MobAD users' needs and preferences in an optimal manner.

7.3.2.1. Design environment

In Rhino 3D, the script previously developed in Grasshopper 3D (Chapter 7.2.2) was imported to visualise the design environment. This process outputted the platform train interface space and a placeholder for the ramp solution. Figure 7.12 portrays the design environment in Rhino 3D.

The script – visualised in Figure 7.13 – also provides a comparative resource for estimating the optimal width and length of the ramp for different PTIs and deployment angles. That is, the user can enter specific PTI characteristics (i.e., distance between train and platform in width and height) and choose from accessible deployment angles (according to BS Standards, angle < 10°). The script then returns the optimal ramp width and length for the given conditions, which can be visualised in a Rhino viewport.

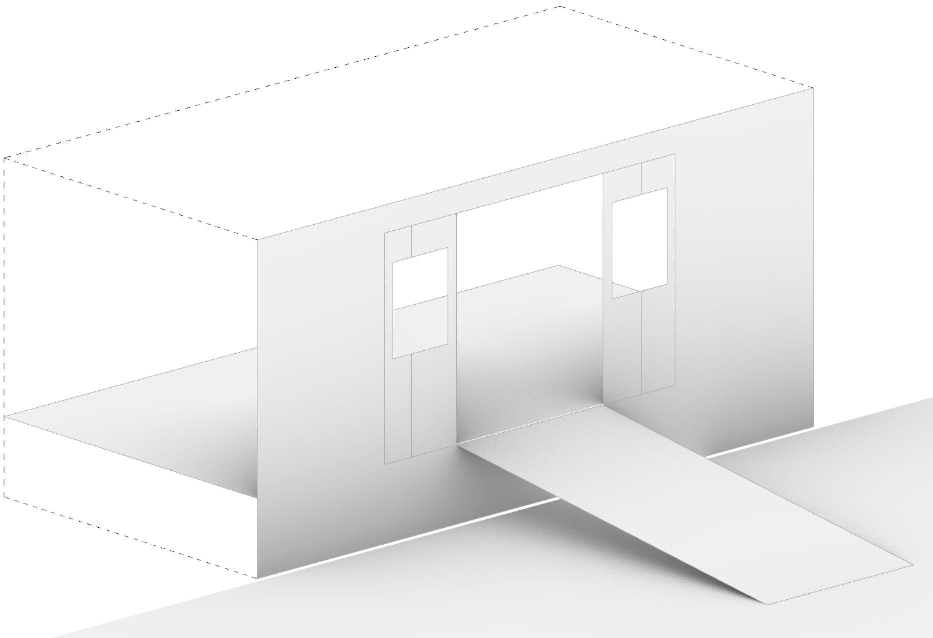


Figure 7.77: Design environment in a Rhino 3D interface

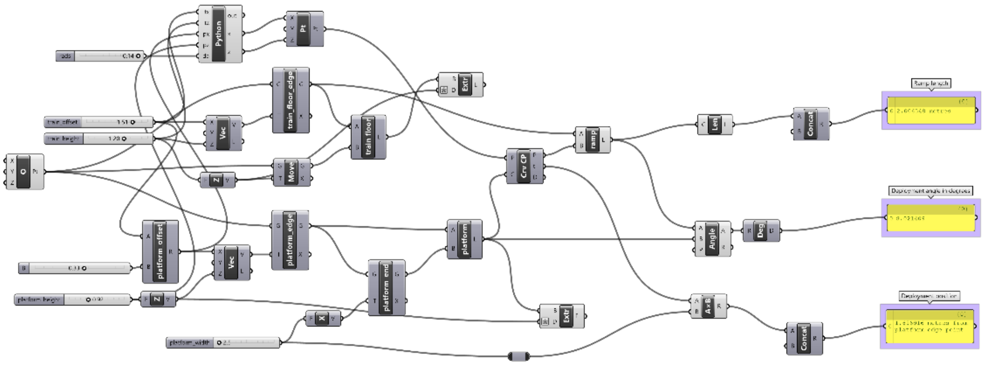


Figure 7.78: Grasshopper script for returning optimal ramp width and length at various PTIs

7.3.2.2. Generation of 3D models

To generate 3D models, the 36 reference images containing drawings from precedent projects were inserted into the Point-E system. Ten iterations were run for each image using the 1B base model, on which Point-E had been trained (see section A.5.2. of the Appendix). For each iteration, Point-E models produced a pair of outputs consisting of a 3D-like point-cloud model and a 3D mesh model. In total, the system produced 360 pairs. Figure 7.14 provides an example set of outputs from this process.

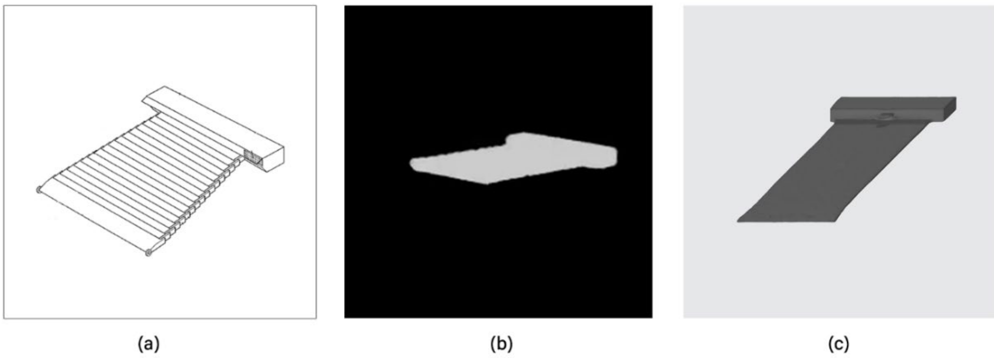


Figure 7.79: An example from the 3D model generation process - a precedent drawing (a) is fed into Point-E, which produces a point-cloud model (b) and a 3D mesh model (c).

Overall, the outputs indicated that the Point-E system frequently generates coherent and superior quality 3D mesh models in response to intricate images, such as technical drawings. However, the point cloud generation occasionally encountered difficulties in comprehending or extrapolating the conditional image, culminating in a shape that diverges from the initial drawing.

7.3.2.3. Contextualisation of 3D models

After removing duplicates—i.e. two or more generated 3D objects that referred to the same 2D drawing—and eliminating erroneous interpretations of the input forms (e.g. severely deformed 3D representations), 3D objects that were incongruous with user preferences – as formulated in the co-design workshops (Chapter 6.4.1) – were also omitted. Specifically, ramp or ramp-type models that lacked handrails or were associated with non-adaptable and non-standalone objects were excluded as these qualities were identified as desirable design features based on user feedback. As such, the final models qualified for further exploration were those illustrated in Figures 7.15a -7.18a, with each one corresponding to a different reference project (Figure 7.15b-7.18b).

A common characteristic of these projects was their high degree of structural adaptability, as all four drawings represent ramp-type structure that can physically change their form to maximise their functionality. For example, the set presented in Figure 7.15 visualises a loading ramp structure, which is constructed out of a plurality of relatively small and rectangular links that are joined end to end to form a span of any desired length. The way these links are joined together allows the span to be rolled up for storage when it is not in use. Also, the last set (Figure 7.18) illustrates a retractable footbridge comprised of eight segments that can simultaneously lift, causing the bridge to curl until the ends touch to form a perfect circle, when the bridge is not used by pedestrians.

Another feature that all four objects share is the presence of handrails. Integration of a type of side support, such as handrails, was amongst the top priorities for MobAD users who participated in the design ideation workshops. Handrails ensure that a person using the ramp has additional support in their effort to negotiate the sloped surface, especially if this develops in higher gradients than anticipated.

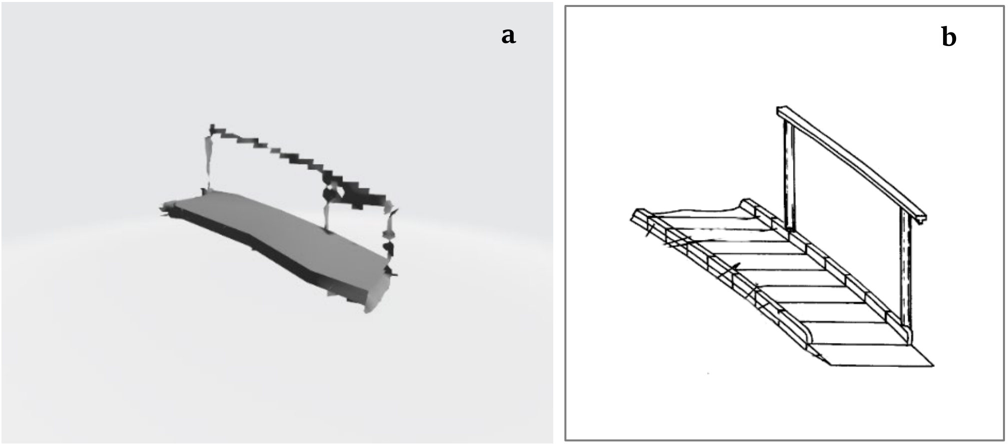


Figure 7.80: a) qualified model for further exploration; (b) source project: rollable ramp device - patent number US 6643878

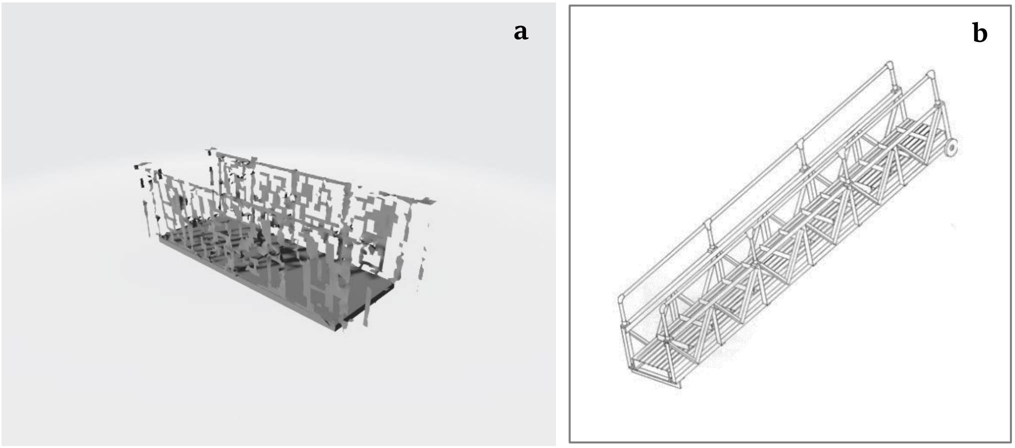


Figure 7.81: (a) qualified model for further exploration; (b) source project: sliding gangway ladder, PW Platforms Inc.

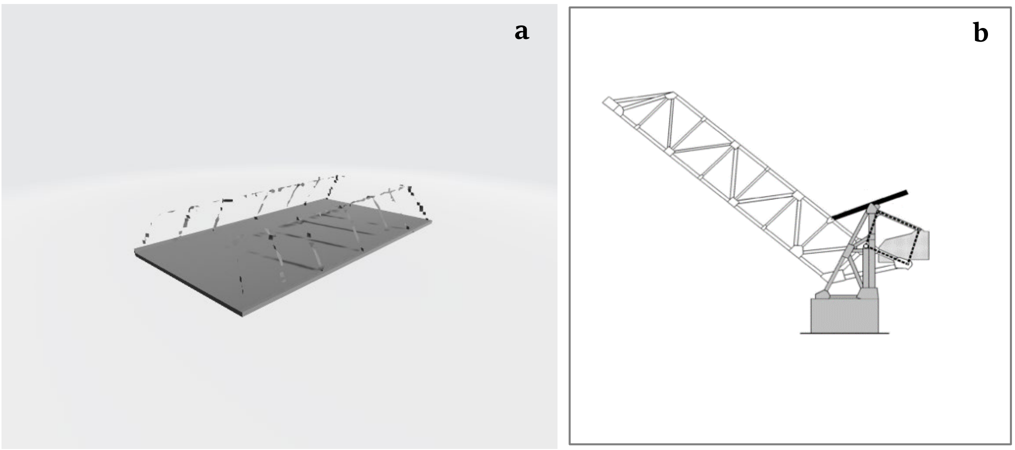


Figure 7.82: (a) qualified model for further exploration; (b) source project: Kinzie Street railroad bridge

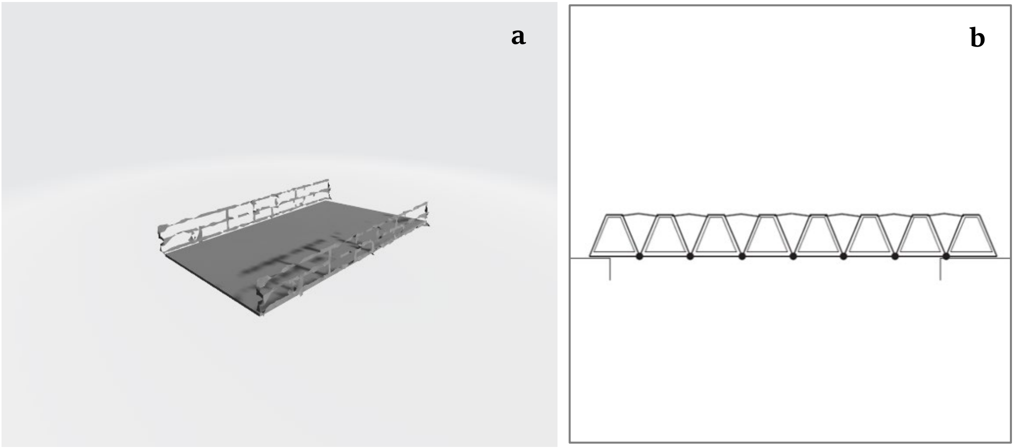


Figure 7.83: (a) qualified model for further exploration; (b) source project: curling footbridge by Heatherwick Studio

It is obvious from Figure 7.15-7.18 that a common challenge for all four 3D objects was the disintegration of meshes. That is, the constituent meshes were produced in a semi-refined way, and thereby they appeared either slightly deformed or disjoint or perforated. This is because Point-E cannot capture fine-grained details (e.g., complex shapes or textures), which are commonly found in engineering imagery or drawings. Using Rhino's "Repair Mesh" command, the meshes were refined and all holes filled, ensuring that the 3D objects almost precisely represented the initial 2D drawings. Another issue concerned the parametrisation of the mesh objects, as meshes are innately difficult to parametrise, and subsequently link to local design factors (e.g., user needs and spatial constraints). For this reason, a small script was written to convert meshes into surface boundary representations (i.e., Brep) in Grasshopper, as surfaces are easier to manipulate. Figure 7.19 depicts the developed script in a Grasshopper viewport.

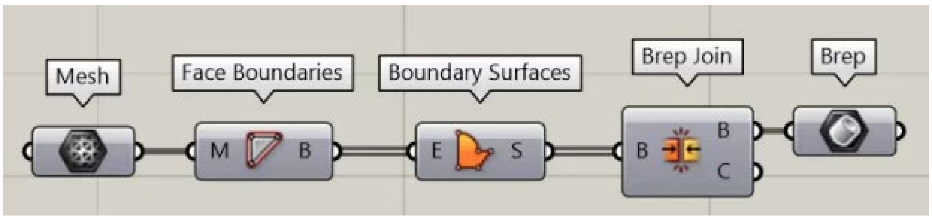


Figure 7.84: A script for converting mesh objects to Brep.

As an example, Figure 7.20 presents a refined version of the mesh model illustrated in Figure 7.18a, after the deployment of the "Mesh Repair" command in Rhino and conversion into Brep in Grasshopper.

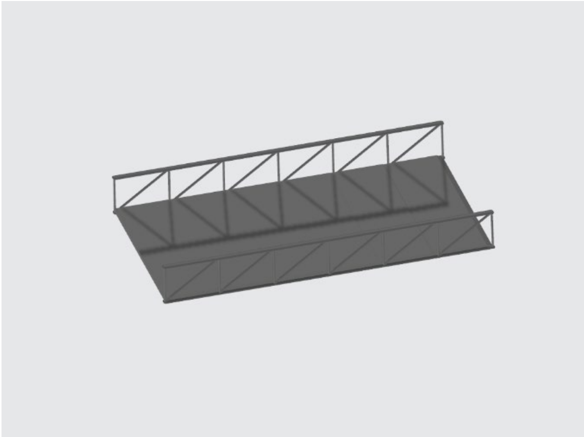


Figure 7.85: A refined version of 3D model illustrated in Figure 9.8a

Once the conversion from meshes to surfaces was completed, the 3D objects were integrated into the design problem space. This was achieved using the previously developed script (see Chapter 7.2.2), which returns the optimal ramp width and length based on various design criteria that influence the design environment, namely platform characteristics (i.e., width, length, height, and distance from rail tracks), train step characteristics (i.e., height, distance from rail tracks), and user requirements (i.e., accessibility gradient). However, the developed script does not take into account some other crucial design criteria, such as handrail integration and positioning, ramp movement, and structural deployment of the ramp.

7.3.2.4. Design optimisation and evolutionary simulation

Since the proposed solution is intended to be structurally adaptable, movable, and responsive to user requirements, the Wallacei evolutionary engine was therefore utilised to complement the script operation and incorporate the missing criteria into the form-finding process for the prospective solution. The design intention was to optimise the design of a ramp to accommodate various gaps across the UK rail network, considering the diverse characteristics of trains and platforms as well as user functioning characteristics. It is important to mention that the functioning characteristics of MobAD users were identified in validated design resources (D’Souza et al. 2011; D’Souza et al. 2020; Lenker et al. 2011).

Each of the four objects was linked to Wallacei as distinct phenotypes, and separate simulations and analyses were carried out for each one. The same genes and fitness objectives were inputted for all simulations, as described in Table 7.2. The genes referred to design characteristics defining the ramp form, as well as train steps and platforms. The fitness objectives represented design criteria or user requirements (e.g., maximal access gradient) that needed to be fulfilled. Gene and objective values were retrieved from the Grasshopper script, as described in Table 7.1. In total, 12 genes and 4 fitness objectives were fed into the engine; Table 7.2 provides an outline of the genes and fitness objectives used. To illustrate the optimisation process, the following lines demonstrate the outcomes of the evolutionary simulation conducted for one of the ramp-type objects (Figure 7.20). Figure 7.21 portrays the genes (design variables) in the design environment.

Genes	Fitness objectives (FO)
▪ **Platform width (P_W)** ▪ **Platform length (P_L)** ▪ **Platform offset from rail tracks (P_O)** ▪ **Platform height (P_H)** ▪ **Train footstep vertical difference (T_V)** ▪ **Train footstep horizontal difference (T_H)** ▪ **Ramp length (R_L)** ▪ **Ramp width (R_W)** ▪ **Ramp sections count (R_S)** ▪ **Handrail type (truss) (H_T)** ▪ **Handrail height (H_H)** ▪ **Deployment angle (D_A)**	▪ FO1: minimise deployment angle (angle (deg.) $\leq 7.5^o$) ▪ FO2: maximise ramp width (length $\leq$ 1.0 m) ▪ FO3: maximise handrail height (0.70m $\leq$ handrail height $\leq$ 0.90m) ▪ FO4: minimise ramp length (length $\leq$ 2.5m)

Table 7.24: Genes and fitness objectives for optimisation through the Wallacei engine

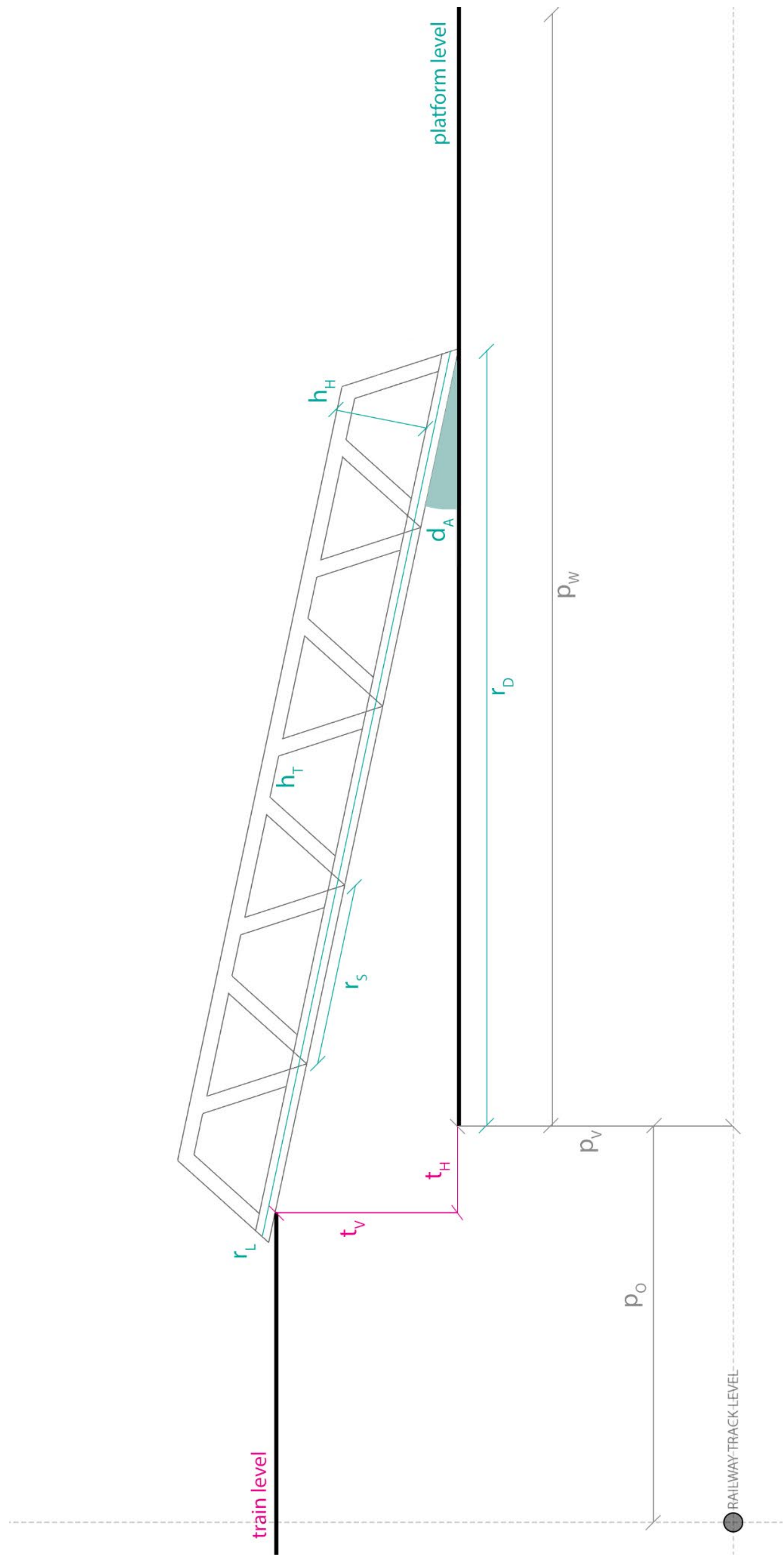


Figure 7.86: Genes (design variables) inside the design environment

In this task, crossover probability was set at 0.9, mutation probability at 1/n - where n is the number of variables in the design problem (Deb et al. 2002), mutation distribution index at 10, and crossover distribution index at 20. Given the topological range of the evaluated geometries comprising the phenotype, the simulation time per iteration varied substantially, averaged at 32sec in my computing system. Three optimization runs in Wallacei assisted in optimising the process by looking at the following graphs (Makki et al., 2022):

- *"Standard Deviation (SD) Graph: The SD curves are plotted for each generation separately from the first (red) to the last (blue). They represent the distribution of the values from the mean. A low SD factor indicates less variation within the population., while a high SD factor indicates more variation.*
- *Mean Trendline Chart: The mean trendline chart presents the mean fitness value for each fitness objective independently for each generation across the entire simulation from start to finish.*
- *Fitness Values (FV) Chart**:** The FV chart analyses the FVs for each FO independently across the entire population. The aim is to visualize how the solutions are performing in relation to one another."*

The population size was optimised in two separate runs, taking into account the duration of the simulation, the standard deviation trend, and the fitness values. In the first run, a population of 1000, 20 generations, and 50 generation counts resulted in a simulation time of 8 hours and 50 minutes. The second run featured a 200-member population, 10 generations, and 20 generation counts, which reduced the simulation time to 2 hours and 9 minutes. Figure 7.22 illustrates the Parallel Coordinate Plots for both runs, which analyse each solution in the population by comparing their fitness values across all fitness objectives (FOs), with red representing the first and blue the last.

A consistent pattern emerges for FO1, FO2, and FO3, where stability was achieved after the sixth generation. However, FO4 (ramp length) displayed no discernible pattern and varies throughout the generations. The best fit values for FO1 (deployment angle), FO2 (ramp width), and FO3 (handrail height) exhibited an absolute difference of 0.6, 0.04, and 0.03, respectively.

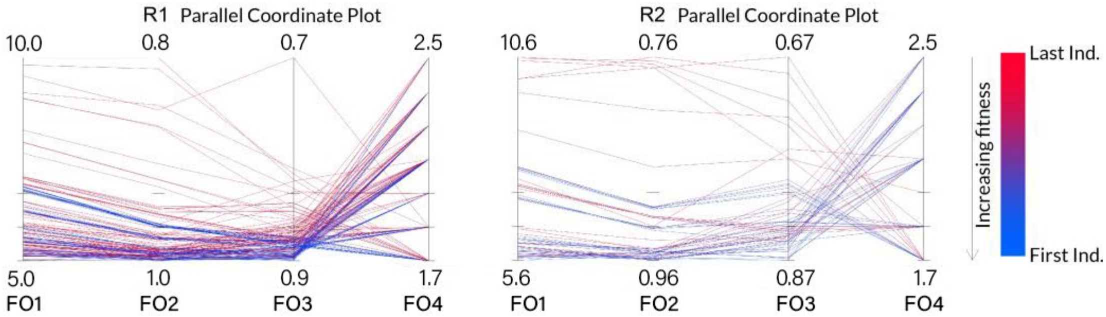


Figure 7.87: Parallel Coordinate Plot for run 1 (R1) and run 2 (R2)

The second experiment focused on optimising fitness objectives (FOs) and determining their priority. A third run followed, which was identical to the second one but excluded FO4 to assess the impact of deployment angle. Fitness values were monitored, and their performance is documented in Figure 7.23 (second run) and Figure 7.24 (third run). The average trendlines for FO1, FO2, and FO3 indicated enhanced stability after the second generation and improved fitness values (5.9, 0.92, and 0.85). The last 74 solutions featured geometries with the maximum lengths, implying that largest shapes do not negatively influence the results; however, this would not be preferred due to spatial restrictions in station arrangements.

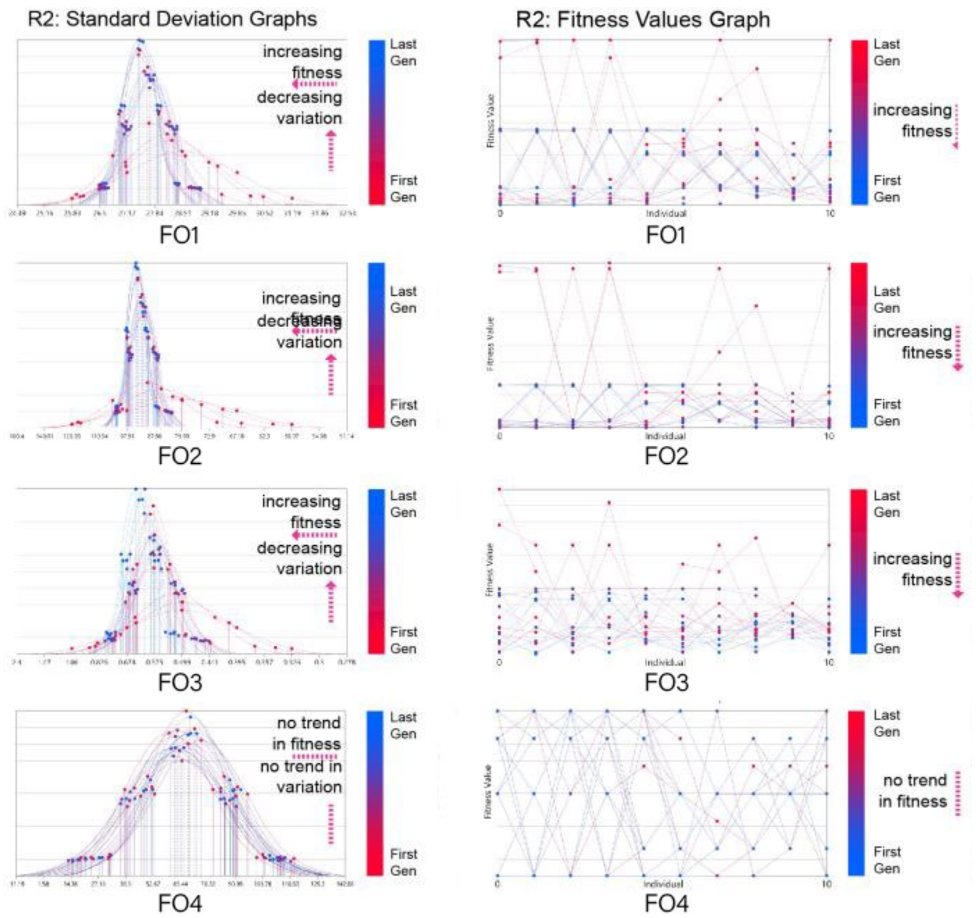


Figure 7.88: Graphs for fitness values in second run (R2)

The second run was further analysed as it is time-efficient, accurate, and employs the deployment angle criterion to regulate excessive lengths. The objectives were prioritised in the following order: deployment angle (FO1) and ramp width (FO2) received the highest priority, handrail height (FO3) was secondary, and the ramp length (FO4) was the lowest indicator for selecting the solution to be validated.

Six design solutions were chosen for further examination using Wallacei selection analysis methods, including the best-ranked solutions for FO1, FO2, and FO3, the solution with the best relative difference between fitness ranks, the solution representing the average fitness ranks, and the best average solution from the last generation.

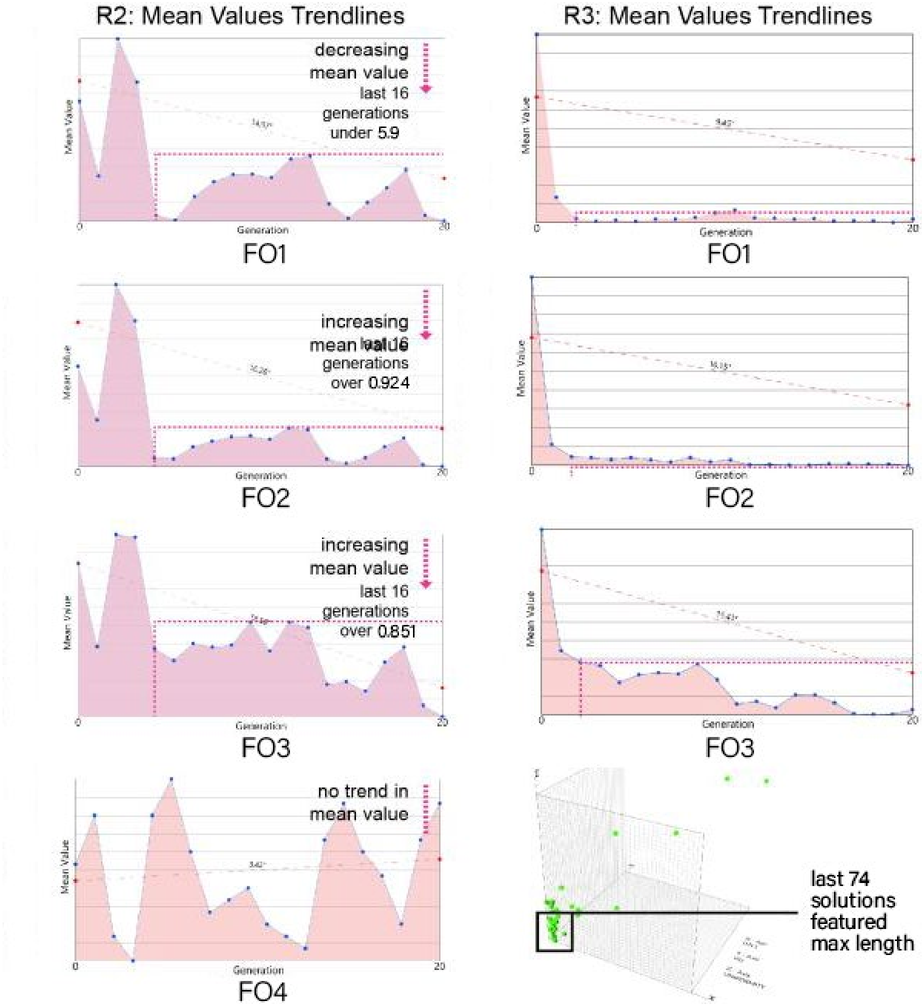


Figure 7.89: Graphs for fitness values in third run 2 (R3)

These chosen solutions are plotted on the Parallel Coordinate Plot (PCP) (Figure 7.25, left), showing a good fit in deployment angle (values under 5.9) and width (values above 0.92), a medium fit in handrail height (values between 0.80 and 0.85), and a medium to low fit in the ramp width criterion (values between 1.96 and 2.5). The entire population is displayed in the objective space (Figure 7.25, right), with FOs 1, 2, and 3 on the X, Y, and Z axes, respectively, and FO 4 represented by colour (Green (fittest) to Red (least fit)). The chosen solutions are highlighted in blue.

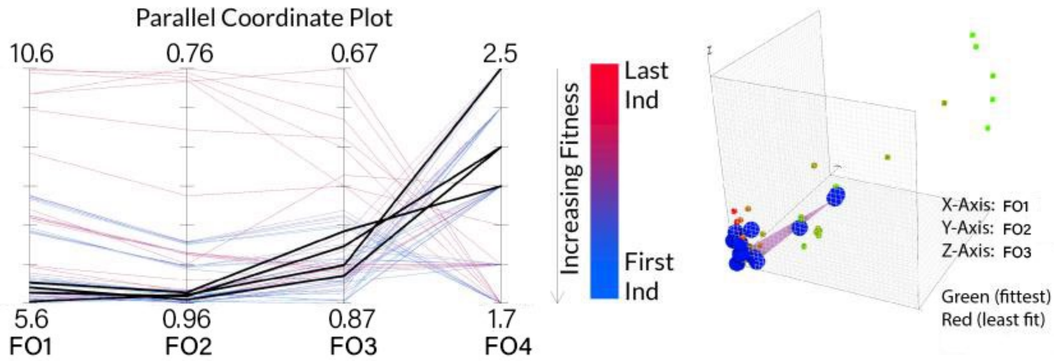
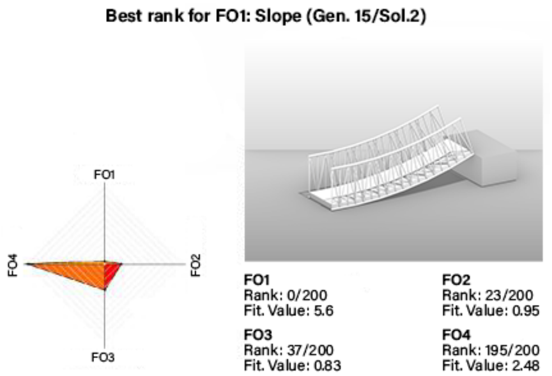
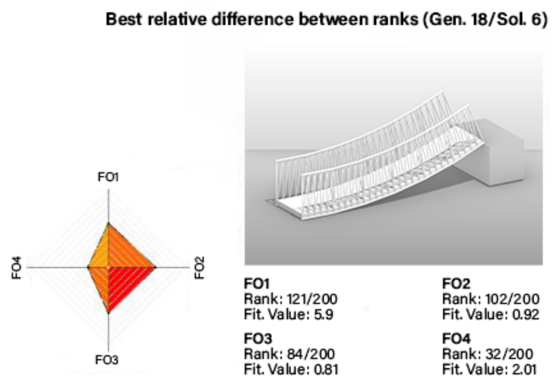


Figure 7.90: Parallel Coordinate Plot with the selected solutions highlighted in black (left). On the right, the objective space of all populations and the selected solutions highlighted in blue.

Figure 7.26 presents the phenotypes and their diamond fitness charts for all selected solutions, detailing fitness values and rankings for each objective. Diamond fitness charts compare the performance of different fitness objectives for a specific solution; the closer an objective is to the chart's centre, the fitter it is. The evolutionary form-finding process demonstrated significant design variability among the solutions, occasionally with minimal differences in performance results. It should be highlighted that this multi-objective evaluation did not provide a single "ideal" solution; rather, it offered substantial directions in the early formation stage of the ramp design.





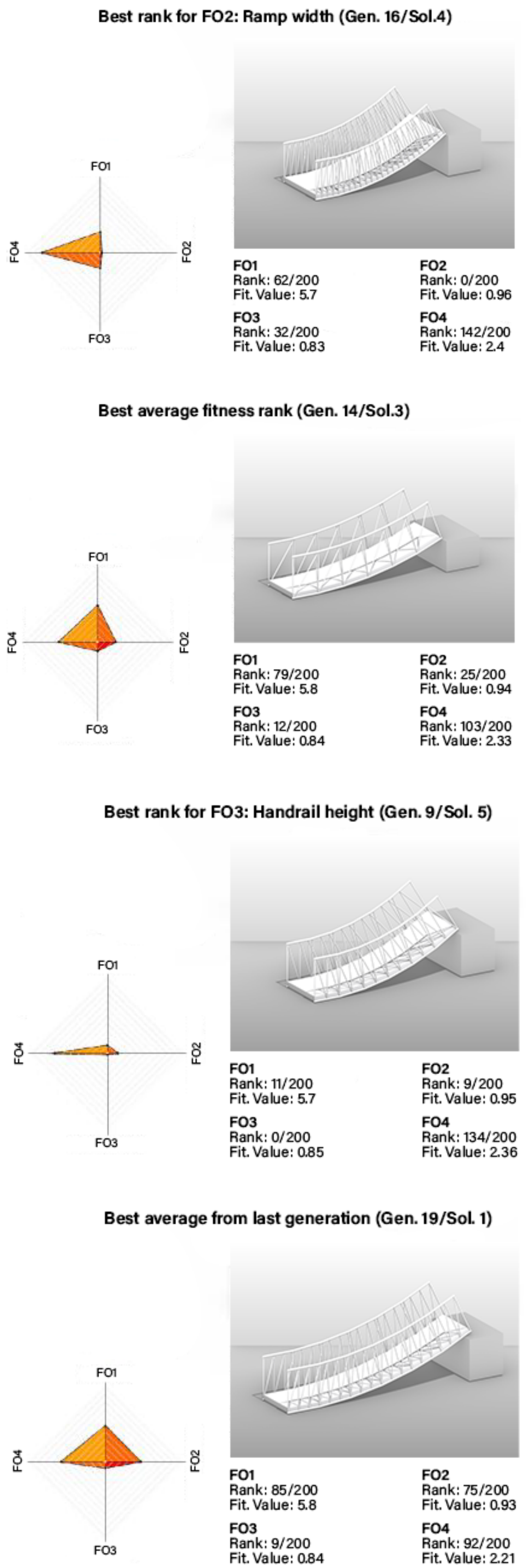


Figure 7.91: The six fittest design solutions emerging from an example precedent project

Finally, Figure 7.27 visualises the the qualified precedents for further exploration (a-d) as indicated in Chapter 7.3.2.3, alongside their fittest solutions at the end of overall evolutionary optimisation process. In the following chapter (Chapter 8), one of these solutions will be selected as the most suitable to address the research problem (i.e., PTIs) and its design will be presented in full detail.

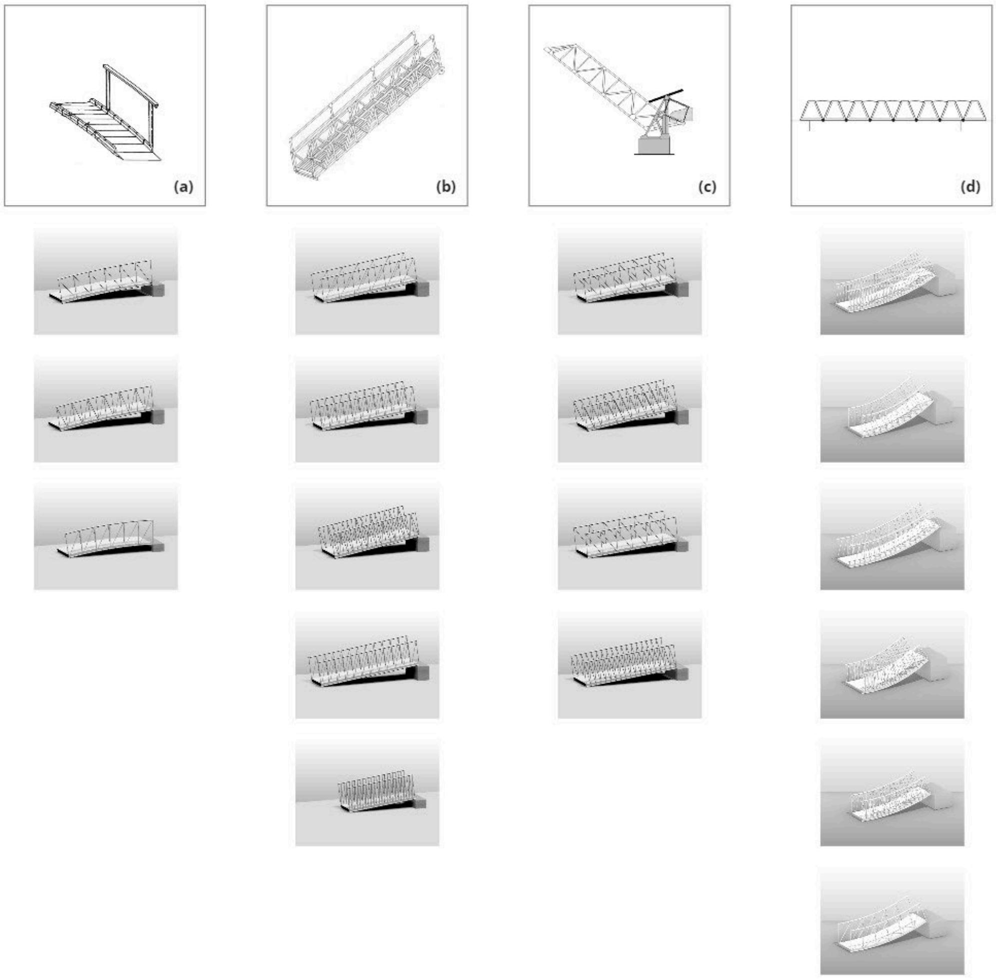


Figure 7.92: An overview of the overall fittest solutions coming from the four qualified precedent projects.

7.4. Discussion

The current chapter focused on gathering inspiration from precedent projects to inform the creation process. Next, it explored the design optimisation of possible solutions for addressing the physical gap between trains and platforms. As such, work undertaken in this chapter addressed research objective 3 (RO3) with respect to developing solutions to enhance accessibility at critical points within the built environment using modern design techniques and advanced technologies.

7.4.1. Insights from the content-based image retrieval

Stage A (Chapter 7.2.1) presented a novel approach that set out to seek inspiration from precedents, namely architectural objects and industrial patents, in a bid to discover ramp-type artefacts and use those as reference projects for the proposal stage of this thesis. For this reason, a deep convolutional autoencoder was developed which was trained to recognise technical drawings from populous databases. Also, a suite of interactive evolutionary algorithms (i.e. Biomorpher) was utilised to produce a variety of design alternatives and reinforce the retrieval process.

The application of this content-based image retrieval system highlighted the potential of employing advanced computational techniques such as convolutional autoencoders and evolutionary algorithms in the exploration and identification of ramp-type structures within architectural collections and global patent databases. By analysing over 100,000 drawings and subsequently filtering the results according to specific exclusion criteria, the study yielded 36 relevant drawings that can provide valuable insights into the topological and functional aspects of ramp-type structures.

One notable finding from this research is the relatively low number of relevant ramp-type drawings (n=36) that emerged from the extensive search of the databases. This result could be indicative of the limited presence of ramp-type structures in the explored databases or a reflection of the stringent exclusion criteria that guided the selection process. Further research might consider refining the search parameters or broadening the inclusion criteria to capture a more diverse range of relevant drawings. One of the key aspects of this study lies in the role of analogy in the design process. The retrieved drawings, which may or may not directly refer to ramps, can significantly enhance creativity by providing a rich source of patterns and elements that can be incorporated into the design of a functional ramp. For instance, numerous drawings referring to bridge structures were found amongst the retrieved content. This can be attributed to the schematic similarity between the ramp forms provided and the bridge structures. Although these drawings may not explicitly describe ramp structures, they offer valuable insights into various design elements and patterns (e.g. handrails and trusses) that can be applied during the design formation stage of the process. As an example, Figure 7.28 illustrates a retrieved drawing, which refers to a footbridge, and was selected for further exploration in the forthcoming design formation stage. Although this drawing does not represent a ramp, it does include a truss structure that can be a great source of inspiration for the proposed design solution. Considering that most workshop participants opted for integrating handrails in the ramp design, the truss structure can potentially serve as a basis for developing a robust and aesthetically pleasing handrail system that complements the overall design and functionality of the ramp.

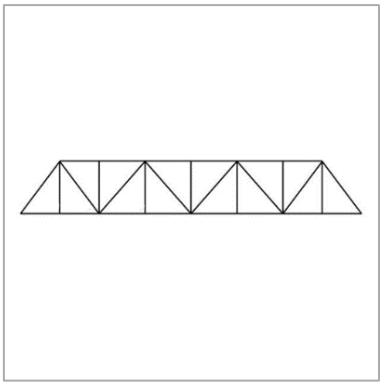


Figure 7.93: Example of a retrieved drawing that refers to a bridge structure.

The retrieval was conducted according to the nearest neighbour algorithm (kNN). The results showed that higher k values would result in the retrieval of a larger population of images. In certain scenarios, this can be beneficial; for instance, in applications where it is critical to retrieve a diverse and comprehensive set of relevant images, such as medical diagnostics or design inspiration search, the increased recall afforded by larger k values ensures a more exhaustive representation of potential matches. Additionally, in cases where the user can efficiently filter or navigate through the retrieved images, the increased image population may not pose a significant challenge.

However, there are situations where retrieving a larger population of images may present challenges. In contexts where users have limited time or cognitive resources to sift through the results, a high number of returned images could lead to information overload and impede decision-making. Furthermore, increasing the image population may also impact system performance, requiring more computational resources and potentially increasing latency, which could be detrimental in time-sensitive applications. Consequently, it is important to strike an optimal balance between improved precision and the practical limitations imposed by retrieving larger image populations and to tailor the choice of k value to the specific needs and constraints of the application domain.

The constructed CBIR system had a notable limitation: after completing the image retrieval process, non-relevant drawings had to be manually filtered out. This task was tedious and time-consuming. Manual filtering was necessary because most inclusion criteria (e.g. non-ramp type objects, non-adaptive elements, no meaningful analogies) were qualitative and design-oriented, making them difficult to parametrise mathematically. Consequently, a machine learning model could not be applied to moderate inclusion criteria and select relevant drawings. Further research is needed to explore data-driven methods, such as machine learning models, to facilitate a less burdensome non-manual selection based on qualitative criteria. A promising direction for future research is reinforcement learning from human feedback (Bai et al. 2022; Christiano et al. 2017), which defines metrics to better capture human preferences, often from natural language prompts as demonstrated by ChatGPT[6]. Extending this approach to quantify

[6] ChatGPT is a chatbot launched by OpenAI in November 2022. See more: https://openai.com/blog/chatgpt/

qualitative criteria from human preferences or design requirements could eventually enable automated filtering based on these criteria.

Finally, the application of a CBIR system to retrieve drawings from precedent projects may introduce significant limitations related to intellectual property and design plagiarism. While AI tools like CBIR systems can be used to efficiently identify and further optimise design elements, they may inadvertently infringe on existing intellectual property rights if not carefully managed. This risk arises from the potential replication or adaptation of proprietary design features without proper attribution or permission, leading to possible legal and ethical issues. To overcome this limitation in future research, a rigorous framework for intellectual property management should be established. This framework would include thorough vetting of retrieved designs to ensure originality and the implementation of AI algorithms designed to generate unique design solutions rather than merely replicating existing ones. Additionally, seeking collaboration or permissions from original designers and incorporating proper citation and attribution practices can further mitigate the risk of design plagiarism, ensuring that the innovative aspects of the proposed solutions remain both legally and ethically sound.

7.4.2. Insights from the design optimisation

In Stage B (Chapter 7.2.2), a workflow consisting of three main parts was developed: (a) conversion of reference drawings with the highest similarity scores as emerged from Stage A into 3D models, (b) contextualisation of reference models into a digital design environment, and (c) evolutionary optimisation of the reference models based on functional, spatial, and aesthetic criteria.

Regarding the application of this workflow, a set of deep neural networks (i.e. Point-E) was first utilised to efficiently vectorise drawings from precedent projects and convert them into 3D models. Next, a parametric script was developed to assist with contextualisation into the environment of the design problem (i.e. PTIs) and an evolutionary simulation engine (i.e. Wallacei) was used to optimise the design of the most suitable precedents, ultimately returning six optimised design forms that fully addressed the design problem space while satisfying MobAD users' requirements at the same time.

The biggest strengths of the workflow developed in Stage B for design professionals lie in its efficiency, user-centric approach, and data-driven decision-making. Specifically, the workflow uses deep neural networks like Point-E to efficiently convert 2D drawings into 3D models, significantly speeding up the transition from initial sketches to detailed representations. Also, the inclusion of an evolutionary simulation engine such as Wallacei allows for the optimisation of design models based on functional, spatial, and aesthetic criteria, resulting in more refined and effective solutions. By incorporating user requirements and preferences, the workflow ensures that the final design solutions are not only technically proficient but also aligned with user needs, enhancing overall satisfaction. Additionally, the modular nature of the workflow provides flexibility and adaptability, enabling design professionals to apply it across various projects and contexts. Finally, the reliance on advanced computational methods and machine learning models facilitates data-driven decision-making, empowering designers to make informed choices backed by quantitative analysis.

A limitation of the workflow proposed in Stage B for design professionals is the requirement for high digital proficiency. Effective use of deep neural networks for vectorising drawings, parametric scripting for contextualisation, and evolutionary simulation engines for optimisation demands advanced computational skills and familiarity with sophisticated software tools such as Point-E, Grasshopper, and Wallacei. This level of expertise may not be universally possessed among designers, potentially creating a barrier to the workflow's adoption. Another limitation is the need for significant computational resources and time, particularly during the evolutionary optimisation stage. Running multiple simulations and analyses to refine design models can be resource-intensive, posing challenges for professionals who may not have access to high-performance computing infrastructure or the time required to complete these processes.

Future work should focus on developing more user-friendly interfaces and tools that simplify the use of advanced computational methods, making them accessible to a broader range of design professionals. Additionally, research into optimising computational efficiency and reducing the resource intensity of these processes could help mitigate the challenges associated with high-performance computing requirements.

B5. Bridge section: towards a MobAD-inclusive solution for PTIs

Chapter 7 concluded with the identification of the fittest design solutions for addressing the physical gap between trains and platforms. These solutions emerged from a comprehensive evolutionary optimisation process informed by precedent projects and realised through advanced computational methodologies. The chapter highlighted the innovative characteristics and functional requirements identified in earlier research phases, ensuring that the proposed solutions align closely with MobAD users' needs and preferences.

Building on this groundwork, Chapter 8 will present a detailed analysis of the selected design solution chosen from among the fittest scenarios identified in Chapter 7. This solution is meticulously crafted to address the design problem by incorporating the diverse functional capabilities of different MobAD users. The design process has been ushered by universal design principles and guidelines presented in Chapter 2, ensuring inclusivity and accessibility for all users. Additionally, the solution reflects the specific design preferences and requirements gathered from MobAD users during the co-design workshops outlined in Chapter 6.

In Chapter 8, the chosen design solution will be examined comprehensively, demonstrating how it effectively bridges the physical gap of various dimensions between trains and platforms. The analysis will cover various aspects of the design, including its adaptability, usability, and overall effectiveness in enhancing the accessibility of PTIs. By integrating insights from previous chapters, this chapter aims to provide a thorough presentation of the proposed solution, showcasing its potential to significantly improve the experience of MobAD users.

8. Description of the proposed design solution

This chapter synthesises the insights and knowledge gained from the preceding chapters, particularly the optimisation process in Chapter 7 as well as universal design guidelines (Chapter 2.2.1) and MobAD users' design preferences as solicited in Chapter 6.3.2, to produce an effective and inclusive solution for the design problem.

Previously, Chapter 7.3.2 presented results from the AI-enabled vectorisation and 3D modelling of 36 precedent projects After the application of spatial and human-centred criteria, only four precedents (Figures 7.15-7.18) were qualified for the evolutionary optimisation in the simulation engine. This process was presented through the optimisation of an example 3D model that represented one of the four qualified objects (Figure 7.18) whose fittest solutions were illustrated in Figure 7.26. Figure 7.27 visualises the fittest solutions for all four objects at the end of overall optimisation process.

8.1. Reference project

After carefully examining the fittest design scenarios originating from all four reference projects (Chapter 7.3.2.4, Figure 7.27) , it became clear that the Footbridge by Heatherwick Studio would be the most relevant precedent to build on. The Heatherwick Bridge (Figure 8.1) is a type of structurally adaptive curling bridge completed in 2004 as part of the Grand Union Canal office and retail development project at Paddington Basin, London. It consists of eight triangular sections hinged at the walkway level and connected above by two-part links that can be collapsed towards the deck by hydraulic cylinders mounted vertically between the sections. When extended, it resembles a conventional steel and timber footbridge and is 12 metres long. To allow the passage of boats, the hydraulic pistons are activated, and the bridge curls up until its two ends join to form an octagonal shape measuring one half of the waterway's width at that point. Figure 8.2 illustrates the operation phases of the bridge when in an open (left), curling (middle), and enclosed (right) state.

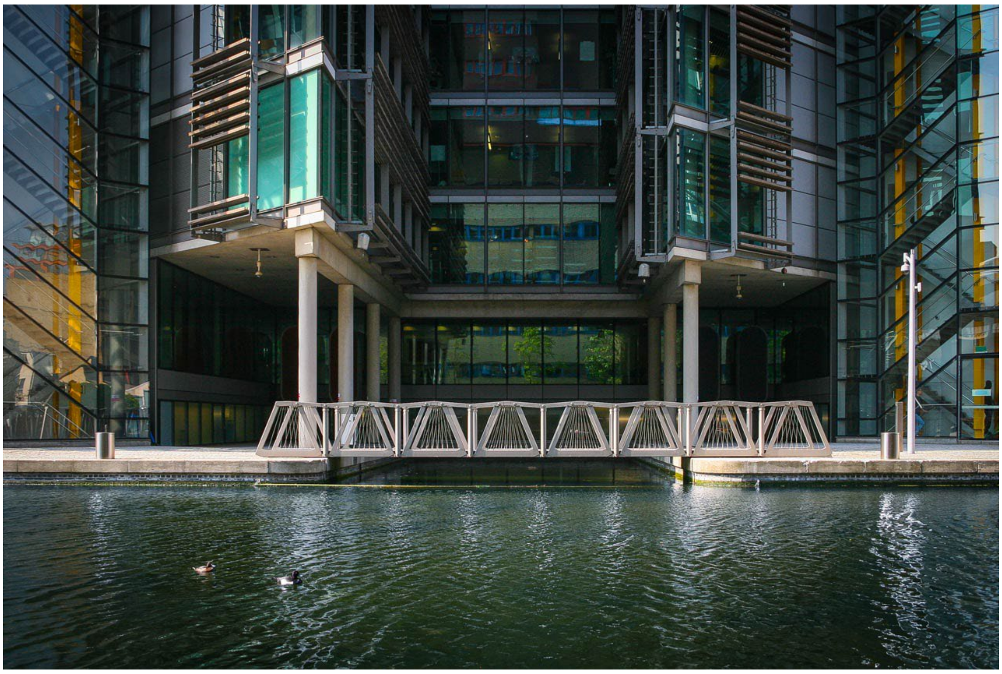


Figure 8.94: Heatherwick Bridge. Source: Littlehampton Welding Ltd.

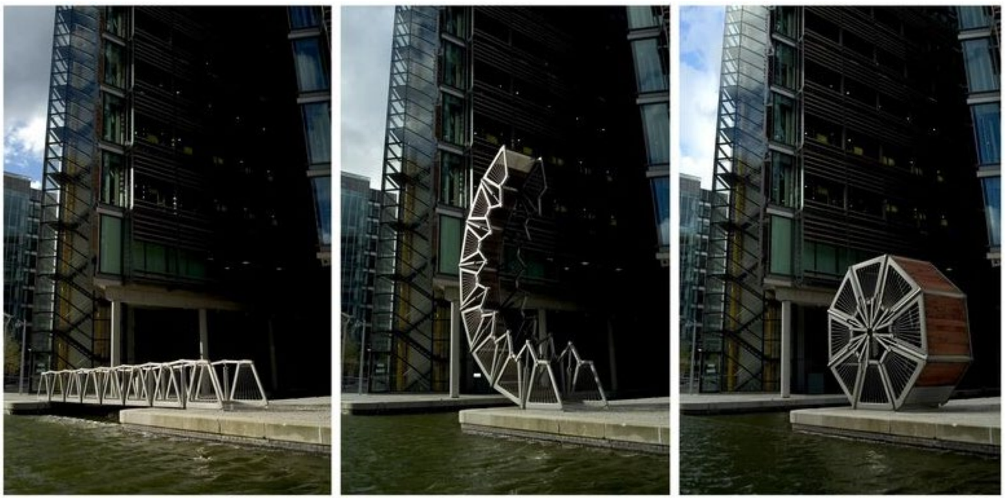


Figure 8.95: Operation stages of the footbridge. Source: Heatherwick Studio.

A reason for selecting the footbridge as the primary source of inspiration is because the fittest design scenarios that simulated the bridge design were closer to optimising all four of the fitness objectives than those of the other three reference projects. Moreover, this bridge is capable of functioning with minimal human intervention due to its automated operation, a coveted design feature amongst participants of the ideation workshops. Another reason is the aesthetic practicality of the bridge, as it can curl up in an efficient and appealing way when not in use, only occupying a limited amount of space. This would make a similarly operated ramp an ideal choice for train platforms where space is at a premium. An additional advantage of the Rolling Bridge is that it has been designed in such an efficient way that its lifting mechanisms (i.e., hydraulic pistons) also operate as handrails for pedestrians when the bridge is open. As discussed in Chapter 6.3.2.2.4, integration of handrails would be a top priority for most of the workshop participants.

Perhaps the most desirable characteristic of the Heatherwick Bridge that is of great pertinence to the design problem lies in its structural adaptability. The adaptation of the bridge would be a great facilitator for an access ramp, which intends to cover a wide range of gaps between trains and platforms. The bridge curls up and down according to different purposes (i.e., boat and pedestrian traffic respectively). In an analogous way, an access ramp could expand and contract in an arch-like form to cover gaps that develop in varying dimensions. This was also corroborated by the results of the evolutionary simulation process as analysed in Chapter 7.3.2.4.

Extracting inspiration from Heatherwick Bridge, this thesis now arrives at the culmination of the creative process – an ***adaptive access ramp*** is suggested as a solution to the design problem. The following sections will provide a comprehensive overview of the ramp's structural form, performance capabilities, main components, and operation. To ensure clarity and facilitate understanding, a series of technical drawings has been prepared to intricately detail every aspect of the ramp design. Before analysing the operational logic of the ramp and its components, it is important to highlight two points. Firstly, the design of this proposed solution is based on the fittest average alternative according to the optimisation objectives (Table 7.2), as this presented in Figure 7.26 (labelled as “best average fitness rank” alternative). Secondly, despite the undisputable design excellence of the Rolling Bridge, this refers to a fixed object that won’t move to facilitate different points – i.e., the bridge has a specified start and end point. As most MobAD users preferred an access ramp that would facilitate different access points (Chapter 6.3.2.2.3), various engineering patent libraries were browsed to identify similar projects, such as the moveable deck illustrated in Figure 8.3 (Patent ID: CN 110789539 A).

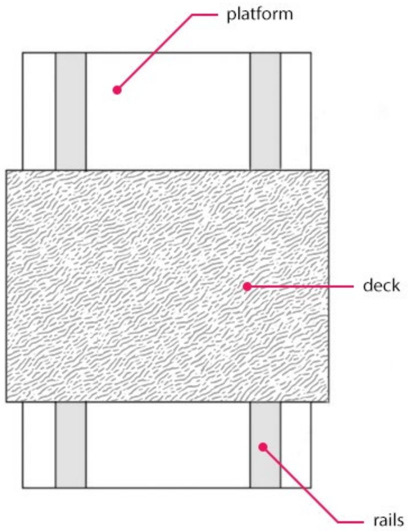


Figure 8.96: A movable deck (top view). Source: Patent CN 110789539 A.

The deck includes a set of wheels and is capable of sliding along paved surfaces on rails. This technique would possibly be a very practical way to enable the ramp to move along the platform and accommodate different points, as shown in Figure 8.4. In this way, the ramp may reach different train doors and assist MobAD users who potentially want to use different carriages of the same train.

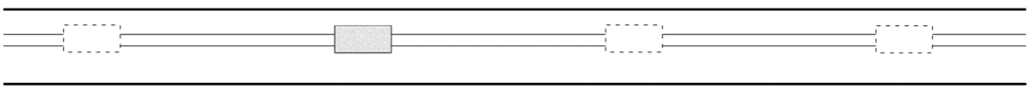


Figure 8.97: Ramp moving along the platform and catering for different points (top view)

8.2. Structural form of the proposed solution

The ramp has been designed to span gaps ranging from 0-470mm in width and 0-460mm in height. These dimensions account for approximately 95% of the total UK rail network, as indicated by RSSB (2020). As demonstrated in the evolutionary optimisation stage (Chapter 7.3.2.4), the ramp dimensions can be adjusted to accommodate various platforms and trains while consistently maintaining low deployment angles. Figure 8.5 portrays the proposed ramp deployed in the design problem space (i.e., platform train interface).

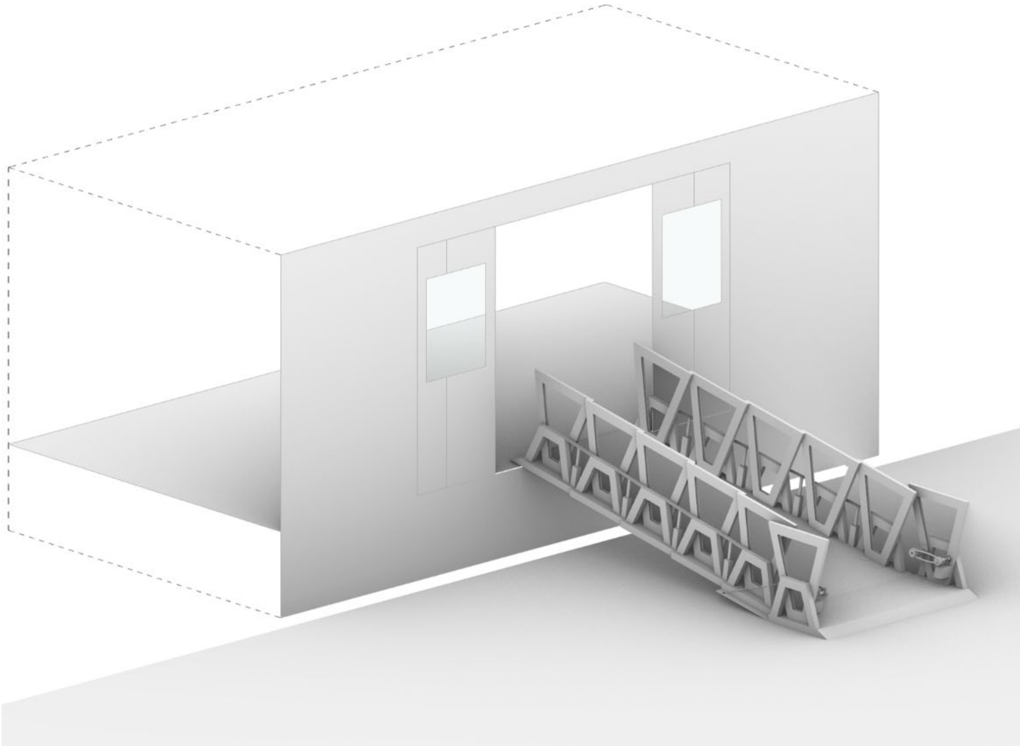


Figure 8.98: Proposed solution localised in the design environment

The ramp comprises of six segments, which are linked together in a stacked nesting configuration. That is, every upper segment of the ramp nest in its adjacent next lower segment. Figure 8.6 presents an exploded axonometric view of the ramp, where the division in segments is visible.

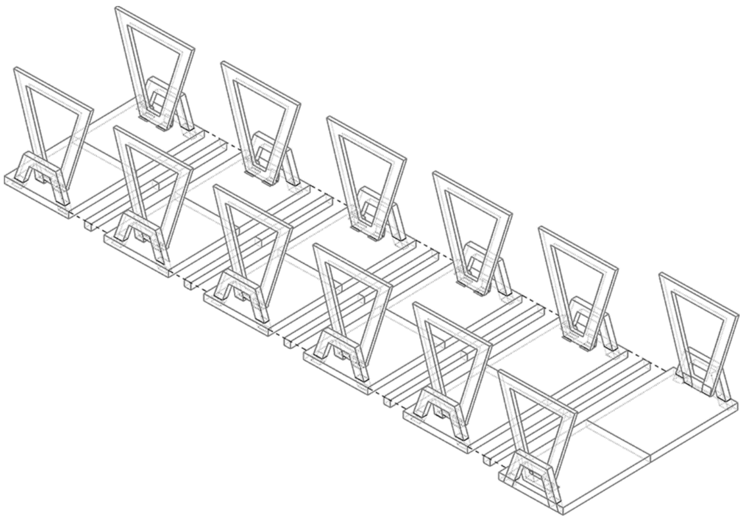


Figure 8.99: An exploded axonometric view of the ramp

The nested configuration of the ramp segments is presented in Figure 8.7.

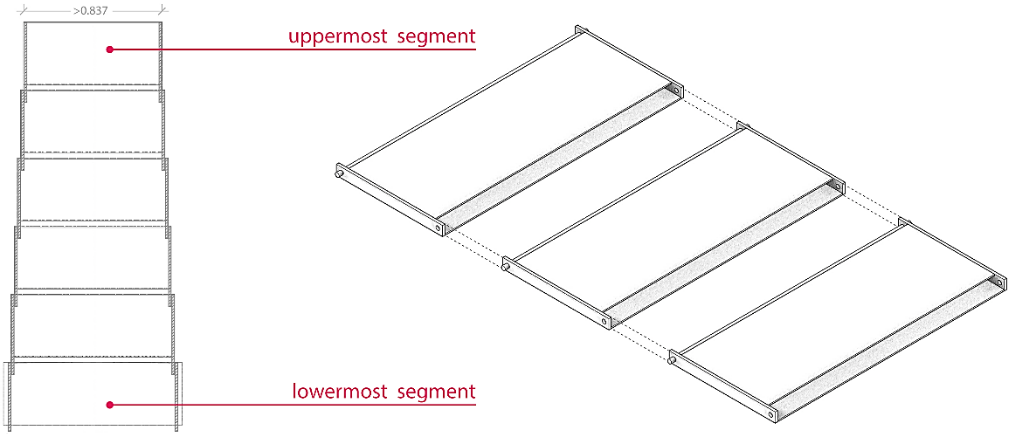


Figure 8.100: Nested configuration of ramp segments in top (left) and exploded axonometric (right) view

Due to the nested configuration of the segments the ramp width incrementally decreases, moving from the lowermost segment to the upper ones, as indicated in Figure 8.7. In any case, the width of the uppermost segment never drops below 0.873m, which is the minimum threshold of clear width according to universal design criteria (D'Souza 2011). This ensures that all MobAD users, regardless of their functioning capabilities and device characteristics, can comfortably fit through and traverse the ramp.

8.3. Performance capabilities

To meet MobAD users' design preferences, as defined in Chapter 6.3.2.2, the ramp has been designed to structurally perform two discrete moves. Specifically, the ramp is capable of (1) *changing in form*, to bridge different types of physical gaps, and (2) *transferring among numerous locations on the platform*, to cater for different boarding/alighting points (i.e., train doors).

The transformation stages of the ramp are illustrated in Figure 8.8. Initially, the ramp rests on the platform in an enclosed state (Figure 8.8a), resembling a hexagonal solid. The lowermost segment of the ramp remains affixed at all times. When the ramp is instructed to bridge a gap, the adjacent (i.e., second to lowermost) section performs a centrifugal rotation away from the joining point, which connects it to the lowermost segment (Figure 8.8b). Once this movement is complete, one-by-one the remaining sections perform an analogous, “unfolding” motion, as they rotate by 60º centrifugally (Figure 8.8c-f), in such a way that all – but the lowermost – segments create a uniform, linear, and flat block (Figure 8.8f). This block is the main passage, which MobAD users can use to board or alight trains. Once the ramp has served its purpose, it performs the exact opposite movement to reinstate its enclosed form, which is also conducive for storage purposes. Essentially, the driving force of the unfolding movement is the rotation of the second lowermost segment, as the degree of its rotation defines the gap coverage, in the same manner that the deployment angle of a conventional ramp defines its steepness. At any case, the rotation of that segment should not exceed 7.5º, which is the maximum threshold of negotiable slope, according to universal design criteria (D’Souza et al., 2020; Lenker et al., 2016).

Figure 8.101: Structural adaptation of ramp in stages (side elevation)

Regarding the transfer of the ramp, this is achieved through a sliding movement along the platform. This controllable movement ensures that the ramp accommodates different boarding or alighting points on platform, if required. Figure 8.9 depicts the shifting movement of the ramp, where it slides along the platform (in an enclosed state) to cater for different train doors (in an expanded state).

Figure 8.102: The sliding movement of the ramp on platform (axonometric view)

8.4. Structural components

As mentioned in Chapter 8.2, the ramp consists of six segments. Each segment comprises of a top plate (i.e., load-bearing surface), a bottom plate, and a set of parallel side plates. A trapezoid-shaped wing is screwed on top of each side plate. A set of oppositely arranged handrails is screwed on top of every top plate. To facilitate the nesting configuration (Figure 8.7), each of side plates has two apertures adapted to overlap apertures of adjacent sections and receive a connecting means thereby connecting adjacent sections. Figure 8.10 visualises the component parts of a ramp segment.

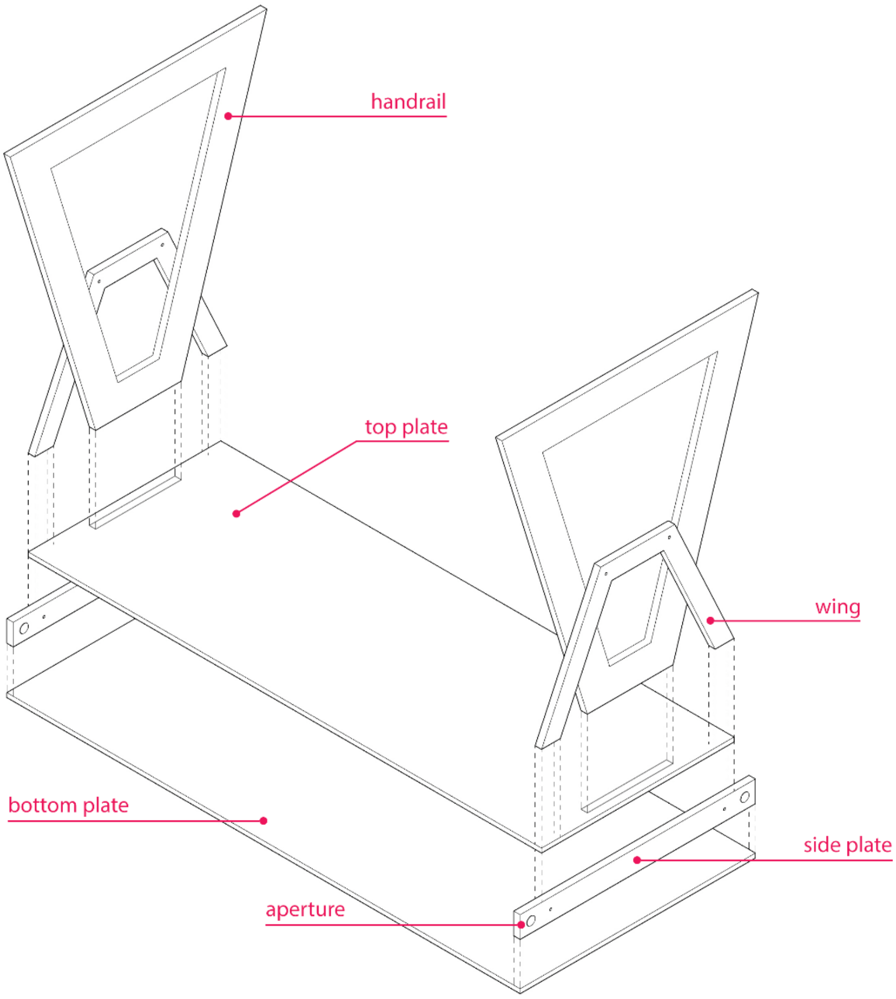


Figure 8.103: Segment component parts (exploded axonometric view)

The lowermost section of the ramp is screwed on a rectangular-shaped box, which functions as a supporting base for the ramp, as shown in Figure 8.11. The base is responsible for conducting the sliding movement along the platform (see Figure 8.9), as it includes two pairs of wheels that can slide on a set of rails affixed on the platform (Figure 8.12). A set of magnetic brakes is incorporated on each of the wheels, which can firmly lock the ramp on the sliding track, as it arrives at a boarding/alighting point. The base also serves as a storage box for any electronic equipment required so that the ramp can successfully conduct the intended movements (i.e., sliding and curling).

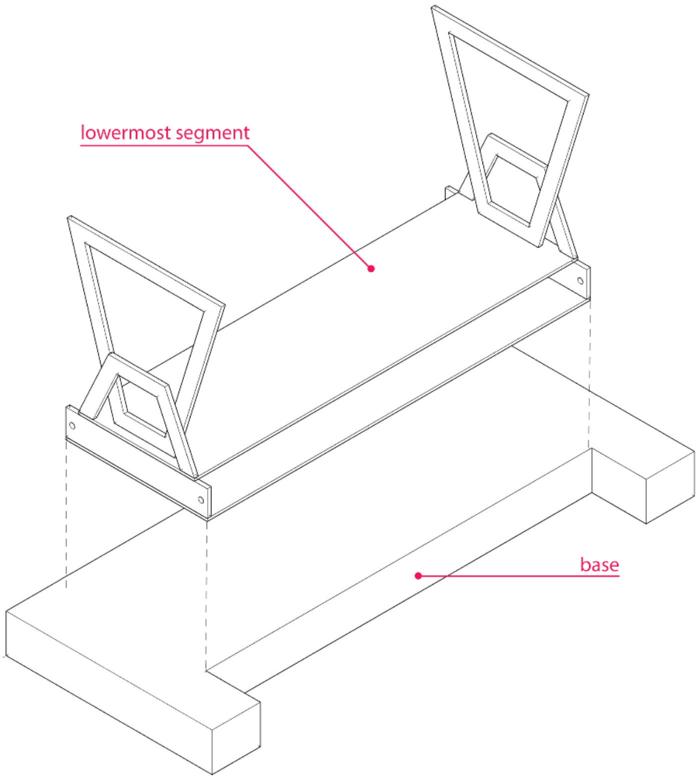


Figure 8.104: Lowermost segment affixed on a base (exploded axonometric view)

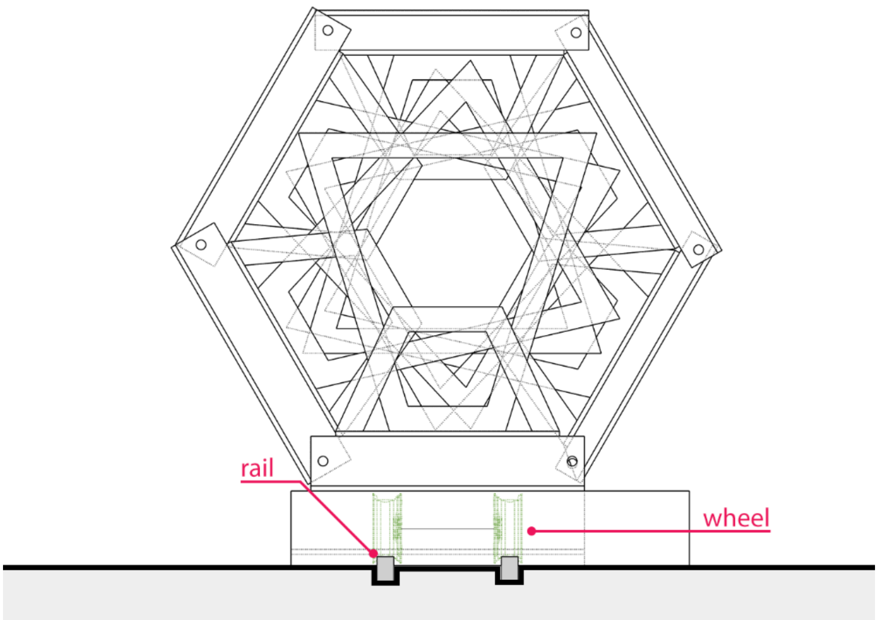


Figure 8.105: Base elements and platform rails (section view)

To ensure a smooth transition for MobAD users, an oblique surface is added between the ground and the lowermost section. The transition surface is screwed on the top plate of the lowermost section, as shown in Figure 8.13.

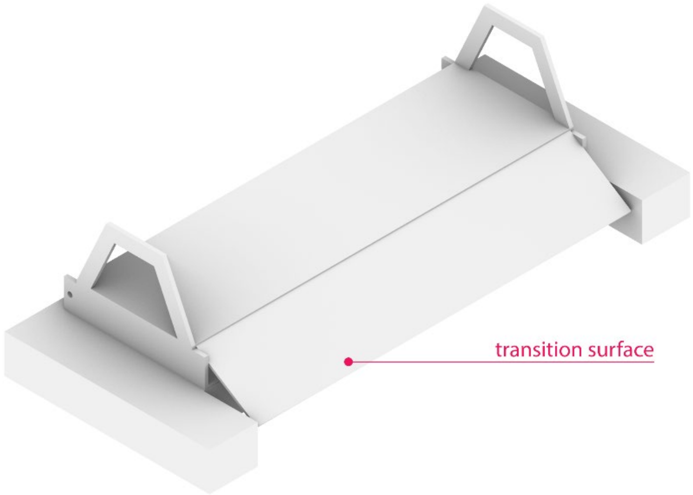


Figure 8.106: Transition surface integrated into ramp base

8.5. Adaptation mechanisms

The structural transformation (i.e., curling movement, see Figure 8.8) of the ramp is implemented through different types of motors. As the lowermost segment always remains affixed to the base, five separate motors drive the motion of the five remaining segments respectively. A powerful motor is located at the lowermost segment and connected to a tension mechanism that includes a pulley, a support driving system and a pull cable (Figure 8.14). The cable is attached to a flange which is mounted underneath the second segment. When actuated, the pulley brings down the second lowermost segment, whose degree of rotation regulates the total transformation from an enclosed arched structure to a linear continuous bridge (see Chapter 8.3 and Figure 8.8).

Four more motors are located inside the remaining segments, respectively. Each motor is connected to two lifting columns at each side of a ramp segment through a geared system and a shaft. Each column is pinned to two chords, which are pinned on the side plates two adjacent ramp segments. When actuated, the lifting mechanism brings the chords down and a type of truss is formed for all ramp segments apart from the lowermost one (Figure 8.15). In this way, the lowermost segment of the bridge remains affixed and secured onto the base while the remaining sections form a stable and accessible bridge which can facilitate MobAD users' movement from train to platform or vice-versa.

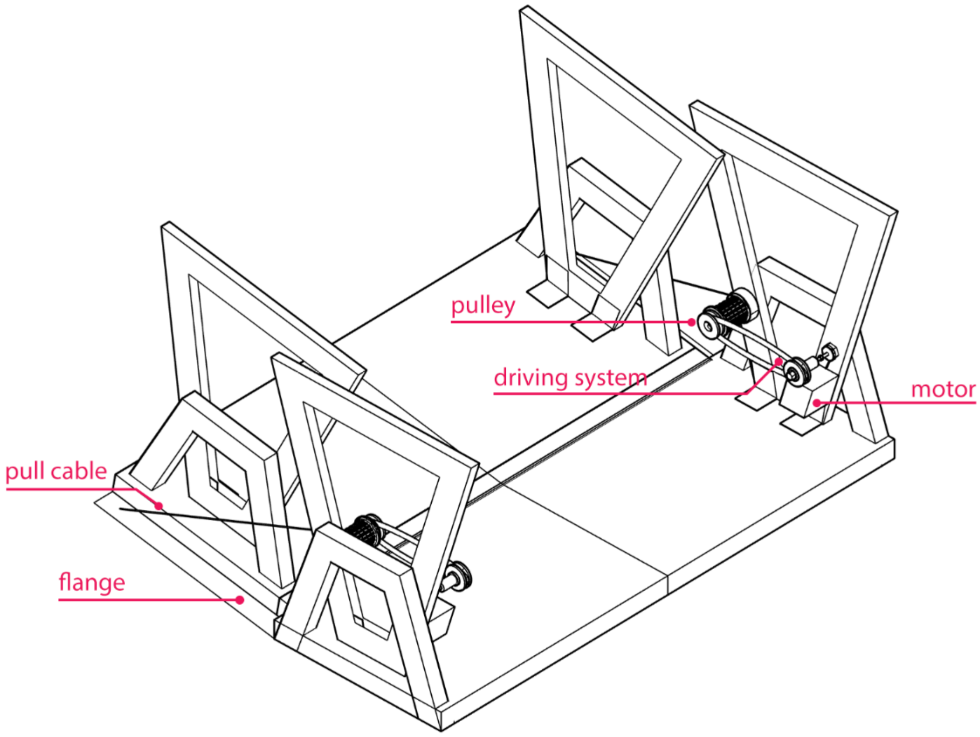


Figure 8.107: Tension system for rotation of second lowermost segment (axonometric view)

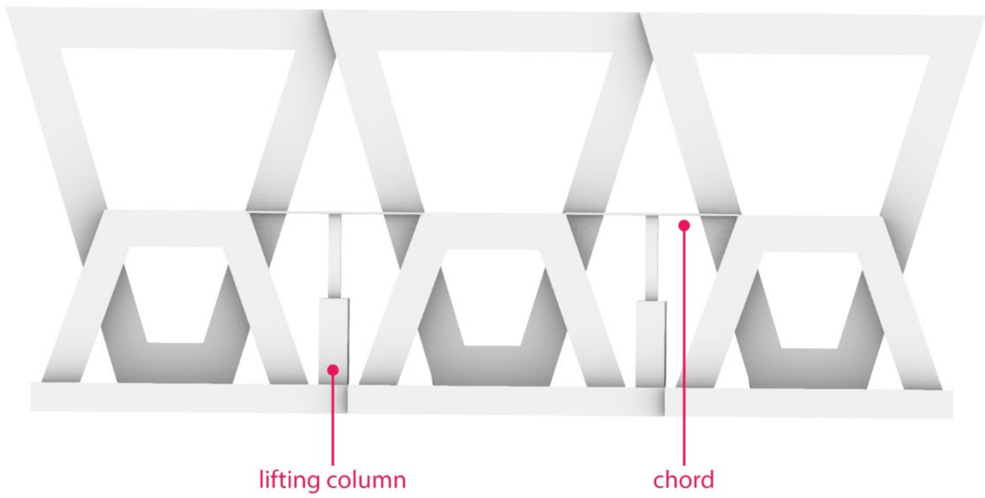


Figure 8.108: Lifting mechanism for ramp segments (side elevation, example segments)

By incorporating a suitable motor transmission system, motor control, and feedback system, the sliding movement of the ramp along the train platform can be achieved with precision. The motor responsible for the sliding movement of the ramp is mounted on the rectangular-shaped base and connected to the wheels through a simple transmission system. This setup allows the ramp to move smoothly and at the right speed along the train platform. To ensure precise control of the movement, a motor controller receives instructions from a control system and adjusts the motor's operation accordingly. In addition, a feedback system comprised of sensors constantly monitors the position of the ramp and provides real-time information to the control system for adjustments. Lastly, the motor control system is synchronised with the magnetic brakes on each wheel, enabling secure locking and unlocking of the ramp when necessary.

8.6. Load-bearing considerations

To construct an adaptive ramp that is both sturdy and flexible, a combination of engineering techniques was selected. Firstly, the arrangement of side plates seamlessly connected by lifting chords creates a type of Warren truss on each side of the ramp. A Warren truss is a type of truss characterised by its equilateral triangular pattern with alternating diagonals forming a series of interconnected triangles. This geometric configuration is inherently strong and efficient in load distribution, as the forces applied to the structure are channelled through the truss members, distributing the load evenly across the entire structure. This reduces the stress concentration on any single member, thereby preventing potential deformation or failure. The triangular configuration of a Warren truss also provides structural redundancy, which is an essential factor in maintaining the ramp's stability. In case one of the truss members fails or gets damaged, the load can still be transferred through alternative load paths in the truss, ensuring that the overall structure remains stable and functional. This built-in redundancy increases the ramp's resilience and enhances its safety. Moreover, the Warren truss design is efficient in terms of material usage as it minimises the amount of material required to achieve the desired strength and stability. This results in a lightweight yet robust ramp structure, which is easier to install, maintain, and transport.

Also, the nesting configuration of ramp segments further strengthens the whole structure. Since the ramp segments are designed to nest within each other, they create an interlocking structure that inherently enhances the overall stability. This interlocking mechanism ensures that the load applied to a segment is not only supported by the segment itself but also shared by the adjacent segments. By distributing the load in such a manner, the weight-bearing capacity of the entire ramp increases, reducing the chances of sagging or failure. Furthermore, the nesting configuration provides a larger surface area for load transfer between the segments. This increased contact area results in a more efficient load distribution, as forces are transmitted through the segments in a manner that reduces the stress concentration at any single point. As a result, each segment can better support the applied loads, further maximising the overall support provided by the ramp structure.

Reinforcing the joints between the ramp segments is a crucial step in ensuring the stability of the entire structure. By using stronger materials (e.g., steel or composite materials) and advanced engineering techniques (e.g., welding, adhesive bonding, load-bearing mechanisms, or pre-stressed joints), the load-carrying capacity of the joints is increased. This reinforcement effectively allows the segments to better distribute the applied load across the ramp, minimising stress concentrations and reducing the likelihood of joint failure. Furthermore, reinforced joints can better withstand dynamic loading conditions, such as those encountered during vehicle movement, enhancing the overall structural integrity and adaptability of the ramp.

Magnetic locks serve as an essential component for maintaining secure connections between the ramp segments. These locks utilise magnetic force to keep the segments firmly attached, preventing unwanted movement or separation, which could compromise the ramp's stability. Magnetic locks also provide a quick and reliable method of connecting and disconnecting the segments, enabling efficient installation, modification, and disassembly of the ramp. By ensuring secure connections between the segments, the magnetic locks contribute to the overall stability by preventing any undesired structural movement that could lead to segment misalignment or failure.

8.7. A scenario for autonomous operation of the proposed solution

In Chapter 6.3.2.2.1, it became clear that the vast majority of MobAD users preferred a design solution that would be able to function with minimal human intervention. While this is an important finding and has influenced the design of the proposed solution, it is beyond the scope of this research to evidence or produce a semi- or fully autonomous operation through an engineering lens. Instead, this section describes a rudimentary scenario for an autonomous operation of the proposed solution, with a view to guiding future applications of the ramp in existing or new rail stations.

A potential scenario for the autonomous operation of the ramp involves the integration of various systems to ensure seamless communication, precise positioning, and smooth actuation. Firstly, a user-friendly mobile app allows interested persons, whether on the platform or in the train, to request the ramp, communicating securely with the control system. This centralised control system manages the overall operation, processing the user's location data and issuing commands to the ramp components.

To accurately determine the user's location and the closest-to-user door, a versatile positioning system, such as a combination of GPS technology, RFID tags, or other sensors, is employed. The positioning system not only determines the user's position but also the train's position and door locations on the platform. The control system integrates and processes this information to identify the closest door to the user, considering factors such as distance and train orientation. As the train moves or the user changes their position, the positioning data is continually updated, allowing the control system to make real-time adjustments to the ramp's movement and ensure that it is always directed towards the closest-to-user door.

With this information, the actuation system, consisting of a motor and transmission system, is responsible for the precise sliding movement of the ramp along the platform, guiding it towards the identified closest-to-user door. A locking system, which may include magnetic brakes or other mechanisms, securely locks the ramp in place once it reaches the desired location, ensuring safe boarding and alighting for the user. By incorporating these systems and ensuring their seamless coordination, the ramp can effectively operate on demand, providing a convenient and accessible experience for MobAD users.

To fully automate the ramp operation, a possible scenario involves incorporating gap measurement sensors, such as ultrasonic sensors, infrared sensors, or laser rangefinders, to accurately estimate the physical gap between the train and the platform edge. Strategically placed on the ramp and connected to the control system, these sensors provide real-time data, which the control system processes to determine the dimensions of the gap. Based on this information, the control system adjusts the ramp's extension length, angle, or curvature, ensuring a safe and smooth transition between the train and the platform edge. During deployment, the control system continues to receive feedback from the sensors, making real-time adjustments to optimise alignment and minimise the risk of accidents or misalignments. By integrating these components and effectively adapting the ramp's deployment, the system provides a convenient and accessible boarding and alighting experience for users. In the future, a possible implementation of the ramp design could integrate the aforementioned system to achieve autonomous operation.

8.8. Summary

Having identified user design preferences (Chapter 6) and utilised AI methods to optimise precedent design accordingly (Chapter 8), the purpose of this chapter was to describe a universal design solution which would enhance the accessibility of PTIs. Heatherwick's footbridge was selected as a reference design point, and an optimised version of it became the basis on which an operable solution was conceived: an adaptive access ramp. The rest of the chapter presented the structural form, components, performance capabilities, operation and load-bearing considerations for the proposed solution as well as a draft scenario where the ramp could operate autonomously.

The proposed design seamlessly combined two unique features that enable the ramp to be used across a wide variety of PTIs throughout the UK rail network. First, the ramp's form had been optimised based on spatial limitations and structural elements, including gap width and height, as well as the height-to-length ratio of the handrail. This had been made possible through the parametrisation and evolutionary optimisation of the ramp's form. By inputting two values for gap height and width, the parametric script can determine the shortest possible ramp length that efficiently accommodates MobAD users within accessible slope thresholds (i.e., below 7.5 degrees).

Another quality that maximised the operability of the proposed ramp is its capability of structurally transforming to cover gaps of different characteristics. In essence, this physical adaptation could realise the design outcomes that emerge from the optimisation process. It is important to note that physical gaps manifest in numerous dimensions across the UK rail network, making a dimension-specific design for the ramp unfeasible. By adhering to the analogies between different elements of the ramp produced by the optimisation process and presented in the technical drawings of this chapter, a ramp with specific dimensions can effectively cover the majority of gaps for one platform, while a ramp with different dimensions can accommodate most gaps for another platform. Consequently, aside from illustrative purposes, the majority of the technical drawings presented in the chapter sections were not dimension-specific, emphasising the ramp's adaptability and versatility in diverse settings.

It is crucial to highlight that the proposed solution has been thoroughly designed to meet all primary user requirements as established through the design ideation workshops (see Chapter 6.3.2.2). Table 8.1 offers a comprehensive overview of the correlation between user requirements and the design features of the proposed ramp, along with their respective locations in the text.

USER REQUIREMENTS	DESIGN FEATURES	PLACE IN TEXT
Ability to function with minimal human intervention	Autonomous operation	Chapter 8.7 (scenario only)
Ability to accommodate different access points (i.e., train doors)	Sliding movement on platform	Chapter 8.3; Figure 8.9
Broad serviceability (i.e., gap coverage)	Structural transformation	Chapter 8.3; Figure 8.8
Side support	Integration of handrails	Chapter 8.4; Figure 8.10
Even transition	Integration of transition surface	Chapter 8.4; Figure 8.13
Standalone solution	Overall design	Chapter 8.2; Figure 8.5; Figure 8.9; Figure 8.12

Table 8.25: Correlation between user requirements and the design features

The information presented in this table clearly demonstrates how each design feature addresses specific user needs, underlining the effectiveness of the proposed solution. This strong alignment between user requirements and design features emphasises the human-centred approach employed throughout the design process and illustrates the successful integration of feedback from the workshops. By carefully considering the diverse needs of various users, the solution ensures maximum accessibility and usability across a wide range of platforms and gap scenarios.

Finally, the ramp design effectively integrated the functional characteristics of a diverse range of MobAD users by considering crucial aspects such as reach range, clear width and negotiable slope. Drawing upon the IDeA design resources for creating inclusive environments (D'Souza et al. 2011; D'Souza et al. 2020; Lenker et al. 2016), the ramp incorporated features tailored to accommodate the unique needs of these users. Specifically, the handrail height, ramp width and deployment angle have been designed to align with the functional characteristics of MobAD users.

By incorporating these elements, the ramp design caters to a broad spectrum of MobAD users, ensuring that individuals with varying abilities can safely and comfortably access the rail network. This attention to the diverse needs of users contributed to crafting a universal design solution that promotes inclusivity and accessibility in PTIs. In turn, this comprehensive approach can possibly enhance the overall user experience and foster more equitable and human-centred PTI conditions for all passengers, regardless of their physical capabilities.

B6. Bridge section: transitioning from design formation to evaluation by MobAD users

As Chapter 8 primarily focused on the description of the design solution, it paved the way for a comprehensive evaluation of the proposed intervention by MobAD users in Chapter 10. The developed solution addressed the design problem space and incorporated the insights gathered from user requirements and precedent projects. The adaptive access ramp, with its structural form, components, performance capabilities, operation, and load-bearing considerations, was thus established as the foundation for the subsequent evaluation process.

Transitioning to Chapter 9, the primary objective is to involve MobAD users in the evaluation of the proposed access ramp, ensuring that their unique perspectives and needs are taken into account. By engaging with users from diverse backgrounds and abilities, the research aims to identify potential areas of improvement and further refine the design to better accommodate their requirements. This human-centred approach enriches the design process and contributes to the development of a more effective and accessible solution, which aligns with the principles of universal design.

The dialogue between Chapters 8 and 9 illustrates the iterative nature of the design process, where the initial design feeds into the evaluation phase, which in turn informs further refinements and adaptations to the proposed solution. By connecting the two, the research transitions from the deliverable outcomes based on practical considerations of user needs and preferences (i.e., Research Objective – RO 3) to the evaluation of the actual users of the proposed intervention (i.e., Research Objective - RO 4).

9. User evaluation of the proposed solution

Evaluation is a crucial part of the design process, especially for interventions or products aimed at specific user groups. Prototypes play a key role in this, allowing users to interact with a tangible version of the intervention, which provides a realistic context for assessing usability, accessibility, and safety. This hands-on experience enhances the quality of feedback, helping researchers identify issues and refine designs based on actual user interactions rather than theoretical assumptions.

Evaluating the match between users' capabilities and the design qualities of the intervention is essential. This ensures the design meets the performance needs of target users, identifying potential barriers and allowing for design improvements to maximise usefulness and usability. For accessibility-oriented interventions, understanding users' perceptions of safety, usability, and accessibility is vital for successful implementation. Insights from users highlight areas for improvement and build confidence in the intervention, increasing the likelihood of adoption. This feedback is crucial for iterative design improvements, leading to more effective and well-received solutions.

9.1. Purpose

The purpose of this study is to solicit feedback from MobAD users about the proposed design solution (i.e. adaptive access ramp) to assess the design and proceed to modifications or refinements, if required, according to users' responses.

9.2. Methods used

The study design received ethical approval from the Engineering Ethics Committee of the University of Nottingham in November 2020. This process also covered aspects of data protection, data handling and retention, participants' anonymity and confidentiality, and participants' consent. The oral communication part was recorded and later transcribed using the Microsoft Stream service.

9.2.1. Study population

In line with Universal Design goals, the study population comprised a diverse group of MobAD users in terms of demographics, functional capabilities, and device characteristics. This is likely to reinforce the credibility of findings as the study includes a wide range of potential users of the proposed intervention. People involved in previous stages of this research (i.e. accessibility assessment and ideation workshops) were invited to participate in the evaluation study through direct communication. The sample size was selected based on precedent studies which have shown that a sample of twenty to thirty people can be sufficient for the purposes of this type of research (Lenker et al., 2016; Choi & Sprigle, 2011; Nasarwanji et al., 2008; Storr et al., 2004). Table A.3 of the Appendix provides anonymised information on the study participants.

9.2.2. Prototype description

A significant component of the evaluation was a prototype model of the proposed intervention. Previous research has indicated that prototypes could be an effective way to communicate design and collect users' feedback (Houde & Hill, 1997; Lim et al., 2008). For this reason, a downsized prototype of the adaptive ramp was constructed. This scaled prototype could replicate the two basic movements – i.e. shifting movement on the platform and the "roll-up-and-gather" structural adaptation – of the adaptive ramp as shown in Chapter 8.3. Also, the prototype includes every structural component of the proposed intervention as presented in Chapter 8.4. Some rough dimensions of the structure – in an expanded state – are: 2500x1200x700 (LxWxH in mm). A 1:5 scale was chosen for the prototype so that it can be both transportable and manipulatable.

To accurately simulate the operational environment, three basic elements were constructed: (a) the adaptive ramp – along with a supporting base; (b) a part of a train platform with a rail track – which will facilitate the linear movement of the ramp on the platform; and (c) a mock-up train carriage. All elements were simulated on a 1:5 scale.

As indicated in Chapter 8.4, each ramp segment comprises a top plate (i.e. load-bearing surface), a bottom plate, and a set of parallel side plates. A trapezoid-shaped wing is screwed on top of each side plate. A set of oppositely arranged handrails is screwed on top of every top plate. Top and bottom plates are made of 2mm plastic sheets; side plates are made of 3mm plywood sheets; handrails and wings are made of 3mm plywood sheets. Each of the side plates has two apertures adapted to overlap apertures of adjacent segments and receive a connecting means – in this case, a φ4mm steel axle rod – thereby connecting adjacent sections. Figure 9.1 and Figure 9.2 present the scaled prototype of the adaptive ramp, in an expanded and enclosed state respectively.

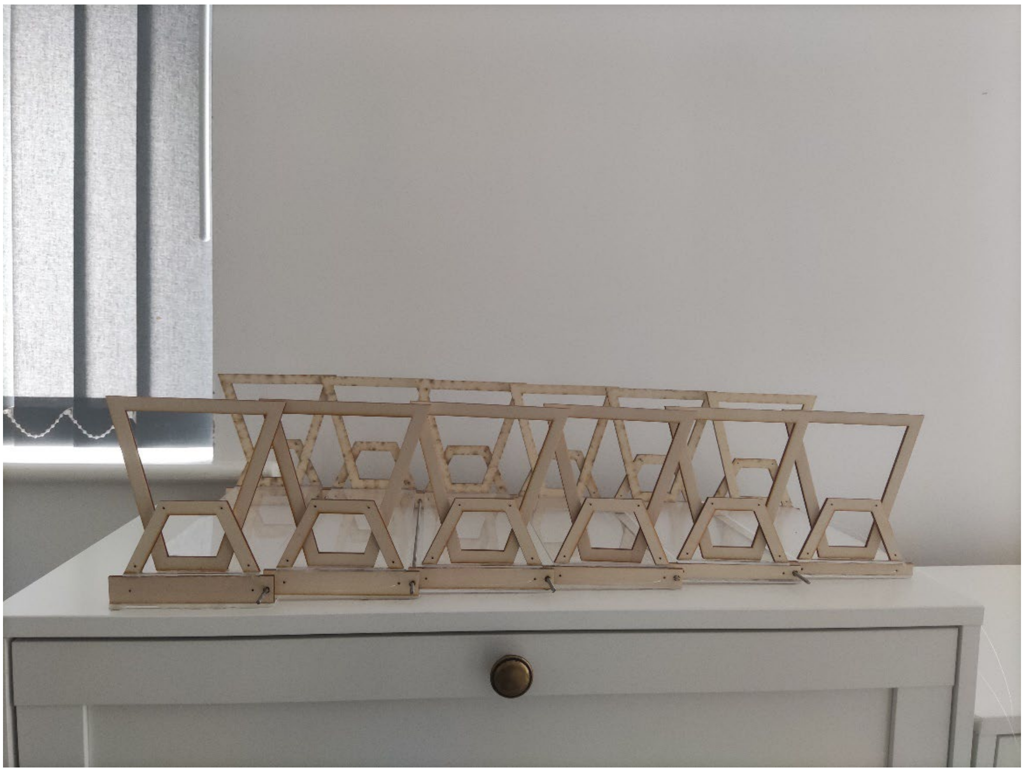


Figure 9.109: Scaled prototype - expanded state

Figure 9.110: Scale prototype - enclosed state

The lowermost section of the ramp is screwed on a rectangular-shaped box which functions as a supporting base for the ramp. Four caster wheels are affixed on the corners of the supporting base to simulate the shifting movement on the platform rail track – each wheel is 60mm in diameter and includes a brake on top. To ensure a smooth transition for MobAD users, an oblique surface is added between the ground and the lowermost section. The transition surface is screwed on the top plate of the lowermost section – this surface is made of 2mm plywood sheets. Figure 9.3 present the ramp model expanding on the supporting base.

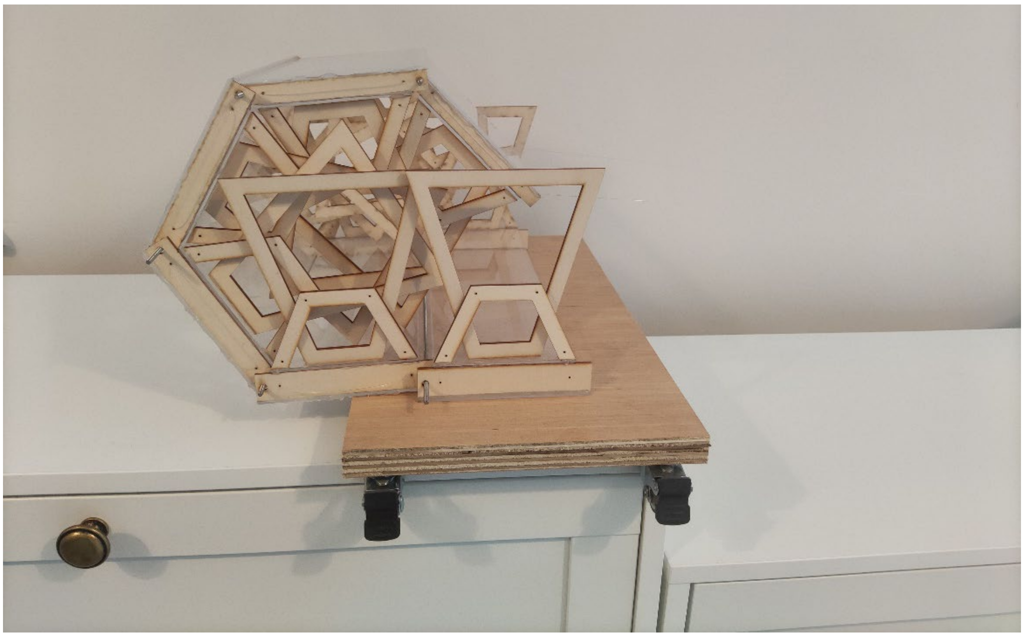


Figure 9.111: Prototype begins to expand on the supporting base

Due to limited project resources, the structural adaptation of the ramp was simulated using a manual technique. In this approach, users interact with a seemingly functional prototype while a human operator – in this case, the author concealed from view – mimics the behaviour of an automated system. This technique is particularly useful when developing a fully functional prototype is time-consuming, expensive, or technically challenging.

As described in Chapter 8.7, the ramp transformation could be possibly implemented through a network of sensors and actuators in an autonomous manner. In this manual simulation, the transformation process was replicated using a set of wires. Wire A was threaded through the wings of the structure, while Wire B was threaded through the side plates. The wires would interchangeably expand and contract the structure as shown in Figure 9.4 and Figure 9.5 respectively.

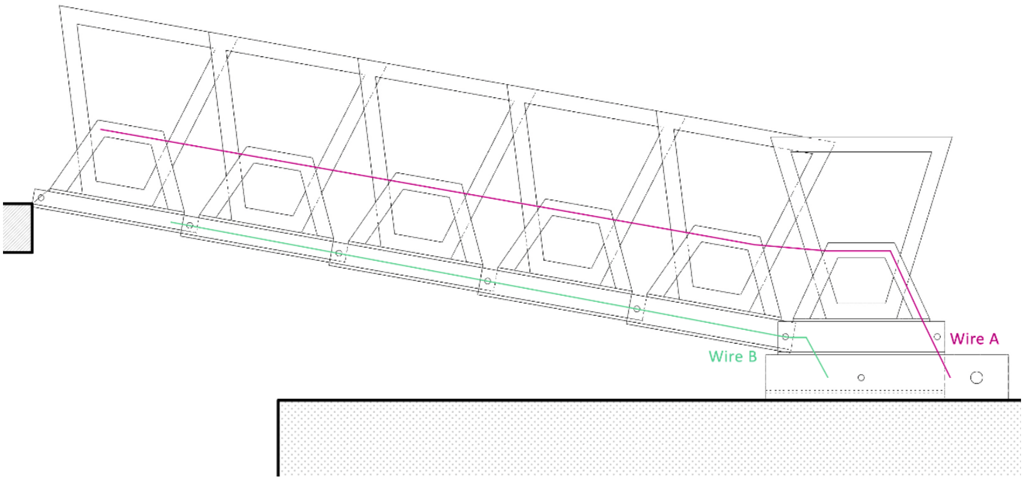


Figure 9.112: Wire configuration – prototype structure expanding

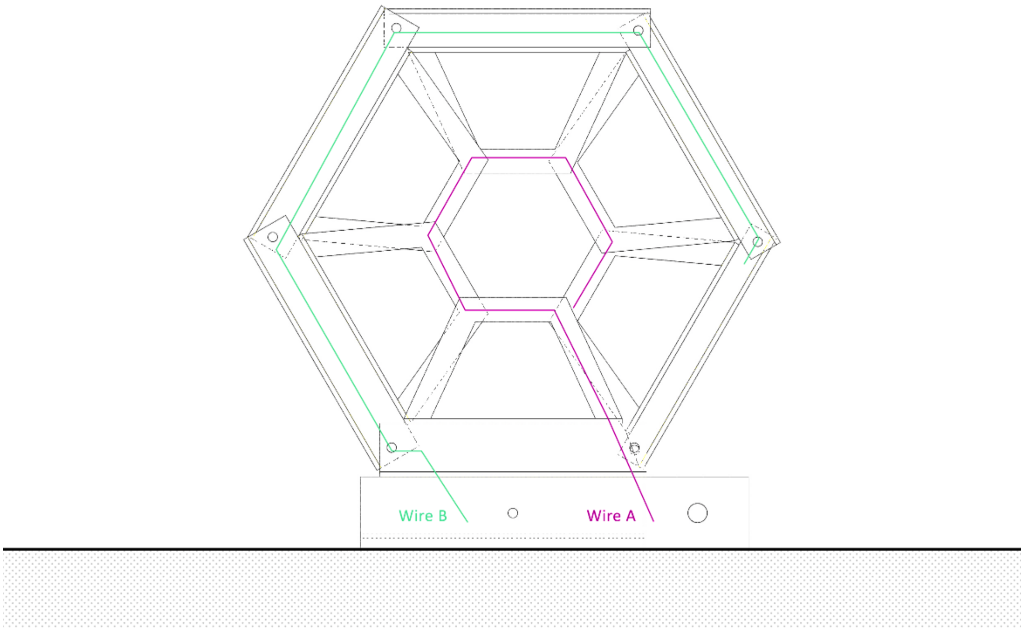


Figure 9.113: Wire configuration – prototype structure contracting

A controlling unit is embedded into the ramp base. The unit includes a steel rod (φ8mm), two wheels, and four plastic-made pipes (as wire outlets). The wheels are secured to the rod; springs are wrapped around the wheels; pipes are affixed between the upper base surface and the bottom plate of the lowermost section. A rotary motion of the rod shall actuate both wheels and – at the same time – pull down one of the wires while releasing the other. This results in the expansion or contraction of the structure. The mechanism is manually driven, assisted by a handle at the end of the rod. Figure 9.6 presents the controlling unit for the adaptation.

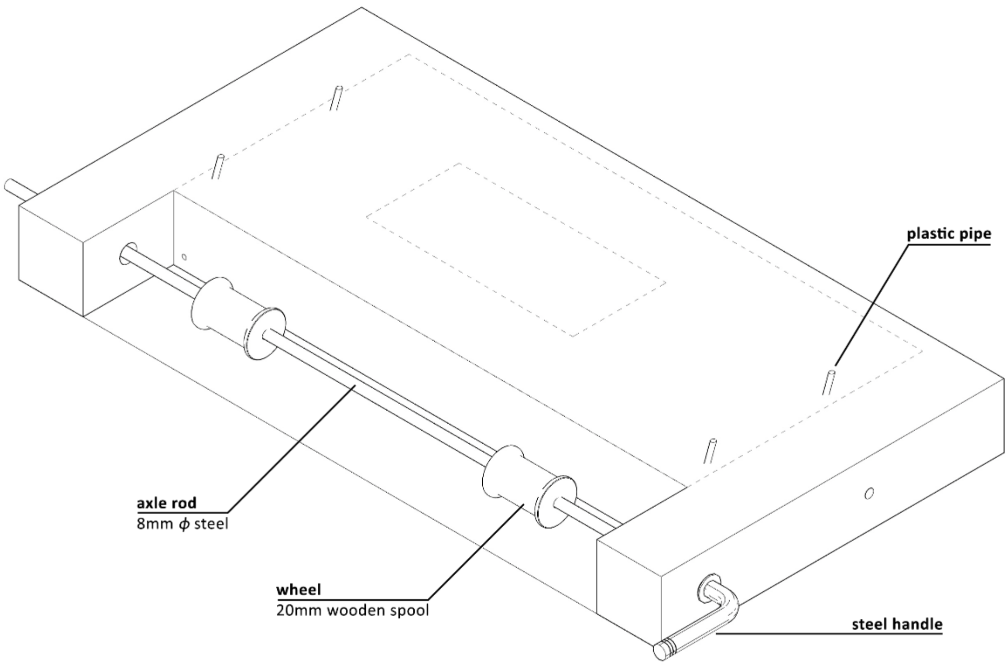


Figure 9.114: Controlling unit for prototype adaptation

9.2.3. Study design

Video narration was used to explain the design vision and present the prototype to study participants. The video included annotated and dimensioned drawings of the ramp, as well as recordings of the scaled prototype. These recordings provided both static and kinetic demonstrations of the ramp's operation, showcasing various functions such as storage, linear movement on the platform, structural expansion and contraction, and on-demand servicing of different locations.

The main part of the design evaluations was implemented through remote, one-on-one meetings with each study participant via the Microsoft Teams platform. Every participant was provided with a link to the video a day before the scheduled meeting.

During the meetings, a reflexive dialogue with participants was conducted to explore the operational aspects and structural elements of the adaptive ramp. The Usability Model for Universal Design Assessment (Cassi et al., 2021) was adopted to streamline the evaluation process. This model facilitates the identification of how spatial settings can enhance human-environment interactions. In this study, this was achieved through a structured evaluation of spatial affordances. Each participant was guided through an investigation of the positive or negative matches between their capabilities or needs (e.g. lateral reach, slope negotiation) and design qualities (e.g. handrail height, ramp width, deployment angles, supporting base) to determine if the proposed intervention could meet their desired performance levels.

The full spectrum of user capabilities and needs was outlined using the categorisation framework from the Inclusive Design Toolkit as described in Chapter 2.1.1. Following the methodology in Chapter 6.2.4, a thematic analysis was conducted based on common topics identified as distinct affordances through the conversations with users. Figure 9.7 explains the application of the Usability Model for Universal Design Assessment on the design evaluation of the proposed solution.

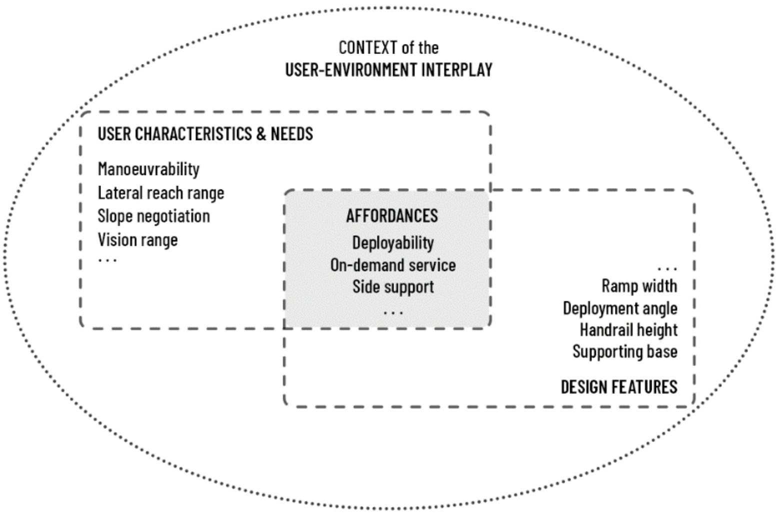


Figure 9.115: User - Environment Interplay

After these conversations, participants were requested to complete an online questionnaire on perceived usability and accessibility of the proposed intervention. For the questionnaire design, the Rapid Assessment of Product Usability & Universal Design (RAPUUD) tool (Lenker et al., 2011) was utilised. Similar studies have used the RAPUUD tool before and its effectiveness has been validated therein (Tabattanon & D'Souza, 2021; Choi et al., 2020; Perez et al., 2019). The questionnaire included 12 questions, rateable on a Likert scale, which were based on the seven principles of Universal Design (see Chapter 2.1). Simple descriptive statistics were used to analyse results from this part. Table 9.1 presents a copy of the online questionnaire.

First name:	**Type of MobAD used:**		**Date of meeting:**	
1. This ramp would be easy to be deployed or prepared to use.				
Strongly disagree	Somewhat disagree	Neutral	Somewhat agree	Strongly agree
2. This ramp would be easy to use.				
Strongly disagree	Somewhat disagree	Neutral	Somewhat agree	Strongly agree
3. This ramp would be easy to get stored.				
Strongly disagree	Somewhat disagree	Neutral	Somewhat agree	Strongly agree
4. For me, potential use of this ramp would NOT pose a personal safety risk.				
Strongly disagree	Somewhat disagree	Neutral	Somewhat agree	Strongly agree
5. I would NOT need assistance to use this ramp.				
Strongly disagree	Somewhat disagree	Neutral	Somewhat agree	Strongly agree
6. If I were to use this ramp, I would NOT make mistakes or errors that would require me to do over some steps.				
Strongly disagree	Somewhat disagree	Neutral	Somewhat agree	Strongly agree
7. I could get the information I need to use this ramp efficiently.				
Strongly disagree	Somewhat disagree	Neutral	Somewhat agree	Strongly agree
8. I would NOT spend more time to use this ramp than it should.				
Strongly disagree	Somewhat disagree	Neutral	Somewhat agree	Strongly agree
9. Potential use of this ramp would require little physical effort.				
Strongly disagree	Somewhat disagree	Neutral	Somewhat agree	Strongly agree
10. Potential use of this ramp would require minimal mental effort.				
Strongly disagree	Somewhat disagree	Neutral	Somewhat agree	Strongly agree
11. Potential use of this ramp would NOT draw unwanted attention at me.				
Strongly disagree	Somewhat disagree	Neutral	Somewhat agree	Strongly agree
12. If I were to use this ramp, I would NOT feel embarrassed.				
Strongly disagree	Somewhat disagree	Neutral	Somewhat agree	Strongly agree

Table 9.26: A copy of the evaluation questionnaire

9.3. Results

9.3.1. Population characteristics

In total, twenty-five MobAD users were recruited for the evaluation study. As shown in Figure 9.8 below, female users (n=15) were the majority.

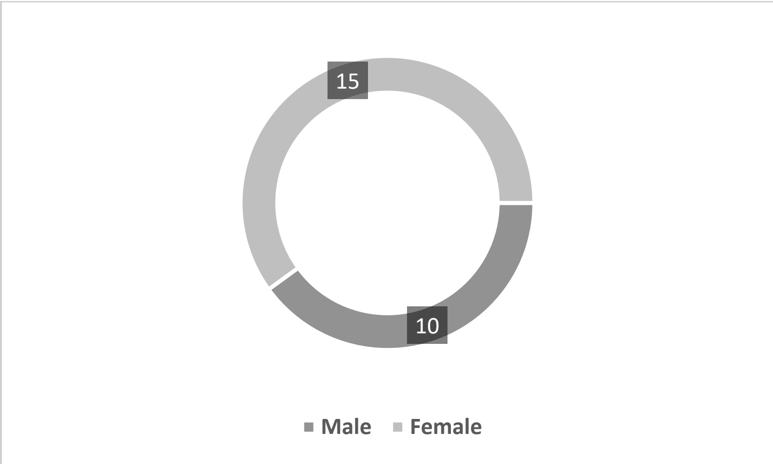


Figure 9.116: Evaluation questionnaires - gender distribution

Looking at Figure 9.9, it is apparent that most respondents (n=8) were in the 46-60 age group, followed by those in the 36-45 (n=6) and the 61-75 (n=6) groups.

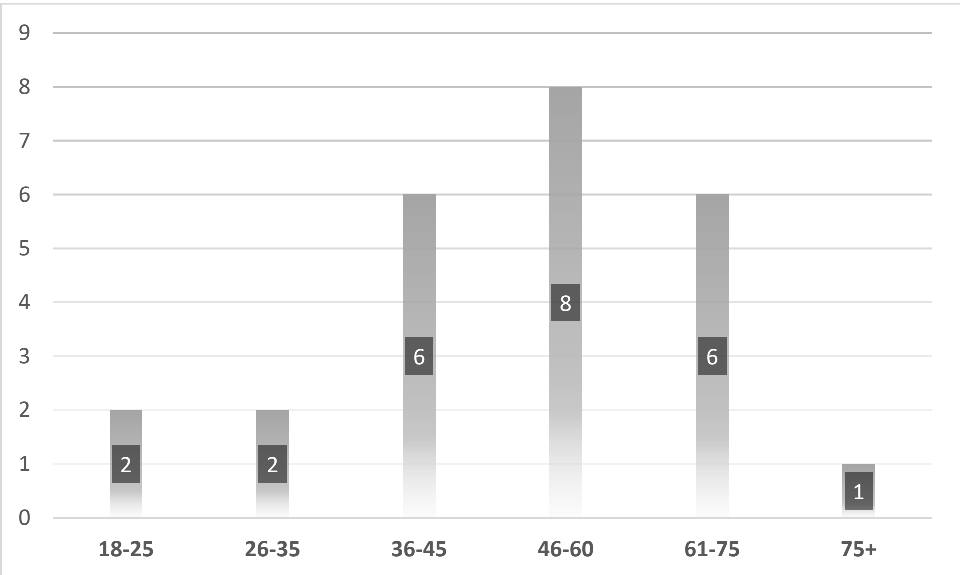


Figure 9.117: Evaluation questionnaires - age distribution

Figure 9.10 presents the summary statistics for the distribution of types of MobAD that respondents used. The majority of the respondents (n=15) were wheelchairs users, with most of those (n=9) using powered wheelchairs.

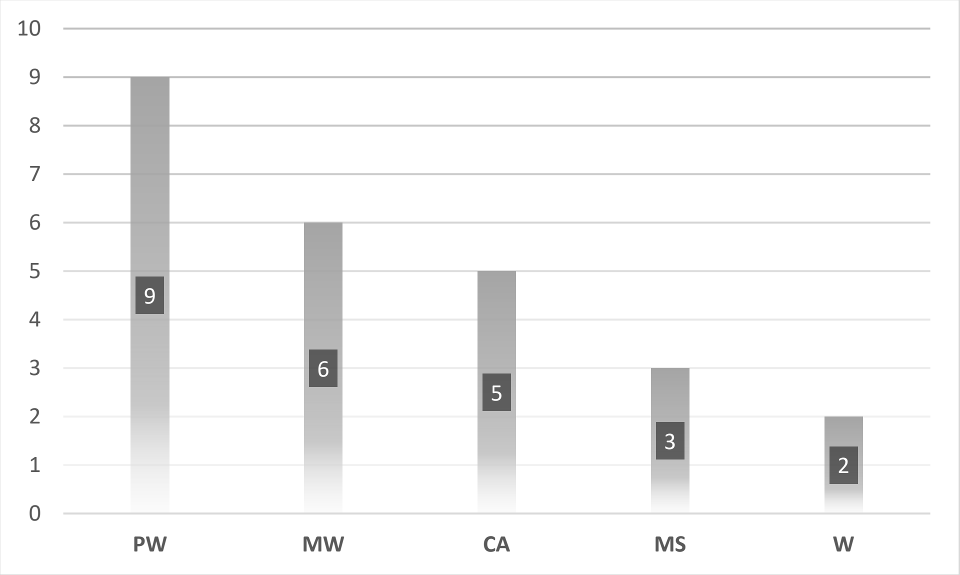


Figure 9.118: Evaluation questionnaires - MobAD distribution. PW = powered wheelchair, MW = manual wheelchair, C = cane, MS = mobility scooter, W = walker.

9.3.2. Questionnaire analysis

The questionnaire included 12 questions, which were rateable on a Likert scale, with 1 being the lowest and 5 being the highest rating per question. Figure 9.11 presents the mean values for all twelve questions in a comparative diagram.

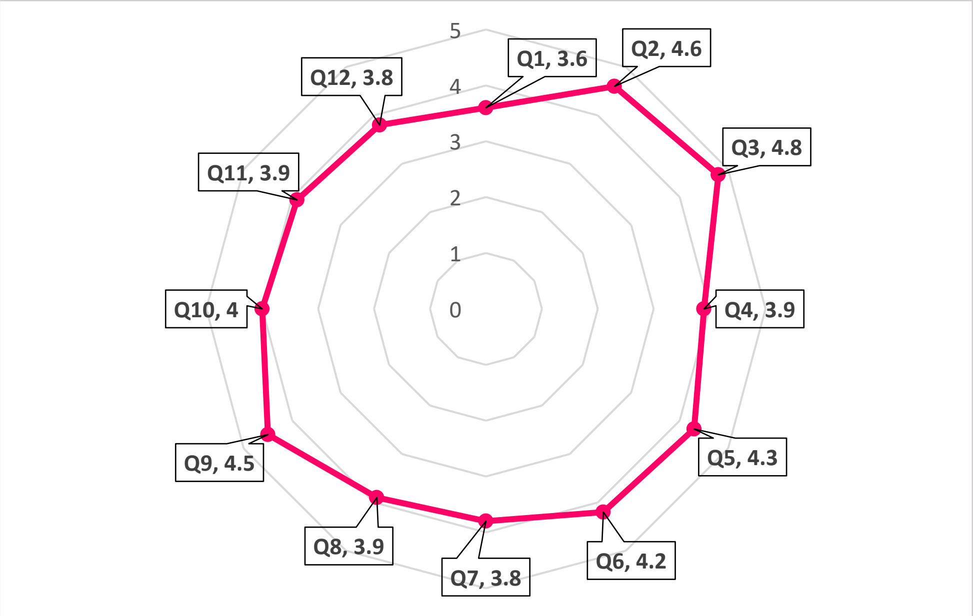


Figure 9.119: An overview of questionnaire mean ratings (question number, mean rating/5)

The most interesting aspect of Figure 9.11 is that no question received a lower mean score than 3, which means that most respondents' perceptions were positive towards the usability and accessibility of the proposed design.

Almost every respondent strongly agreed that the ramp would be easy to use (Question 2) and get stored (Question 3), as reflected by the exceptionally high mean ratings – i.e., 4.6/5 and 4.8/5, respectively.

Also, most respondents found that they would potentially use the proposed ramp with exercising only minimal physical effort (Question 9), as indicated by the respective mean score (i.e., 4.5/5).

Quite reversely, many study participants regarded the proposed ramp as somewhat complicated in terms of deployment (Question 1), as expressed by the relatively low mean score (i.e., 3.6/5), which held the lowest value among all questions.

In addition, some respondents perceived that they wouldn't efficiently get information on how to use the ramp (Question 7) and that they would feel embarrassed when using the ramp (Question 12), as suggested by the somewhat low mean score (i.e., 3.8/5) of both items.

9.3.3. Affordances-based thematic analysis

To determine whether the proposed intervention could accommodate MobAD users' desired levels of performance, the transcripts of all 25 evaluation sessions with study participants were analysed. A thematic analysis was conducted based on identified affordances, which are the positive or negative relationships between design features and MobAD users' functioning capabilities or needs. The most common affordances identified were side support, ramp operation, movement on the platform, gap coverage, safe transition, and structural stability.

9.3.3.1. Side support

The evaluation outcomes pertaining to the side support of the ramp brought to light both positive and negative relationships with MobAD users' performance capabilities. The inclusion of handrails in the ramp design exemplified a positive relationship, as they provided crucial support and stability for users with varying abilities. With a height range of 700-850 mm, the handrails catered to a diverse user base, ensuring that the majority can comfortably and safely navigate the ramp, positively impacting their locomotion and dexterity.

However, Participant 22, an elderly cane user, expressed concerns regarding the handrail arrangement, which underscores a potential negative relationship between side support shape and the specific needs of some users:

> "When I looked at the model, the handrails seemed a bit tricky to use with my cane. I'm not sure they'd give me the support I need to feel safe. This makes me worry about using the ramp on my own because I might not feel steady. If the handrails were easier to grip and better suited for cane users, it would help me feel more secure and confident in navigating the ramp independently."

The confusion surrounding the handrail configuration indicates that the design could benefit from further optimisation to better accommodate the unique requirements of certain individuals, making the ramp more intuitive and user-friendly for all users. This observation highlights the importance of addressing functioning categories such as reach and stretch as well as considering the diverse needs and preferences of all users when refining the ramp design.

9.3.3.2. Ramp operation

The evaluation outcomes regarding the operation of the ramp revealed varying preferences among participants which can be linked to relevant performance capabilities of MobAD users. The majority of participants agreed that using the ramp on-demand as a standalone platform feature was beneficial as it would cater to the thinking, communication, and reach & stretch performance categories. Some participants suggested that this could be achieved with an app, enabling them to order the ramp before boarding or alighting, which would further enhance the communication and thinking aspects of the user experience.

However, a specific subgroup of participants, predominantly older and more frail individuals, expressed a preference for the ramp to be manually operated by a conductor. For instance, Participant 7 who was a mobility scooter user, mentioned:

> “I would feel much safer if the ramp were operated by a conductor. With my limited vision and hearing, having someone there to assist would give me more confidence and reduce my anxiety about boarding and alighting.”

In the similar vein, a powered wheelchair user (Participant 11) said:

> “Using an app to order the ramp sounds complicated to me. I’d prefer if someone could just help with the ramp directly, as it would make me feel more secure and supported.”

This preference can be associated with their concerns regarding personal safety and crowd control due to limited vision, hearing, or locomotion. A manually operated ramp would provide additional support and reassurance to these users, addressing their unique needs.

In contrast, younger MobAD users were more inclined towards fully autonomous scenarios for ramp operation, which they claim it could positively impact their independence, communication, and dexterity. Participant 17, a young wheelchair user, expressed their positive view:

> “I think having an app to operate the ramp would be great. It would make me feel more independent and in control, and it’s something I could easily manage on my own.”

This preference highlights the importance of considering the diverse needs and abilities of all users when refining the ramp design and its operation.

9.3.3.3. Movement on platform

The ramp's ability to move along the platform to accommodate different train doors demonstrated wider acceptance among MobAD users as it catered to the locomotion as well as reach and stretch needs of various users. By ensuring effective positioning, users can access train doors more easily and safely.

However, the concerns expressed by participants regarding ramp movement along crowded platforms highlight a potential negative correlation between this design feature and users' vision, hearing, and communication capabilities. The presence of crowds could make it difficult for users with visual or hearing impairments to navigate the platform, and the ramp movement might exacerbate these challenges. Furthermore, communication difficulties could arise in crowded situations, making it harder for users to understand the ramp's intended path. Participant 3 – a cane user with limited vision – indicated:

> "I worry that moving the ramp along a crowded platform would be confusing and hard to navigate, especially with my poor vision. It might make things more chaotic and stressful for me. If I can't see where the ramp is going, I could easily bump into other passengers or miss the right door. This makes me anxious about using the ramp in busy stations."

To mitigate these potential issues, the majority of participants agreed that the installation of an alert system could be a useful addition to the ramp design. As Participant 13, a wheelchair user, mentioned:

> "Having an alert system would be really helpful. If there were notifications about the ramp's movement, it would make me feel more aware and safer on the platform.

> Clear alerts would help everyone know when and where the ramp is moving, reducing confusion. This system would make it easier for people with hearing or vision issues to stay informed and navigate the platform safely."

This system would amplify users' vision, hearing, and communication status, by notifying passengers of impending ramp movement on the platform, ultimately enhancing safety and accessibility for all users.

9.3.3.4. Gap coverage

Assessing the gap coverage of the ramp reveals both positive and negative associations with the relevant performance capabilities of MobAD users. All participants were delighted to learn that the ramp could cover wide gaps (up to 470mm) and high gaps (up to 460mm) between trains and platforms, which addresses the locomotion and reach & stretch performance categories for a broad range of users.

However, a valuable remark from an experienced wheelchair user and retired mechanical engineer highlighted a potential limitation in the ramp's structural adaptation. This participant pointed out that excessively high and narrow gap combinations might not be accommodated effectively as the lengthy deployment of the ramp in these cases could result in a steep, non-negotiable slope for MobAD users. Specifically, Participant 1 stated:

> "While it's great that the ramp can cover wide and high gaps, I have concerns about extremely high and narrow gaps. What I noticed is that in these situations, the ramp might extend too much and create a steep slope. For example, if the gap is 460mm high but only 100mm wide, the ramp would need to be very long to bridge this gap safely, resulting in a steep incline. This could make it difficult and unsafe for users like me to navigate, as the incline would be too sharp to manage comfortably and securely. Such a steep slope could

> pose serious challenges for people with limited strength, too."

This observation suggests a potential negative relationship with the performance categories of locomotion and dexterity, as users may struggle to safely and comfortably navigate the ramp in such situations.

9.3.3.5. Safe transition

In evaluating the ramp's ability to facilitate safe transitions, both strengths and areas for improvement emerged in relation to MobAD users' performance capabilities. The oblique extension of the supporting base was well-received by participants, as it eases the movement between the ground and the ramp. This aspect of the design effectively caters to users' locomotion and dexterity needs, ensuring a more accessible and secure experience.

Nonetheless, participants indicated that incorporating an analogous feature for transitions between the train floor and the upper ramp segment would further enhance the design. Participants 5 and 15, both users of wheelchairs, commented:

> "The oblique extension at the base is a great feature, but having something similar for the transition between the train floor and the upper ramp would be even better. It would make it much easier and safer for users of wheelchairs to move onto the ramp, especially when dealing with different heights and angles."

> "I think adding a smooth transition from the train floor to the ramp would really help. Without it, there might be a small bump or step that could be tricky for people with mobility issues to navigate. This would definitely improve the overall safety and accessibility of the ramp."

Apparently, the omission of such an element would possibly expose users to challenges related to locomotion, reach and stretch, and dexterity when moving between the train floor and the ramp. This limitation could compromise their safety and overall ease of use.

9.3.3.6. Structural stability

Finally, the evaluation outcomes concerning the structural stability of the ramp revealed some concerns among MobAD users, particularly those utilising powered mobility devices such as electric wheelchairs and mobility scooters. These users were unsure about the ramp's stability and load-bearing capacity when expanded, which could potentially impact their confidence in using the ramp. Participants 14 and 25 seemed concerned about stability:

> "The load-bearing capacity of the ramp is a major concern for me as a mobility scooter user. If the ramp doesn't support my device securely, it could be dangerous. I need to trust that the ramp is stable and strong enough to handle the weight, turning, and movement of my scooter, otherwise, I might avoid using it altogether."

> "I'm worried about the ramp's stability when it's fully extended. Using an electric wheelchair, I need to be confident that the ramp can handle my weight without wobbling. If it doesn't feel stable, I might hesitate to use it, which would impact my ability to travel independently."

This apprehension might create a negative relationship with the users' locomotion and dexterity capabilities, as users might hesitate to utilise the ramp or may experience difficulty in manoeuvring their powered mobility devices near/on it. Moreover, this uncertainty could also affect the users' perception of personal safety, further complicating the boarding and alighting process.

9.4. Discussion

The aim of this chapter was to gather input from MobAD users regarding the proposed access ramp to proceed with necessary adjustments or improvements to it. Twenty-five MobAD users with diverse characteristics were recruited for the evaluations, which were conducted through online interviews. Participants were presented with a scaled prototype of the proposed intervention in both digital and physical formats. After a thorough analysis of different ramp features (i.e. structural components, kinetic behaviour, operation scenarios, and stability considerations) by the author, participants assessed the alignment between their capabilities or needs (e.g. lateral reach, slope negotiation) and design qualities of ramp features (e.g. handrail height, ramp width, deployment angles, supporting base) to determine if the proposed intervention met their desired performance levels. By the end of the sessions, each participant was asked to complete a questionnaire on the ramp's usability based on Universal Design principles. In the end, the proposed solution was evaluated by MobAD users in terms of usability and accessibility, realising the fourth research objective (RO4) of this thesis.

The interviews revealed that autonomy is a critical aspect of the ramp's design for MobAD users. Many participants, particularly younger users, valued the potential for autonomous operation of the ramp via an app, which they believed would enhance their independence. This preference highlights the importance of integrating modern user-friendly technology that allows users to control their access needs directly. Conversely, older participants expressed a preference for manual operation by a conductor, reflecting a need for assistance to ensure their autonomy without compromising their safety. This balance underscores the necessity of offering multiple operational modes to cater to different levels of independence among users, thereby enhancing overall autonomy.

Health and safety were key themes in the participants' feedback, particularly regarding the ramp's structural stability and safe transition features. Users of powered mobility devices such as electric wheelchairs were particularly attentive to the ramp's load-bearing capacity, seeking reassurance that it would remain stable during use. Additionally, participants highlighted the benefit of the oblique extension at the base for easing transitions and suggested a similar feature for the transition between the train floor and the upper ramp segment. These insights suggest that the ramp design must ensure robust structural integrity and safe, seamless transitions to protect users' health and prevent accidents.

The ramp's ability to support social participation was also a key consideration in interviews. Participants appreciated the ramp's movement along the platform to align with different train doors, facilitating easier access. However, using the ramp in crowded environments posed challenges, particularly for those with visual or hearing impairments, as navigating a moving ramp in such conditions could be difficult. The suggestion of an alert system to notify users of the ramp's movement was well-received, as it could enhance users' ability to interact safely and effectively in busy public spaces. Addressing these aspects is vital for ensuring that the ramp design supports social inclusion and allows all users to participate fully in public transportation settings.

Findings from both activities indicated that the study population was satisfied with the proposed design overall. Results from both the interviews and questionnaires show that the proposed ramp design was largely well-received by users in terms of usability and accessibility. The evaluation revealed that using the ramp on-demand as a standalone platform feature was appreciated, which is reflected in the high mean score for the ramp being easy to use (Question 2). The presence of handrails and the oblique extension of the supporting base also contributed to the perception that users could use the ramp with minimal physical effort (Question 9). Participants' satisfaction with the ramp's ability to cover wide and high gaps while providing manageable slopes further supports the positive results from the questionnaires.

Negative findings from both the interviews and the questionnaires, however, indicate areas where the proposed ramp design could be further improved. The preference of older and frail participants for a manually-operated ramp and their concerns regarding personal safety and crowd control could be linked to the perceptions of inefficient information on ramp usage (Question 7). Additionally, concerns about ramp movement along crowded platforms might also contribute to users' perceived difficulties in understanding the ramp's intended path, leading to lower scores in the same question.

Most importantly, some participants found the ramp somewhat complicated in terms of deployment (Question 1). This difficulty is likely related to the evaluation findings that indicated excessively high and narrow gap combinations, which may hinder smooth deployment and make it challenging for participants to use the ramp effectively. This highlights the need for further design refinement to address irregular gap dimensions. Moreover, suggestions for incorporating a feature for smoother transitions between the train floor and the upper ramp segment demonstrate that users identified potential improvements that could enhance the overall safety and accessibility of the ramp design. Therefore, after further consideration of the ramp design, the decision was made to revise the design of the uppermost segment of the ramp to better align with users' feedback.

9.4.1. Design refinement

Specifically, the top and bottom plates are replaced with a solid rectangular box (load-bearing box) which is split into two equally-sized partitions in such a way that the uppermost part fits inside the lowermost one. At the end of the uppermost partition, a wedged extension is mounted. The wings and handrails of the segment are affixed on the side plate which have been scaled up to ensure extra stability. Figure 9.12 visualises the revised design of the uppermost segment. When actuated, a sliding mechanism moves the uppermost partition (and the mounted extension) towards the lowermost one, in an inwards manner, as visualised in Figure 9.13.

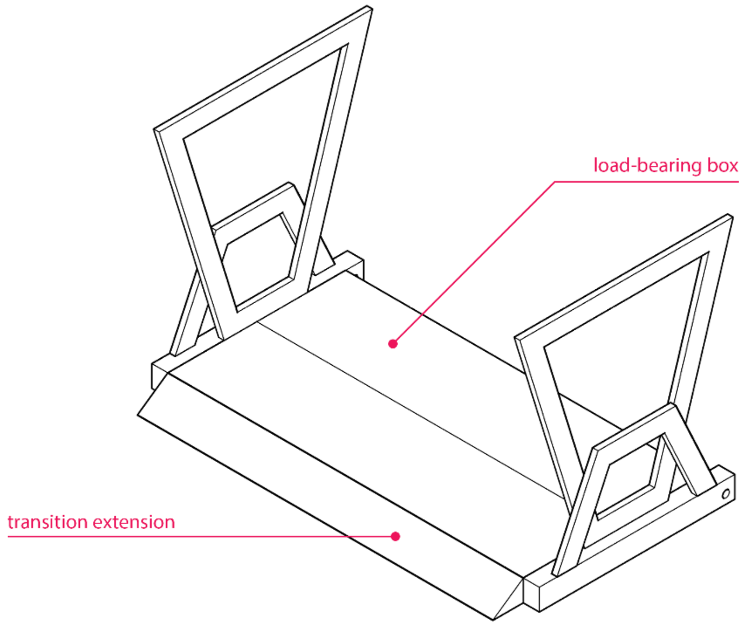


Figure 9.120: Revised design of uppermost ramp segment

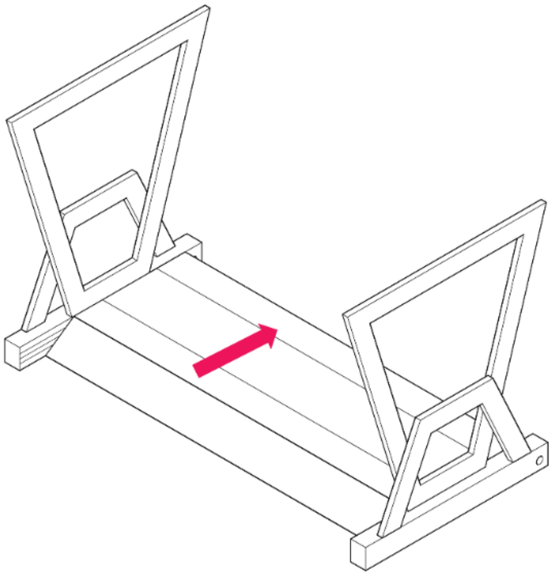


Figure 9.121: Retractable movement using a sliding mechanism

This revised configuration has two main benefits: (a) it provides a smooth transition from the train floor to the ramp and (b) it momentarily decreases the length of the uppermost segment in such a way that the ramp can accommodate extremely tight PTIs – where the ramp is called to bridge excessively high and narrow gaps – without obstructing the even movement of MobAD users (Figure 9.14). According to the scenario of autonomous ramp operation described in Chapter 8.7, the ramp can be equipped with intelligent systems (e.g. infrared sensors) which are capable of accurately estimating the physical gap between the train and the platform edge. In the case where an extremely tight gap is identified, those systems can order the actuation of the sliding mechanism so that the uppermost section is retracted and users' access is facilitated (Figure 9.15).

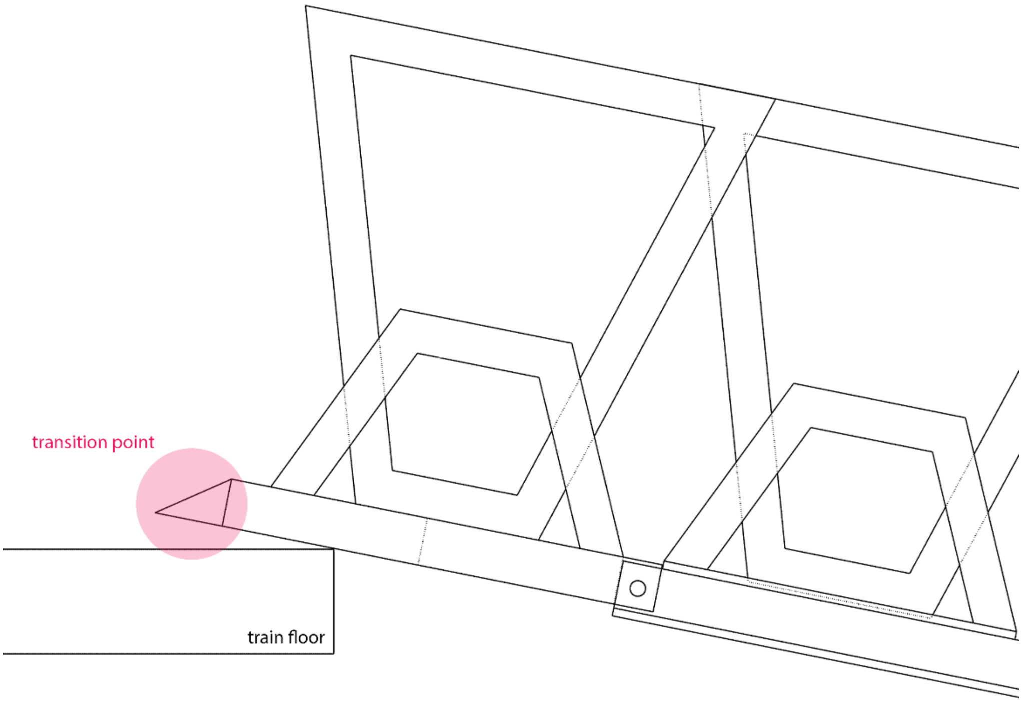


Figure 9.122: Pre-refinement: design obstructs MobAD users to use the ramp in the case of tight gaps.

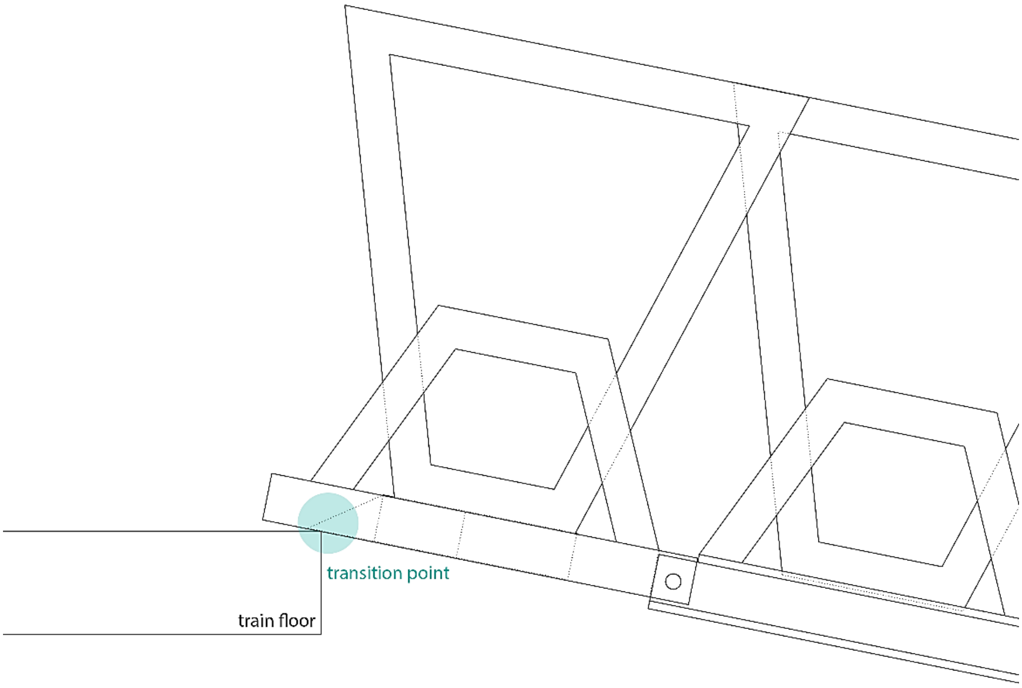


Figure 9.123: Post-refinement: revised design allows the uppermost ramp segment to compress until the ramp provides a smooth and even transition to MobAD users.

In conclusion, the iterative process of refining the ramp design based on users' feedback has been instrumental in ensuring the final design effectively addresses the needs and preferences of a diverse range of MobAD users. The refined version of the proposed ramp embodies the design qualities identified during the co-design workshops in the ideation stage (Chapter 6.3.2), demonstrating a successful integration of users' insights into the design process. Specifically:

- The ability to function with minimal human intervention could be possibly realised through the autonomous ramp operation as described in Chapter 8.7, which employs intelligent systems (e.g. infrared sensors) to estimate the physical gap and facilitate users' access.
- The ramp's ability to accommodate different access points on the platform is achieved through its sliding movement along the platform, allowing users to access the ramp at various boarding points and ensuring flexible usage across the UK rail fleet.

- The wide range of gap coverage is made possible through the structural transformation as well as the revised design of the uppermost segment, which retracts to accommodate extremely tight PTIs and address excessively high and narrow gaps without obstructing MobAD users' movement.
- Side support is provided by the inclusion of handrails in the design, ensuring essential stability and support for users with varying abilities while also accommodating a broad range of user heights.
- The smooth transition from/to the ramp is addressed through the addition of the wedged extensions mounted on the uppermost partition and the supporting base, allowing for seamless movement among the three parts of the interface (i.e. the train floor, the ramp, and the platform).
- Finally, the standalone design of the ramp, which renders it not vehicle-specific or fixed on certain points on the platform, contributes to its adaptability and versatility. This allows the ramp to be compatible with various public transport infrastructures and not limited to specific train carriages or fixed platform locations.

By considering users' feedback and refining the ramp design accordingly, this research has successfully developed a solution that aligns with the desired design qualities and has the potential to significantly enhance the accessibility and usability of public transportation for MobAD users.

9.4.2. Study limitations and critical appraisal of the design concept

Despite efforts to ensure the methodological credibility of this study, several limitations were identified. One limitation is the use of the Rapid Assessment of Product Usability & Universal Design (RAPUUD) tool instead of open-ended questions. The decision to use RAPUUD was based on its proven effectiveness and validation in similar studies (Lenker et al., 2011; Tabattanon & D'Souza, 2021; Choi et al., 2020; Perez et al., 2019). The structured nature of RAPUUD facilitates efficient data collection and ensures consistency across responses. However, this approach may have restricted participants from expressing nuanced insights and diverse perspectives that open-ended questions might have captured. Additionally, some of the questions included in the RAPUUD tool were difficult for participants to answer as the presented prototype was a scaled model of the proposed ramp solution and there was no physical interaction with the prototype. To address these limitations in future research, a mixed-methods approach could be employed, combining the RAPUUD tool with open-ended questions and/or in-person evaluation sessions to gather more comprehensive and detailed feedback from users.

Another limitation is the absence of design experts in the evaluation process. This choice was made to focus exclusively on the experiences and feedback of MobAD users, ensuring that their voices were prioritised in assessing the ramp's usability and functionality. However, the lack of input from design professionals means that the evaluation may have missed expert insights on technical feasibility, innovative design solutions, and potential improvements. In future studies, involving design experts alongside end-users could provide a more holistic evaluation. Expert feedback can complement user insights, offering advanced perspectives on design refinements and ensuring that the proposed solutions are both user-friendly and technically sound.

The study was conducted online only due to COVID-19 restrictions, which presented a significant limitation regarding digital exclusion, particularly among older adults. While online methods allowed for safe and timely data collection, they may have excluded participants who are less comfortable with digital technology, thereby potentially skewing the sample towards more tech-savvy individuals. This limitation may have affected the representativeness of the findings, as older adults who face digital barriers might have different usability needs and preferences. To mitigate this issue in future research, hybrid methods that combine online and in-person data collection should be employed.

This approach would ensure inclusivity, allowing all demographic groups to participate and providing a more comprehensive understanding of the ramp's usability across diverse user profiles.

The design concept of the adaptive access ramp represented a significant step forward in addressing the PTI challenges faced by MobAD users. By integrating user feedback into the design process, the ramp aims to bridge the physical gap between trains and platforms, enhancing accessibility for individuals with diverse mobility and dexterity needs. The iterative process of refining the design based on user input demonstrates a commitment to human-centred design principles, ensuring that the ramp is functional and responsive to the real-world needs of its intended users.

However, while the concept shows promise, it is important to critically appraise its practicality and scalability. The inclusion of features such as handrails, adjustable components, and potential digital interfaces reflects an understanding of the varied requirements of MobAD users. Yet the feedback also highlighted areas where the design could be improved, such as the need for better transition features between the train floor and the ramp and ensuring the ramp's stability under different conditions. These reflections underscore the complexity of designing for a diverse user group, where the needs of elderly users and those with specific disabilities must be balanced with the preferences of younger, more tech-savvy individuals.

Moreover, considering the user group's feedback, the design must account for practical implementation challenges, such as the ramp use in crowded environments and its integration into existing transport infrastructure. Future iterations of the design should incorporate these considerations to enhance the ramp usability and effectiveness further. By continuing to engage with a broad spectrum of users and incorporating expert insights, the design can evolve to meet the PTI challenges more comprehensively, ultimately fostering greater autonomy, safety, and social participation for all users.

10. General discussion

The purpose of this research was to explore how ill-designed spatial environments impact MobAD users and identify ways designers can create accessible settings for them. Following a research-by-design approach, the first part of the thesis, particularly Chapters 4 and 5, investigated the effects of inappropriately designed environments on MobAD users. The findings revealed that platform-train interfaces are the most problematic, significantly affecting the quality of life of MobAD users. The second part of the thesis, covering Chapters 6 to 9, focused on developing an adaptive access ramp as a potential solution to this design problem. Consequently, the main aim of this work was achieved, demonstrating how certain spatial conditions act as barriers to MobAD users. The developed design methodologies and outcomes have the potential to enhance access for MobAD users in the built environment.

10.1. Implementation of research objectives

It is also important to mention how different parts of the thesis realised the research objectives as those were defined in Chapter 1.3.

Beginning from research objective 1 (RO1 - identifying accessibility barriers in the built environment), findings from the systematic literature review (Chapter 3) indicated a substantial number of inaccessible elements for MobAD users in public spaces. Pathway characteristics, boarding ramps, entrance features, confined spaces, and service surfaces were deemed to be the least accessible elements. This knowledge was augmented by the objective accessibility assessment (Chapter 4.3.1), which corroborated that transport facilities were identified as particularly problematic in terms of MobAD accessibility, with most problems attributed to platform-train interfaces (PTIs).

Transitioning to research objective 2 (RO2 - engaging with MobAD users to gather insights on challenges due to barriers and co-ideate solutions), findings from the subjective accessibility assessment (Chapter 4.3.2) showed that the majority of MobAD users faced considerable difficulties when boarding or alighting rail carriages. Taken together, evidence from Chapters 3 and 4 ushered this research to closely investigate the physical gaps that develop between trains and platforms as the design problem of this work. Discussions with actual users of MobAD (Chapter 6) foregrounded that not only problematic PTIs impacted users' everyday life activities, but also existing solutions such as conventional ramps were insufficient in terms of accommodating their access. As such, it was decided that a novel solution should be sought. After a comprehensive series of co-ideation workshops, MobAD users and experts provided valuable feedback on their requirements and design preferences for a new solution (Chapter 6.3.2).

The third research objective (RO3 - developing solutions to enhance accessibility within the built environment using innovative methods) was realised through the development process of a possible solution for PTIs (Chapters 7 and 8). Specifically, advanced AI methods were utilised to extract design information from precedent projects (Chapter 7.4.1) and then optimise the retrieved design outputs to satisfy the functional needs of a wide range of MobAD users (i.e. the "universal" MobAD user) (Chapter 7.4.2). Building on the results of the optimisation process, this work proposed a solution (i.e. an adaptive access ramp – Chapter 8) which was designed based on MobAD users' preferences as those were solicited in the co-ideation workshops.

Lastly, Chapter 9 implemented the fourth research objective (RO4 – assessing the effectiveness of the developed solution). Using online interviews and questionnaires, the adaptive ramp was evaluated by MobAD users in terms of usability and accessibility. This evaluation was very fruitful to the creative process, as users' feedback highlighted areas where the design of the ramp could be improved. It also indicated practical implementation challenges that need to be addressed before the proposed solution is realised.

10.2. Role of theoretical background in research activities

It is also noteworthy to mention how different theories and concepts, as described in the theoretical background section of this thesis (Chapter 2), have influenced research undertakings.

Universal design principles and guidelines (Chapter 2.1) contributed to almost all stages throughout the design process, including assessment of existing environments, design ideation and formation, and user evaluation stages (see Table 2.3). This contribution referred to methodological structures (e.g., “Strategies for universal design” by Steinfeld & Maisel (2012) was used to inform the spatial audit instrument for the accessibility assessment – Chapter 4.2) as well as practical aspects (e.g., universal design resources from the IDEA Centre were used as design objectives in the optimisation process – Chapter 7.3.2).

Co-design methods (Chapter 2.2) were elemental to the engagement/co-ideation and evaluation stages of this work (see Table 2.4). Knowledge from co-design resources assisted with building a methodological basis for soliciting users’ feedback throughout the creative process (e.g., remote co-design workshops – Chapter 6.2.3 and use of prototypes for usability evaluation – Chapter 9.2.2).

Computational design techniques and tools (Chapter 2.3) enabled the implementation of the design development stage to a considerable extent (see Table 2.5). Algorithmic approaches (e.g., machine learning) as well as parametric models have allowed this research to retrieve knowledge from numerous precedent projects (Chapter 7.3.1) and mathematically optimise designs models to satisfy MobAD users’ requirements (Chapter 7.3.2), thus formulating the proposed design solution.

Structural adaptation techniques (Chapter 2.4) and most importantly components of the Adaptive Architecture Framework (Schnädelbach, 2010) facilitated the development of the design solution and the evaluation stage (see Table 2.6). Essentially, the design concepts described in this framework were integral to the creation of a flexible solution (Chapter 8), which would change its structure, thereby responding to the needs of MobAD users PTIs. Also, this structural adaptability characterised the development of the prototype, which was used in the evaluation sessions (Chapter 9) as a scaled model of the proposed solution.

10.3. Contribution of this work

This section delineates the contributions of this PhD research across four distinct areas: advancing research knowledge, improving relevant methodologies, informing the design practice, and benefiting society at large. By systematically addressing these aspects, the contributions of this study underscore its multifaceted value and relevance to both academic and real-world contexts.

10.3.1. Research contribution

This work provides a comprehensive identification and analysis of the physical barriers present in built environments that significantly impede the access of MobAD users. By employing a mixed-methods approach, including surveys, user interviews, and spatial analysis, the research meticulously mapped out the specific architectural and design elements that create challenges. These findings contribute to the existing body of knowledge (Atoyebi et al., 2019; Bigonnesse et al., 2018; Zhang et al., 2017) by offering detailed insights into how various physical barriers affect the daily lives and independence of MobAD users, highlighting the urgency for inclusive design practices. A key contribution of this research is the extension of existing knowledge regarding physical obstacles that impact less-studied aspects of functioning for MobAD users, such as knee and toe clearances. The accessibility assessment (Chapter 5) provided empirical evidence supporting the importance of these factors in terms of MobAD accessibility in built environments. Additionally, this study found that older, fully dependent users of non-powered MobAD (e.g. manual wheelchairs, canes) were more intensely affected by physical barriers, emphasising the need for targeted interventions and design considerations for this vulnerable population group.

This research significantly advances the universal design approach by integrating co-design methodologies wherein MobAD users actively participate in the design process. Previous studies, such as those by Tuinstra et al. (2018) and De Couvreur & Goossens (2011), have demonstrated the value of co-design in enhancing the inclusivity and usability of design outcomes. Building on these foundations, this study involved MobAD users through co-design workshops, interviews, and user evaluations, ensuring that their lived experiences and feedback directly inform the design solution. By engaging MobAD users in co-design, this research contributes to the field by demonstrating how such participatory methods can lead to more innovative and human-centred design solutions. This participatory approach aligns with the principles highlighted in earlier works, emphasising the importance of user involvement in creating environments that truly meet the needs of all users (Simonsen & Robertson, 2012). The expansion of universal design to incorporate co-design broadens the scope of universal-design principles and sets a precedent for future research and practice to prioritise inclusivity and collaboration with MobAD users. This enhancement ensures that developed environments are more inclusive, effectively addressing the specific needs and preferences of MobAD users, and thereby advancing the field of inclusive design.

It is also worth mentioning that this thesis has utilised structural adaptation to design for MobAD-accessibility, thereby expanding the ambit of the Adaptive Architecture Framework (Schnädelbach, 2010) towards universal design. Specifically, the design process incorporated structural transformations, such as curling and shifting, to create elements that are easily accessible and adjustable to the unique needs of MobAD users. This novel approach complements the existing components of Schnädelbach's framework, which primarily focus on aspects like environmental adaptation, material responsiveness, and user interaction. By integrating structural adaptation with universal design principles, the thesis enhances the Adaptive Architecture Framework with a human-centred and inclusive dimension, ensuring that built environments cater to a diverse range of user requirements and preferences. This showcases the potential of this effort, with respect to incorporating structural adaptation into a universal design approach, to inform and possibly influence accessibility regulatory guidelines like Building Regulations - Document M (UK Government, 2024). Ultimately, this fusion of adaptive architecture and universal design contributes to the creation of more equitable and adaptable spaces, promoting greater accessibility and inclusivity for all users.

10.3.2. Methodological contribution

This research introduces an innovative co-design workflow that leverages remote asynchronous co-design workshops and interactive whiteboards, addressing the challenges of traditional synchronous co-design methods. While a few studies, such as those by Voorend et al. (2019) and Winschiers-Theophilus et al. (2022), have explored remote co-design methods, the integration of asynchronous elements and advanced interactive tools remains relatively under-explored. This approach allowed participants of the co-design workshops (Chapter 6) to contribute at their own pace and convenience, enhancing inclusivity and accommodating diverse schedules. The use of interactive whiteboards facilitated real-time collaboration and ideation, creating a dynamic and engaging environment for participants to share and refine ideas. This methodological innovation broadens the scope of co-design by making it more accessible and flexible and provides a structured – yet adaptable – framework that can be utilised in various design contexts. By incorporating these advanced tools and methods, this research significantly contributes to the field by demonstrating how remote and asynchronous co-design can be effectively implemented to yield human-centred design solutions, particularly benefiting those with mobility disabilities.

This work promotes a sophisticated AI-mediated workflow designed to recognise and retrieve design knowledge from precedent projects using machine learning tools. Prior research has mainly utilised machine learning to generate floor plans based on precedent projects, often overlooking other built environment elements or specific projections (Chaillou, 2019; Evangelou, 2021). This system, a content-based image retrieval (CBIR) workflow, leveraged deep neural networks to analyse and categorise vast amounts of visual data from architectural projects (Chapter 7.3.1). Unlike traditional methods, which often rely on manual searches and subjective judgement, this automated system provided a precise and efficient way to access relevant design precedents. By employing deep neural networks, the system could accurately identify and interpret complex design elements and patterns. This innovative approach streamlines the retrieval of design knowledge and enhances the quality and relevance of the information accessed, offering significant advancements in the way design research is conducted. The unique integration of advanced data-driven technologies marks a significant contribution to the field, setting a new standard for how design precedents can be effectively utilised in contemporary architectural practices.

This research presents a pioneering evolutionary-computing workflow specifically tailored to designing inclusive environments by considering user functioning capabilities as optimisation objectives. This approach utilised evolutionary algorithms to generate and refine design solutions that accommodate the diverse needs of MobAD users (Chapter 7.3.1). By incorporating various user functioning capabilities (e.g. reach range and manoeuvrability) into the optimisation process, the workflow ensured that the resulting designs are practically effective in enhancing accessibility and usability. This method marks a significant departure from traditional design optimisation techniques, which often neglect the nuanced needs of disabled users. Through iterative cycles of mutation, crossover, and selection, the evolutionary algorithm evaluated numerous design alternatives, progressively improving them to meet the specified accessibility criteria. This innovative application of evolutionary AI in inclusive design demonstrates the potential for advanced computational methods to solve complex design challenges and sets a new benchmark for future research and practice in the field. The ability to systematically and efficiently optimise designs for inclusivity purposes represents a major advancement, contributing significantly to the development of more accessible built environments.

10.3.3. Practical contribution

This research puts forward an adaptive access ramp as a novel solution to bridge the physical gaps at PTIs, addressing the critical issue of accessibility in public transport facilities. As the results from the co-design workshops showed (Chapter 6.3.1), traditional solutions for PTIs were met with disapproval from MobAD users due to their limited effectiveness and usability. In contrast, the proposed adaptive access ramp was meticulously optimised to meet the functioning capabilities of a wide range of MobAD users (Chapter 7.3.2). Also, this solution was developed based on extensive user feedback, ensuring it aligns with users' design preferences and practical needs (Chapter 8.8). Key features of the adaptive access ramp included its potentiality to function with minimal human intervention, empowering users' autonomy. Additionally, the ramp was designed to accommodate different access points, potentially offering broad serviceability across various train and platform configurations. The inclusion of side support and an even transition could further enhance safety and comfort, providing a seamless and secure boarding experience. As a standalone solution, the adaptive access ramp could operate independently of existing infrastructure modifications, making it a versatile and practical option for improving accessibility in public transportation systems. This innovative approach addresses the limitations of previous solutions and can possibly enhance the mobility and independence of MobAD users, contributing to more inclusive urban environments.

A sophisticated visual algorithm – developed within a CAD environment – provides an innovative solution for determining the optimal ramp width and length for PTIs. This algorithm considered various design criteria that influence the design environment, including platform characteristics (width, length, height, and distance from rail tracks), train step characteristics (height, distance from rail tracks), and user requirements (accessibility gradient) (Chapter 7.2.2). By integrating these diverse factors, the algorithm ensured that design solutions are tailored to the specific conditions of each PTI and the needs of MobAD users. For urban designers and transport planners, this tool is particularly valuable as it offers a reliable method to ensure accessibility at transport facilities. The algorithm enhances the design process by providing precise data-driven recommendations for ramp dimensions, facilitating safe and efficient boarding for all users. Automating the estimation of optimal ramp configurations improves the accuracy and efficiency of design workflows and ensures that accessibility considerations are systematically addressed. This contribution is crucial for developing inclusive environments that accommodate the needs of all passengers, particularly those with mobility impairments, thereby advancing the principles of universal design in urban infrastructure.

A significant contribution of this research is the emphasis on interdisciplinary collaboration. By combining insights from disability studies, industrial design, architecture, structural engineering, and artificial intelligence, urban designers and transport planners can receive comprehensive multidisciplinary information that enhances their ability to create more inclusive built environments. This collaborative approach ensures that produced solutions are technically robust, practically viable, and specifically tailored to the diverse needs of all people, regardless of their functioning status. Disability studies provide deep insights into user needs and barriers, while architecture and design contribute to functional and aesthetically pleasing environments. Structural engineering ensures the feasibility and safety of these designs, and artificial intelligence offers advanced tools for their optimisation and customisation. By adopting an interdisciplinary outlook, this research can serve as a model for future research and interventions aimed at improving the accessibility of the built environment, resulting in urban spaces that are more inclusive for all individuals, including MobAD users.

10.3.4. Societal contribution

This work makes significant societal contributions by corroborating concepts such as the “social construct of disability” (Finkelstein, 1993; Goldsmith, 1997) and “design apartheid” (Imrie, 2000) while identifying gaps in existing accessibility regulations (Chapter 4). The social construct of disability is a critical concept in understanding the challenges faced by disabled individuals in contemporary society (Goldsmith, 1997). As demonstrated in the systematic review (Chapter 3), physical barriers in public spaces often exacerbated inequalities and the exclusion of people with disabilities. The findings underscore the assertions of disability scholars and activists who argue that the built environment can play a significant role in perpetuating these inequalities (Hamraie, 2018; Null, 2013).

Imrie's (2000) concept of “design apartheid” is central to understanding the societal implications of this research. The term refers to the way in which the built environment can act as a “disabling” factor, discriminating against users of spaces by impeding their access (ibid.). The findings of the accessibility assessment (Chapter 4) revealed that MobAD users were more likely to encounter difficulties when accessing or using public spaces that do not adhere to accessibility standards. This indicates that the existing set of guidelines may accurately reflect the functioning needs of the majority of MobAD users in relation to access and use of public spaces. However, the research also identified shortcomings in current regulatory frameworks that need to be addressed to ensure a more inclusive environment for all. As such, this work signifies the need to update and refine these guidelines to better accommodate the diverse needs of all users, ensuring truly inclusive public spaces.

This PhD research plays a crucial role in raising awareness about the challenges faced by MobAD users when accessing public spaces. By providing empirical evidence and real-life examples, the work sheds light on the daily struggles of individuals with disabilities, which might otherwise remain invisible to the majority of the population. This increased awareness can foster empathy and understanding among the general public, policymakers, urban planners, and spatial designers. Highlighting specific barriers such as uneven pavements, inadequate ramp provisions, and inaccessible building entrances, the research offers a compelling narrative that underscores the importance of accessibility in everyday life.

The findings from this research hold significant potential to inform policy and advocacy efforts aimed at promoting the rights of people with disabilities and ensuring equal access to public spaces and transport. By identifying the shortcomings in existing accessibility regulations and providing empirical evidence on the most problematic situations faced by MobAD users, this study offers valuable insights for policymakers, advocates, and decision-makers. These insights can help guide the development of more effective policies, strategies, and regulations to address accessibility challenges and contribute to the creation of a more inclusive and equitable society.

Furthermore, by offering evidence-based solutions to improve accessibility for MobAD users, this research empowers the disability community by demonstrating that change is possible and that their needs can be addressed through thoughtful design and policy interventions. This empowerment can enhance the overall well-being and sense of agency among individuals with disabilities, reinforcing their right to participate fully in society. By showcasing the potential for improvement, the research serves as a catalyst for change, inspiring the disability community and its allies to continue advocating for more inclusive and equitable environments.

10.3. Strengths and limitations

The following lines outline the strengths and limitations of the current work. Strengths reflect the thesis's alignment with responsible research objectives, while limitations refer to methodological shortcomings of the research design.

10.3.1. Strengths

The biggest strength of this research is its alignment with the Responsible Research and Innovation (RRI) principles, which ensured that the developed methods and generated outcomes are relevant, ethical, and beneficial to science and society. RRI is an approach that aims to ensure the ethical, social, and environmental acceptability of research and innovation processes by involving various stakeholders, including researchers, policymakers, industry, civil society, and the public, in the design, implementation, and evaluation of research and innovation activities (UKRI, 2023). In the context of this PhD research, RRI plays a critical role in ensuring that the project's objectives and findings align with societal values and priorities and contribute positively to the well-being of individuals with disabilities. The following aspects of RRI can be identified in this PhD research:

- *Public engagement*: The research actively involved MobAD users in the accessibility assessment (Chapter 4) and design ideation workshops (Chapter 6), soliciting their opinions on physical accessibility and the challenges they face in accessing public spaces. This engagement also ensured that the perspectives of those directly affected by the issue were considered in the research process and the development of the adaptive access ramp.
- *Open access and transparency*: By making the research findings and design outputs openly accessible to the public (e.g. the

created visual algorithms are stored in an online publicly accessible repository), the study promotes knowledge sharing and transparency, which are essential for fostering trust and collaboration among stakeholders working towards more inclusive and accessible environments. Moreover, the developed workflows (Chapters 6 and 7) encourage open, transparent, and collaborative processes, fostering knowledge sharing and mutual learning among stakeholders. This emphasis on transparency and openness aligns with RRI's goals of promoting trust and accountability in research and innovation activities.

- *Inclusivity and diversity*: The research addresses the diverse needs of MobAD users, ensuring that the built environment is more inclusive and accessible to all, regardless of their functioning capabilities or device characteristics. The research also acknowledges the diversity among MobAD users, such as age and type of assistive device used, and considers these factors in its analysis and design solution. This recognition of diversity ensures that the research outcomes are relevant and beneficial to a wide range of individuals with disabilities.

- *Ethics*: The study adheres to ethical principles and guidelines throughout the research process, ensuring that the rights and well-being of research participants are protected and the research findings are presented accurately and transparently. Also, the followed research methodology prioritises user needs and preferences, ensuring that design solutions consider the well-being and functional capabilities of users. This focus on empathy and user needs aligns with RRI's ethical imperatives.

- *Science education*: The research contributes to the field of disability studies by extending existing knowledge on accessibility challenges faced by MobAD users and providing practical design solutions. This knowledge can be used in educational settings to promote understanding of the needs of individuals with disabilities and the importance of inclusive design.

- *Sustainability*: The adaptive access ramp, as a design solution, aims to improve accessibility in the built environment and transport facilities, which can contribute to a more sustainable urban development model by promoting the use of public transportation and reducing the reliance on private vehicles among MobAD users. Also, by putting forward an adaptable and modular solution, this research supports the creation of environmentally-conscious designs in the sense that no modifications of existing spaces are needed. This focus on sustainability aligns with RRI's commitment to long-term social, economic, and environmental viability.

Overall, the main research findings, the adopted methodology, and outputs of this PhD contribute to the RRI context by embedding responsible and inclusive practices throughout the design process, resulting in built environments that are more equitable, accessible, and adaptable to the diverse needs of society.

10.3.2. Limitations

Despite the aforementioned strengths, this work has several limitations.

- Firstly, an adaptive access ramp was designed to enhance the boarding and alighting experience for MobAD users on trains. A crucial aspect of the research was obtaining feedback from the target users regarding the prototype's safety, usability, and accessibility. However, due to the unprecedented circumstances arising from the COVID-19 pandemic and the subsequent closure of university labs, it was necessary to adapt the research process. As a result, a scaled-down 1:5 desktop prototype was created in a home environment rather than a full-scale model in the lab. This limitation potentially impacted the accuracy and comprehensiveness of the user feedback, as the smaller scale may not have adequately represented the true experience of using the ramp in real-world situations. Nevertheless, the findings of this research still provide valuable insights into the design process and offer a foundation for future development and evaluation of a full-scale adaptive access ramp.

- Additionally, an omission of this PhD research is the absence of observational studies, which were initially planned as part of the methodology to analyse spatial accessibility through the behaviours of MobAD users interacting with real-world environments. The intention was to gather valuable insights into the challenges faced by individuals reliant on mobility assistive devices in navigating public spaces and to identify specific areas where design improvements could be made. However, due to the unforeseen circumstances brought about by the COVID-19 pandemic and the resulting lockdown restrictions, it became infeasible to conduct these observational studies. This limitation has implications for the comprehensiveness of the data collected, as direct observation of MobAD users could have provided additional context and a richer understanding of the accessibility barriers they encounter in their daily lives. Nonetheless, the research still offers significant contributions to the field of disability studies, and future research can build upon these findings by incorporating observational studies when circumstances permit.

- Another notable limitation of this research is the failure to solicit opinions of carers, workers at PTIs (e.g. conductors), and other individuals who may face mobility limitations, such as pregnant individuals. The studies involving human participants (i.e. accessibility assessment, co-design workshops, and evaluation) primarily focused on MobAD users, thereby omitting these important groups who also interact with and are affected by accessibility issues in public spaces and transport facilities. This focus was chosen to maintain a manageable study population within the research, allowing for a more detailed and focused analysis of MobAD users, who represent a significant and highly impacted group. This omission delineates the boundaries of the research and indicates a need for a broader range of user experiences and requirements to be considered.

- In addition, the scope of the research was limited in terms of certain design facets and aspects of functioning. For instance, the evaluation study did not examine the grip of handrails with respect to the proposed solution or the anthropometric considerations associated with them. Instead, the research concentrated on stature and reach as the primary ergonomic factors. While these aspects are critical, the exclusion of more design factors and related anthropometric data represents a limitation in providing a comprehensive approach to universal design. This decision was based on the need to focus on specific manageable elements of design. Addressing every possible ergonomic detail within a single study is challenging, and concentrating on stature and reach allowed for a more in-depth analysis. This omission acknowledges the complexity of universal design and the necessity of addressing various needs incrementally, as no single solution or design process can encompass all aspects of universal accessibility.

Despite the limitations encountered, this thesis still offers a valuable contribution to the field of design and disability studies. The research employed a rigorous methodology, ensuring the credibility of the findings by prioritising the target users' perspectives and experiences. In addition, the overall results can be generalised to a broader context, as the identified design principles and recommendations may apply to various public spaces, benefiting a wide range of MobAD users. Hence, even in the face of unforeseen challenges posed by the COVID-19 pandemic, this research has successfully contributed to the advancement of design and disability studies, laying the groundwork for future investigations that can enrich the understanding of spatial accessibility and the needs of the MobAD users.

10.4. Future work

Building upon the findings and insights of this thesis, future work will continue to advance design interrogations and their implications for the accessibility of the built environment. Central to these pursuits will be the ongoing refinement of the research methodology adopted in this study. Moreover, further research will seek to address remaining knowledge gaps and explore new avenues that emerge in the rapidly evolving field of design technology. Key areas of interest include (a) the inclusivity of the research methods used, (b) the role of the digital techniques and tools employed in research, and (c) the potentiality of AI methods to automate parts of the design process.

10.4.1. Improving the inclusivity of research methods

Future studies should incorporate the perspectives and experiences of carers, workers at PTIs (e.g., conductors), and other individuals who may face mobility limitations, such as pregnant individuals. Including these groups will provide a broader and more inclusive understanding of the accessibility challenges encountered in public spaces and transport facilities. Methodologies such as focus groups, interviews, and surveys can be employed to gather detailed insights from these diverse user groups. This inclusive approach will help identify unique needs and barriers that were not addressed in the current research, thereby contributing to more holistic and effective design solutions.

Expanding the focus on ergonomic factors to include other aspects, such as grip, grasp, vision, and turning space, is crucial for developing truly universal designs. Future work should investigate these additional ergonomic factors through detailed studies and analyses. For instance, the grip and grasp characteristics of proposed solutions should be examined to ensure they accommodate users with varying hand strengths and dexterity. Similarly, considerations for vision and turning space can enhance the overall usability of design solutions, ensuring they cater to a wider range of physical abilities and conditions.

To validate and refine design solutions, future research should incorporate expanded user studies and ergonomic assessments in physical mock-up environments using full-scale prototypes. These experimental setups will allow for direct observation and measurement of user interactions with design elements, providing valuable data on their effectiveness and usability. Observational studies can reveal real-world usage patterns and issues, while experimental studies can test specific design modifications under controlled conditions. This hands-on approach will enable researchers to gather precise and actionable insights, leading to more effective and human-centred design interventions.

Continuous evaluation and refinement of accessibility guidelines should be an integral part of future studies. As new insights and data are collected, these guidelines should be updated to reflect the latest understanding of user needs and ergonomic considerations. Regular feedback loops with end-users, stakeholders, and design professionals can help identify areas for improvement and ensure that the guidelines remain relevant and effective. Additionally, pilot projects and real-world implementations of these guidelines can provide practical evidence of their impact, further informing their evolution and enhancement.

10.4.2. Evaluating the role of digital techniques and tools in research

Digital exclusion, particularly among older populations, is a significant limitation when employing digital tools in research. Future studies should implement strategies to ensure that all participants, regardless of their technological proficiency, can effectively engage with digital methods. This can include providing training sessions, user-friendly interfaces, and alternative non-digital options for participation. Additionally, hybrid approaches that combine digital and in-person methods can help bridge the gap, allowing older participants to contribute through familiar traditional means while benefiting from the efficiencies of digital tools. Ensuring accessibility and support for all participants will enhance the inclusivity and validity of the research findings.

The use of online whiteboards and remote collaboration tools can lead to biased views and dominance by stronger voices, potentially skewing the co-design process. Future research should develop mechanisms to track contributions and ensure equitable participation. This can involve implementing features that monitor and record individual contributions, providing visual feedback on participation levels, and using facilitation techniques to encourage quieter participants to share their insights. Structured activities and clear guidelines can also help manage the flow of discussion, ensuring that all voices are heard and valued equally. By addressing these challenges, researchers can create a more balanced and inclusive co-design process that accurately reflects the diverse perspectives of all participants.

Critically assessing the real value of digital methods compared to traditional ones is crucial for understanding their impact and effectiveness. Future work should conduct comparative studies that evaluate the outcomes, efficiency, and participant satisfaction of digital versus traditional methods. This can involve controlled experiments and case studies that highlight the strengths and weaknesses of each approach. Metrics such as engagement levels, quality of insights, time and cost efficiency, and participant feedback can provide a comprehensive evaluation. Understanding the contexts in which digital methods offer significant advantages, as well as their limitations, will inform best practices and guide the appropriate use of digital tools in future research.

10.4.3. Envisioning “design intelligence”

Building upon the foundation set by this research, future work can significantly expand the area of design intelligence by leveraging AI to automate monotonous tasks and enhance the creative capacities of designers. One primary avenue is the automation of finding design inspiration. While this thesis utilised a deep convolutional autoencoder for content-based retrieval of relevant precedent designs, future work could enhance this AI system's functionality and accuracy. Incorporating a larger and more diverse set of architectural drawings and patent databases to train the autoencoder will increase the range of design inspiration it can provide. Additionally, exploring advanced deep learning techniques, such as diffusion models, could generate unique design inspirations and refine the visual similarity metrics used by the CBIR system.

The application of evolutionary algorithms for generating design forms shows great promise. Future research could build on this by employing advanced AI methods to generate a broader array of design alternatives. For instance, multi-objective evolutionary algorithms (MOEAs) can generate solutions that satisfy multiple objectives simultaneously, providing designers with more comprehensive options. Integrating machine learning with generative design systems could allow these systems to learn from past iterations and improve upon them, creating diverse and progressively optimised design alternatives. Investigating other AI methods, such as reinforcement learning, could further enhance design optimisation by enabling the system to learn from each iteration and make more informed decisions, leading to better-optimised solutions. Refining the use of human functioning characteristics as fitness objectives within the evolutionary algorithm could also result in more inclusive design solutions, catering to a broader range of user needs.

The automation of design processes using AI has significant implications for the evolution of the design profession. AI automation shifts the designer's role from creator to curator, enabling them to guide and select from AI-generated alternatives and focus on strategic decision-making. The incorporation of AI transforms the design process into a more iterative and responsive approach, where solutions continually evolve and improve. This dynamic process enhances the efficiency and effectiveness of design, allowing designers to dedicate more time to creative and complex aspects, resulting in more innovative solutions. AI's ability to optimise design based on multiple criteria can lead to designs that better meet user needs and project objectives. Moreover, AI can promote more inclusive designs by incorporating a wide range of user functioning characteristics. As AI integrates more into the design process, designers must acquire new skills and competencies, necessitating ongoing education and training. The future of design lies in the successful integration of human creativity with AI's computational power, heralding a new era of design intelligence.

10.5. Summary statement

To summarise, this work explored how ill-designed built environments could impact MobAD users and identified ways designers could create accessible spatial conditions for them. Following a research-by-design approach, platform-train interfaces were indicated as one of the most problematic elements in the built environment, and an adaptive access ramp was developed to improve accessibility therein. The current research augments existing design frameworks toward more human-centred and inclusive approaches. It also provides methodological as well as practical contributions, offering AI-enabled workflows and novel outputs to advance design research and practice. Lastly, this research holds potential to inform policy and advocacy efforts aimed at promoting the rights of disabled people and ensuring equal access within the built environment.

A. Appendix

A.1. Systematic literature review – supporting material

Classes of information	Codes
Article characteristics	Authors
	Year of publication
	Country
	Methodological approach
	○ Study design (e.g., descriptive, explanatory)
	○ Data collection techniques (e.g., survey, lab trial) & Sample size
	○ Data analysis techniques (e.g., quantitative, qualitative)
	Quality of evidence
	○ Study limitations (e.g., existence of confounders)
	○ MMAT rating (e.g., 80% criteria met)
Objective-related insights	Purpose
	○ Thematic focus (e.g., physical accessibility, impact on QoL)
	○ Types of MobAD examined (e.g., manual wheelchairs, canes)
	Main findings
	○ Types of public spaces examined (e.g., street infrastructure)
	○ Types of physical elements examined (e.g., curb ramps, pathways)
	○ Impacted QoL domains (e.g., pain and discomfort, body fit)

Table A.1: Coding scheme used in the systematic review (Chapter 3)

A.2. Integrative accessibility assessment – supporting material

Equations for sample size

The equation for calculating sample size is shown below:

$$n = \frac{z^2 \times \hat{p}(1-\hat{p})}{\varepsilon^2}$$

Equation A.1: Sample size. Infinite population.

, where:

z is the z score

ε is the margin of error

p̂ is the population proportion.

Since populations of open spaces (e.g., streets) and buildings of public interest (e.g., libraries) in Birmingham city-centre are finite, the finite population correction was used:

$$n' = \frac{n}{1+\frac{z^2 \times \hat{p}(1-\hat{p})}{\varepsilon^2 N}}$$

Equation A.2: Sample size. Finite population correction.

,where:

N is the population size.

Equations for the regression models and ANOVA

The following formulas were used to build the regression model:

$$Y_i = b_0 + b_1X_{i1} + b_2X_{i2} + \ldots + b_pX_{ip} + e,$$

Equation A.3: Regression formula

where, for i = n observations:

Y_i = dependent variable,

X_i = explanatory variables,

b_0 = y-intercept (constant term),

b_n = slope coefficients for each explanatory variable,

e = the model's error term

$$R^2 = 1 - \frac{RSS}{TSS},$$

Equation A.4: Coefficient for assessment of regression model

where:

R^2 = coefficient of determination,

RSS = sum square of errors,

TSS = total sum of squares

$$R^2_{adj} = 1 - \frac{(1-R^2)(N-1)}{N-p-1},$$

Equation A.5: Adjusted coefficient for assessment of regression model

where:

R^2_{adj} = adjusted coefficient of determination,

R^2 = coefficient of determination,

p = number of predictors,

N = total sample size,

The one-way analysis of variance (ANOVA) test was conducted in order to assess the differences in difficulty level across groups of MobAD users when using or accessing access public spaces at Birmingham city-centre. The following formulas were used:

$$F = \frac{MST}{MSE}$$

$$MST = \frac{\sum_{i=1}^{k}(T_i^2/n_i) - G^2/n}{k-1}$$

$$MSE = \frac{\sum_{i-1}^{k}\sum_{j-1}^{n_i} Y_{ij}^2 - \sum_{i=1}^{k}(T_i^2/n_i)}{n-k}$$

Equation A.6: ANOVA formulas

where,

F = the variance ratio for the overall test,

MST = the mean square due to groups (between groups)

MSE = the mean square due to error (within groups),

Y_{ij} is an observation,

T_i is the group total,

G = the grand total of all observations

n_i = the number in group i,

n = the total number of observations.

Opinion Survey on Urban Accessibility for Users of Mobility Assistive Devices

This survey intends to study physical accessibility of Birmingham's public spaces from the perspective of users of mobility assistive devices. Stepped entrances, steep slopes, and narrow pavements can be examples of challenging physical elements that exist in public spaces. The survey attempts to (a) identify the most demanding physical elements, and (b) collect users' suggestions for possible improvements that would enhance accessibility of public spaces.

You have been invited because you are (a) a user of a mobility assistive device; (b) familiar with Birmingham city-centre; and (c) may have either responded to a web-link/e-mail regarding this study or received the relevant information from an organisation of which you are a member. The estimated time to complete this questionnaire is 45 minutes.

By completing this survey, you win a £10 Amazon gift-card. The last section of the questionnaire provides instructions on how to receive your prize.

The study has received approval by Engineering Research Ethics Committee of University of Nottingham; reference number: 2019/82.

Consent Form

Personal Details

2

What is your age group?

- ◯ 18-25
- ◯ 26-35
- ◯ 36-45
- ◯ 46-60
- ◯ 61-75
- ◯ 75+

3

What is your gender?

- ◯ Female
- ◯ Male
- ◯ Non-binary
- ◯ Prefer not to say

4

What type of assistive mobility device do you use?

Please select the most relevant to you, ONE answer only.

- ◯ Manual wheelchair
- ◯ Electric-powered wheelchair
- ◯ Walkers
- ◯ Cane or crutches
- ◯ Mobility scooter
- ◯ Pushchair (stroller)
- ◯ Other

5

Which of the phrases below would best match your mobility status?

Please select the most relevant to you, ONE answer only.

- ◯ I am totally dependent on my assistive device and have a caregiver.
- ◯ I am totally dependent on my assistive device but do not have a caregiver.
- ◯ I am semi-dependent on my assistive device; I use it to perform certain activities both at home and out of home.
- ◯ I am semi-dependent on my assistive device; I only use it to perform certain activities out of home.
- ◯ I do not wish to answer this question / Nothing of the above is relevant to me.

6

To what extend do you have a difficulty with the following activities when visiting Birmingham city-centre?

Please select only ONE answer per row.

	No difficulty	Minor difficulty	Moderate difficulty	Major difficulty	Can't do at all
Using public restrooms (for hand-washing, toileting)	◯	◯	◯	◯	◯
Using seating facilities at public buildings or stores (e.g., cafes, restaurants, refreshment areas)	◯	◯	◯	◯	◯
Getting around in public buildings or stores (e.g., using building corridors, lifts)	◯	◯	◯	◯	◯
Entering or exiting public buildings or stores	◯	◯	◯	◯	◯
Using store facilities (e.g., aisles and shelves) to do the shopping	◯	◯	◯	◯	◯
Using parking areas	◯	◯	◯	◯	◯
Accessing audience or spectator facilities (e.g. cinemas,	◯	◯	◯	◯	◯

auditoria, lecture halls)					
Using public transport facilities (e.g., transport points, ticket machines, boarding aids)	○	○	○	○	○
Using counters and service desks in public buildings (e.g., tills, information/reception desks)	○	○	○	○	○
Accessing public open spaces (e.g. parks, waterfronts, open air markets)	○	○	○	○	○
Using street infrastructure to get around outdoors (e.g., curb ramps, pavements)	○	○	○	○	○

Rating physical obstacles and determining spatial improvements

This section contains ten representations of various public spaces all around UK. Each image illustrates a different spatial case.

The section has two parts. Firstly, you will be asked to rate certain physical elements of each space in terms of access or use. There are four rating grades: easy, neither easy or difficult, difficult, and prohibitive (could not do at all). Please rate the elements according to your own perception and similar experiences.

Secondly, you will be asked to suggest potential improvements that you would made for comfortably accessing or using elements of each space or the space as a whole. For instance, the first image illustrates an open square market. If you consider that the steps would impede your access, you may suggest removing those steps. If you consider that the food stands are too high to use, you could also suggest lowering them. Please try to make as many suggestions as possible according to your mobility needs and personal preferences.

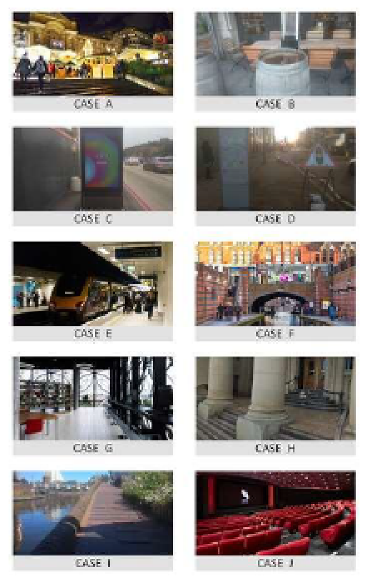
7

Please take a close look at the attached image. Then, rate the ease of access or use of the following physical elements, which are included in the illustrated public space (open air market).

	Clearly accessibly	Somewhat accessible	Moderately accessible	Somewhat inaccessible	Clearly inaccessible
Viewing items on retail counters	○	○	○	○	○
Reaching the retail counters	○	○	○	○	○
Finding a space to rest	○	○	○	○	○
Interfering with crowd	○	○	○	○	○

27

The attached image includes thumbnails of the previously-presented public spaces. Please rank those spaces from "more accessible" to "least accessible" by dragging up and down the relevant items at the list below (with "1." being the most accessible and "10." being the least accessible space). You can also access a larger version of the above image here: https://bit.ly/PublicThumbnailspdf .



- Case A - Open air market
- Case B - Outdoor dining area
- Case C - Obstructed pavement
- Case D - Cobble-made pavement
- Case E - Train platform
- Case F - Canalside
- Case G - Public library
- Case H - Café entrance
- Case I - Queuing arrangements & service counter
- Case J - Movie theatre

Figure A.1: A copy of the opinion questionnaire, selected sections (accessibility assessment, Chapter 5)

A.3. Co-design workshops – supporting material

Participant ID	Role	Assistive Device	Gender	Age Group
1	User	Powered wheelchair	Female	46-60
2	User	Powered wheelchair	Male	36-45
3	User	Scooter	Female	61-75
4	User	Cane	Male	46-60
5	User	Manual wheelchair	Female	61-75
6	User	Powered wheelchair	Female	75+
7	User	Powered wheelchair	Male	26-35
8	User	Powered wheelchair	Female	18-25
9	User	Walker	Male	61-75
10	User	Powered wheelchair	Male	26-35
11	User	Manual wheelchair	Female	18-25
12	User	Powered wheelchair	Male	36-45
13	User	Powered wheelchair	Female	36-45
14	User	Powered wheelchair	Male	46-60
15	User	Manual wheelchair	Female	46-60
16	User	Manual wheelchair	Female	36-45
17	User	Scooter	Male	61-75
18	User	Powered wheelchair	Male	75+
19	User	Cane	Female	36-45
20	User	Powered wheelchair	Male	18-25
21	User	Manual wheelchair	Male	46-60
22	User	Powered wheelchair	Female	46-60
23	User	Scooter	Male	46-60
24	User	Manual wheelchair	Female	26-35
25	User	Walker	Female	46-60

26	User	Powered wheelchair	Male	18-25
27	User	Powered wheelchair	Female	26-35
28	User	Manual wheelchair	Male	75+
29	User	Cane	Female	61-75
30	User	Powered wheelchair	Female	26-35
31	Expert & user	Powered wheelchair	Female	36-45
32	Expert & user	Powered wheelchair	Female	61-75
33	Expert & user	Powered wheelchair	Male	36-45
34	Expert	None	Male	36-45
35	Expert	None	Female	26-35

Table A.2: Anonymised list with participants of the co-design workshops (Chapter 6)

A.4. Content-based image retrieval system – supporting material

A.4.1. Autoencoder implementation

Autoencoders were first introduced in the 1980s by Hinton and the PDP group (Rumelhart, 1986) and have been part of the classical landscape of neural networks for many years (Bourland, 1988; Hinton, 1993; Kamimura, 1995). More recently, autoencoders have taken central stage in deep learning conversations because they can learn with great efficiency and execute reconstructions relatively fast (Baldi, 2011; Bank, 2020).

Autoencoders consist of an encoder function h=f(x) and a decoder function r=g(h), where h is a condensed representation of the input image x. These functions are implemented through artificial neural networks with hidden layers forming a latent-space representation, which is a simplified version of the original data that captures its essential features. The goal is to reduce the image's size and then reconstruct it, though some information is lost in the process.

Neural networks store 2D images in four-dimensional (4D) tensors of shape (samples, height, width, channels). For instance, a batch of 128 grayscale images of size 256 × 256 could thus be stored in a tensor of shape (128, 256, 256, 1).

The encoder consists of convolutional layers, each with a set of learnable filters. These filters detect local patterns and are small in size (e.g., 3x3). The ReLU function activates these filters, except the last layer, which uses a sigmoid function (Figure A.2). Padding is used to ensure the input and output dimensions match. The decoder reverses the encoding process, using up-sampling layers to increase the image size back to its original dimensions.

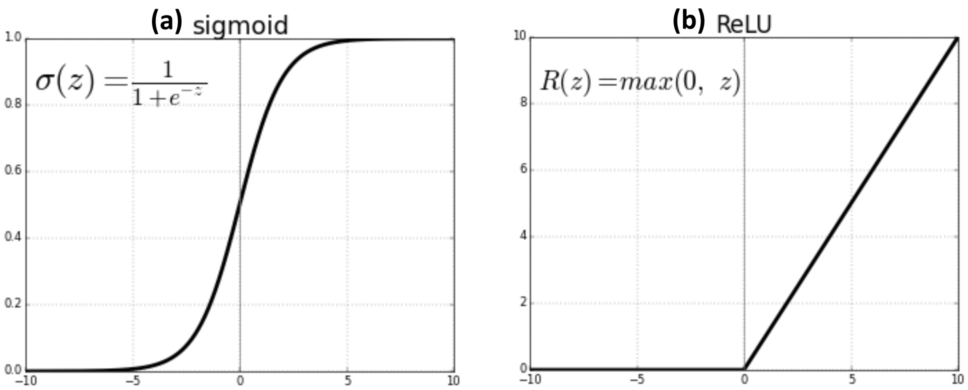


Figure A.2: Filter activation functions for deep CAEs

For this study, a CAE was developed to extract a condensed vector of 512 features from architectural or industrial drawings (Figure A.3).

Binary cross-entropy is a common loss function used in binary classification problems. It measures the difference between predicted output and actual output. The formula is given in Equation A.7:

$$\text{Binary Cross Entropy} = -\frac{1}{N}\sum_{i=1}^{N}[y_i \log(\hat{y}_i) + (1 - y_i)\log(1 - \hat{y}_i)]$$

Equation A.7: Binary cross entropy

Precision measures the relevance of retrieved images. It is calculated as in Equation A.8:

$$\text{Precision} = \frac{|\text{relevant images} \cap \text{retrieved images}|}{|\text{retrieved images}|}$$

Equation A.8: Precision metric

kNN is a non-parametric learning algorithm that uses nearby points to make predictions (Burkov, 2019). It calculates the proximity of latent feature vectors from a query drawing to those of reference drawings in the library.

Cosine similarity measures the angle between two vectors. The formula is given in Equation A.9:

$$\text{Cosine Similarity} = \frac{\sum_{j=1}^{D} X_q^{(j)} X_r^{(j)}}{\sqrt{\sum_{j=1}^{D} (X_q^{(j)})^2} \sqrt{\sum_{j=1}^{D} (X_r^{(j)})^2}}$$

Equation A.9: Cosine similarity

where Xq and Xr are the feature vectors for the query and reference drawings, respectively. If the angle between two vectors is 0 degrees, the cosine similarity is 1, indicating they point in the same direction. If the vectors are orthogonal, the cosine similarity is 0. For vectors pointing in opposite directions, the cosine similarity is -1.

The kNN algorithm was implemented using the Scikit-learn library, which integrates a wide range of state-of-the-art machine learning algorithms for medium-scale supervised and unsupervised problems (Pedregosa et al., 2012).

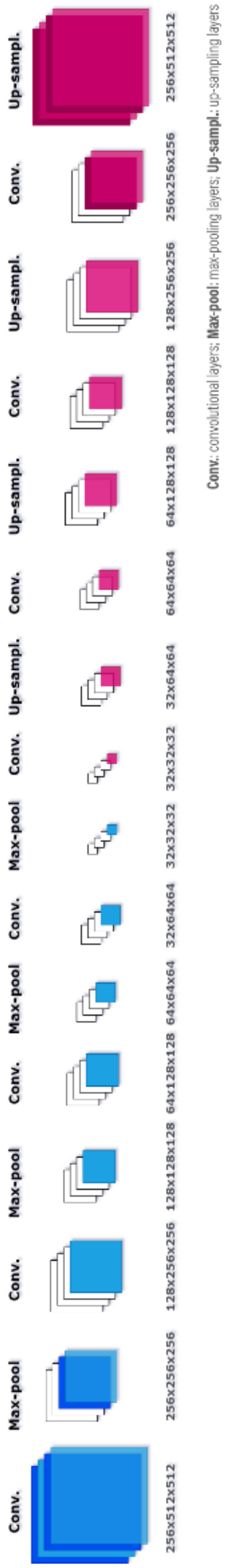


Figure A.3: Architecture of the developed CAE

A.4.2. Interactive Evolutionary Algorithms for generating design alternatives

For constructing a query dataset, the Biomorpher tools was used in a Grasshopper 3D environment. Considering that, the user initially constructs a crude 3D model (*phenotype*) based on a series of mathematical rules (*genomes*), which referred to topological parameters. Genomes can refer to dimensional characteristics (e.g., height, width) of the phenotype or relationships between its constituent geometries. Each genome is defined by min and max bounds, and is graphically expressed with a slider component, through which the user can manipulate its value. Adjusting the value of any of these rules would give a different design outcome, which can be also visualised in the Rhinoceros viewport. The next step is to connect the phenotype and the genomes into the Biomorpher component.

At this step, Biomorpher essentially generates a user-defined number of design solutions (*genotypes*) by randomly tweaking the given genomes and calculating potential solutions. The user can also set the *mutation* rate, or how likely the genes of a design are to change. After each generation, Biomorpher uses the K-means algorithm to group similar genotypes into twelve clusters and returns a tree structure of type {X;Y} where X is the cluster id and Y is the specific design number (Figure A.4a); the number of designs may vary from cluster to cluster. It also visualises the most representative (closest to the cluster centroid in parameter space) design of each cluster in a 3D orientable view (Figure A.4b).

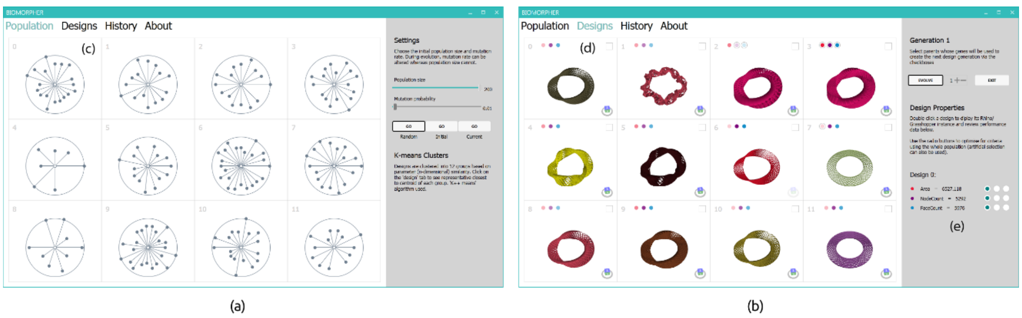


Figure A.4: Biomorpher's environment - (a) generated clusters and (b) representative designs corresponding to clusters. Source: Harding & Brandt-Olsen (2018).

After the user has investigated the twelve designs, one (or more) need to be selected to proceed with the next generation. The selected designs can therefore be thought of as the *parent* phenotypes, whose genes are used in the evolutionary process. The next generation is created based on mutations of each of the parents' genomes. The parent selection can be visual-based or guided by some performance measurements. Depending on both human selection and performance-based criteria, at each generation a *fitness score* is assigned to each phenotype from 0.0 to 1.0. Performance values are initially supplied via the input to the Biomorpher component but are automatically calculated by triggering the Grasshopper canvas to recalculate for each generation. This selection process continues until the user has reached a satisfactory design outcome. It is important to mention that the Biomorpher workspace contains a historical record of choices made by the designer. Previous populations can be accessed and reinstated, thus forming a new evolutionary branch. Initially beginning from a single, crude design form, the user is eventually able to generate as many design alternatives as desired to build the query dataset and then feed it into the trained CAE to retrieve similar drawings from precedent projects.

A.5. Design optimisation – supporting material

A.5.1. Point-E for 3D model synthesis

The Point-E system was recently developed as a 3D model generation method (Nichol et al., 2022). Point-E was chosen as it is capable of efficiently producing diverse and complex 3D shapes conditioned on 2D images. The system samples from some distribution $q(x_o)$ using a neural network approximation $p_\theta(x_o)$. This is generally based on the Gaussian diffusion setup of Ho et al. (2020), through which a noising process is defined as in Equation 1:

$$q(x_t|x_{t-1}) := \mathcal{N}(x_t; \sqrt{1-\beta_t}x_{t-1}, \beta_t\mathbf{I})$$

Equation 9.10

for integer timesteps $t \in [o,T]$. The system is pre-trained on a dataset of several million 3D models and associated metadata by approximating $q(x_{t-1}|x_t)$ as a neural network $p_\theta(x_{t-1}|x_t)$. In this study, I make use of three publicly available image-conditioned models, specifically the 40-million (40M), 300-million (300M), and 1-billion (1B) parameter models.

Point-E first breeds a single synthetic view of an input image using a diffusion-based model. To generate text-conditional synthetic views the 3billion parameter GLIDE model (Nichol et al., 2021) was used and fine-tuned on rendered 3D models from the trained dataset. After that, the system produces a coarse point cloud (1,024 points) conditioned on the synthetic view. To generate the low-resolution point clouds, the authors used a conditional, permutation invariant diffusion model (Nichol et al., 2022). Finally, the system generates a fine point cloud (4,096 points) conditioned on the low-resolution point cloud and the synthetic view. To up-sample these low-resolution point clouds, the authors use a similar (but smaller) diffusion model which is additionally conditioned on the low-resolution point cloud (ibid.). The system is also capable of producing meshes from the generated point cloud using a regression-based approach (Lorensen & Cline, 1987). Overall, this method can generate 3D mesh models from 2D images or technical drawings efficiently and in a timely manner.

A.5.2. Wallacei optimisation engine

Wallacei is an engine that allows users to run evolutionary simulations in Grasshopper (Makki et al., 2022). It was chosen because it offers various options while setting up the design problem, analysing the outputted results, and selecting solutions. Wallacei employs the NSGA-2 genetic algorithm (Deb et al. 2002), as its structural evolutionary component. The main advantage of the NSGA-2 algorithms lays on its ability to emphasise non-dominated solutions using an elitist principle while preserving diversity – i.e., the elites of a population are carried to the next generation (ibid.).

The Wallacei engine requires three sets of inputs: an initial 3D model or set of models (Phenotype), the design variables (Genes) and the fitness objectives (FO). The phenotype serves as the starting point for the optimisation process. It defines the geometry, topology, and other physical properties of the design. They are the inputs that determine the variations in the phenotype. The genes can be continuous or discrete values, and they can be either independent or dependent on other variables. Examples of genes could be the length of a beam, the height of a building, or the thickness of a shell. The fitness objectives are the performance metrics that are used to evaluate the quality of the design solutions generated by the optimisation process. They represent the goals and constraints that the designer wants to achieve or satisfy.

Once the user provides the required input into Wallacei, the engine initiates an evolutionary process to simulate optimal solutions based on the given design variables and fitness objectives. The engine breeds an initial population of design solutions, which are randomly generated based on the given design variables. Wallacei analyses the results from the simulation in order to select the fittest solutions by evaluating each design solution against the given fitness objectives, and a fitness value is assigned to each solution based on how well it satisfies the objectives. The engine uses a mix of statistical analysis (i.e., mean and standard deviation of fitness values), Pareto analysis (i.e., this is to identify trade-offs between fitness objectives), clustering, and sensitivity analysis to evaluate the fitness values of a single solution or the whole population. Based on the analysis findings, the user selects the fittest solutions - i.e., those that correspond most to the fitness objectives. The user repeats the simulation process for the selected solutions as many times as needed until a satisfactory solution is found, which would optimise the initial design according to the design intentions, requirements, or constraints.

A.6. User evaluation – supporting material

Participant ID	Mobility Aid	Gender	Age Group
1	Powered Wheelchair	Male	46-60
2	Mobility Scooter	Male	61-75
3	Cane	Female	26-35
4	Powered Wheelchair	Male	18-25
5	Manual Wheelchair	Female	36-45
6	Walker	Male	36-45
7	Mobility Scooter	Female	61-75
8	Manual Wheelchair	Female	36-45
9	Cane	Female	61-75
10	Powered Wheelchair	Male	46-60
11	Powered Wheelchair	Male	46-60
12	Powered Wheelchair	Male	46-60
13	Manual Wheelchair	Female	36-45
14	Mobility Scooter	Female	61-75
15	Powered Wheelchair	Female	46-60
16	Walker	Male	75+
17	Powered Wheelchair	Female	18-25
18	Powered Wheelchair	Female	46-60
19	Cane	Female	61-75
20	Manual Wheelchair	Female	36-45
21	Cane	Male	26-35
22	Cane	Male	61-75
23	Manual Wheelchair	Female	46-60
24	Manual Wheelchair	Female	36-45
25	Powered Wheelchair	Female	46-60

Table A.3: Anonymised list with participants of the user evaluation studies (Chapter 9)

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