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Leveraging Local Digital Twins for planning age-friendly urban environments

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A B S T R A C T

In an era of rapid urbanisation and an ageing population, innovative urban planning paradigms and tools are essential for creating inclusive, safe, resilient, and sustainable cities. Moreover, in the digital age, untapped potential exists for using disruptive technologies in urban planning to enhance evidence-based decision-making.

This study explored the promotion of age-friendly environments through the transformative potential of Local Digital Twins (LDTs) by integrating geographic information system (GIS) data, data analytics, and artificial intelligence. Tested in the European Commission-funded URBANAGE project, this study presents a digital twin-based Long-Term Urban Planner tool with simulation capabilities that allow for a comprehensive analysis and modelling of the effects of urban interventions. Two use cases are showcased: one suggesting public space intervention and the other tackling future demographic trends.

The main contribution of this study is the definition and development of an LDT using a modular-component-based approach that facilitates reuse and adaptation. Unlike isolated approaches, it provides a holistic solution that integrates social and technological domains. This study advances the understanding of the use of LDTs to create inclusive neighbourhoods by assessing neighbourhood age-friendliness and proposing informed urban interventions while underscoring the importance of robust data governance and capacity building among civil servants.

1. Introduction

Urbanisation is a primary global trend that influences contemporary societies. Cities are expanding with a rising proportion of older residents; yet, even within this acknowledged scenario, considerable disparity endures. Prevailing urban planning methods frequently neglect sustainability considerations associated with human factors and the evolving needs resulting from shifts in population dynamics (Ruza et al., 2014).

In the near future, it is anticipated that the proportion of individuals over 65 years of age in Europe will reach 34 % of the population (United Nations, 2017). Moreover, 75 % of the European population currently lives in urban areas, with projections predicting an increase to >80 % by 2050 (Koceva et al., 2016). This demographic shift requires cities to be adequately equipped to address the associated needs and requests (Zhang et al., 2023).

The *World Health Organization* (WHO) recognises the role of cities in promoting longevity, equity, and sustainability. Its 2007 handbook outlines the essential features of an age-friendly city across eight aspects: outdoor spaces and buildings, transportation, housing, social participation, respect and social inclusion, civic participation and employment, communication and information, and community support and health services (World Health Organization, 2007).

These guidelines are crucial in shaping global urban planning in age-friendly environments. Effective execution of this agenda requires a deep understanding of the complex nature of urban spaces (Buffel et al., 2015) (Wood et al., 2022). Urban planning, a key competency for local authorities, significantly influences the lives of citizens. It involves understanding the intricate interactions in areas such as the built environment, social dynamics, economics, environment, and culture (Gandini et al., 2018).

Despite their multidimensional nature, traditional urban planning

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systems often operate within siloed sectoral approaches (Molina Costa & Jimenez Romera, 2016). Professional planners traditionally rely on various information sources, including historical experience, professional expertise, contemporary data collection, formal education, and engagement with decision-makers and stakeholders (Krizek et al., 2009). Notably, the field is yet to fully leverage the vast potential offered by the extensive production and analytical capabilities of the digital era.

Information and communication technology (ICT) advancements have become increasingly relevant to urban planners in recent decades (Molina-Costa, 2024). The integration of geographic information in urban landscapes has led to potential threats in its use for planning and has sparked debates. With the rise of sensors and mobile communication devices, networks and data have played pivotal roles in shaping interconnected and intelligent cities, often called smart cities (Exner, 2015).

Synergy between technology and urban planning is crucial for meeting the evolving needs of diverse populations. Advanced technologies, especially *geographic information system* (GIS) data and three-dimensional (1D) city models, play key roles in addressing the challenges posed by ageing demographics. GIS data, along with their spatial analysis capabilities, are pivotal in comprehending and optimising urban landscapes. When integrated into Local Digital Twins (LDTs), GIS data provide unprecedented insight into the spatial dynamics of outdoor spaces and buildings.

The digital twin is a virtual representation of a physical object, system, or process. It integrates data from sensors, devices, and various sources to create a dynamic simulation of how the physical entity functions. While the concept is well-established in industry, its application to urban environments is relatively novel (Madubuike et al., 2022). On the other hand, a Local Digital Twin (LDT), as defined by the European Commission (*Local Digital Twins: Forging the Cities of Tomorrow | Shaping Europe's digital future, 2021*), is a subcategory of DT focused on cities or urban environments. An LDT digitally replicates a specific geographic area (e.g., a city, neighbourhood, or municipal infrastructure) to improve urban planning, resource management, and decision-making at the local level. While a DT can model any physical entity on any scale, an LDT is restricted to a particular geographic region and primarily focuses on challenges and applications related to local governance, sustainability, and the development of smart cities. (Garcia Barron et al., 2023).

The intersection of LDTs and urban accessibility is crucial for modern cities. Traditional urban planning often struggles to identify and address accessibility barriers, impeding the seamless movement of diverse populations. Implementing a city's digital twin streamlines city planning and management on a unified platform (Ferré-Bigorra et al., 2022). The WHO framework for evaluating age-friendliness in cities (World Health Organization, 2007) emphasises assessment by older people themselves and encompasses an essential checklist of features spanning various city domains and topics, necessitating an integral approach to analysis. To this end, LDTs, which can analyse and simulate holistic urban scenarios, offer a unique opportunity to tailor landscapes to the specific needs of ageing populations.

This study aims to explore how the use of Local Digital Twins (LDTs) in urban planning can promote age-friendly environments, fostering a holistic approach that prioritises inclusivity and addresses the diverse needs of the population. The urgency of adopting LDTs in urban planning is driven by growing urban populations, complex environmental challenges, and the need for more inclusive and sustainable urban environments. Disruptive technologies, like LDTs, hold great potential to transform public services, including urban planning, by enabling advanced multidimensional analysis and visualisation. By supporting evidence-based decision-making and allowing continuous evaluation of outcomes, LDTs can significantly enhance the planning process, ensuring decisions are inclusive and adaptable to the evolving needs of urban populations.

This paper focuses on the development of the Local Digital Twin (LDT) for the city of Santander, Spain, as a core part of the European Commission-funded URBANAGE project (*Enhanced URBAN planning for AGE-friendly cities through disruptive technologies*). The project addresses the definition and creation of a modular, component-based LDT specifically designed to assess the age-friendliness of neighbourhoods and to conduct comprehensive analysis and modelling of urban interventions. This article presents the creation of the LDT from the ground up, with functionalities co-created through workshops involving older populations and municipal civil servants. The LDT was then tested through two use cases: one addressing public space interventions and another analysing future demographic trends.

From an urban technology perspective, this study focuses on how GIS-informed 1D models help identify and address age-related challenges in cities, fostering environments that enhance accessibility for citizens of all ages.

From an age-friendly city planning perspective, this work addresses some open challenges: the insufficient involvement of older citizens, scarcity of data related to their specific needs, and lack of an integral approach, including social perspectives, in urban planning tools.

This paper is organised into sections aimed at comprehensively addressing the research objectives and coherently presenting the findings. Section 2, the literature review, presents the challenges of age-friendly cities and the potential of GIS-based LDT technologies for enhancing urban planning through evidence-based decision-making. Section 3, “Materials and Methods”, provides a detailed account of the methodologies, tools, and data sources applied in building the Santander (Spain) LDT use case; specifically, it presents the components and interconnections of the URBANAGE LDT. Following this, Section 4, “Results” section, presents two practical use cases developed for Santander. The discussion section, Section 5, critically evaluates the results in the context of the research objectives, highlights the key findings, discusses their implications, and addresses the limitations and challenges encountered during the study. Finally, the conclusion in Section 6 provides a summary of the key findings, reaffirms the significance of the research, and offers insights into future directions for further research and practical applications.

2. Literature review

Urban planners have developed a notable approach to address ongoing urban challenges, focusing on creating a human-centric and environmentally sustainable future. One prominent urban planning response to ongoing urban challenges. The “15-min city” concept (Papadopoulos et al., 2023) appeared in 2016 to reply to this goal but has faced several criticisms, being one of them it's for its one-size-fits-all approach, which often neglects the diverse needs of various demographic groups. Critics argue that it fails to address environmental concerns, energy efficiency, and cultural preservation adequately (Khavarian-Garmsir et al., 2023). Advocating for services within “walking distance” is questioned for evaluating this distance from an average perspective. Research suggests that age-related factors make short walks impractical or unattainable for certain urban groups, especially older individuals (Willberg et al., 2023) due, because of physical-motor dysfunction, among other reasons, which is not considered (Zhang et al., 2023). It's clear that older adults face unique challenges and have needs when moving through urban areas. At the same time, city officials and policymakers find it difficult to advance age-friendly initiatives because they lack the necessary knowledge, data, and tools specifically designed for older adults.

The participation of older adults can be enhanced through the collection of pertinent data to generate insights and develop tools tailored to their needs, facilitated by smart cities. However, the utilization of smart city data for policymaking is hindered by several challenges, including the aggregation of non-age-specific big data, the lack of relevant data, and disparities in access to and usage of digital technology (van Leeuwen et al., 2022).

These challenges can be overcome by an important capacity of the

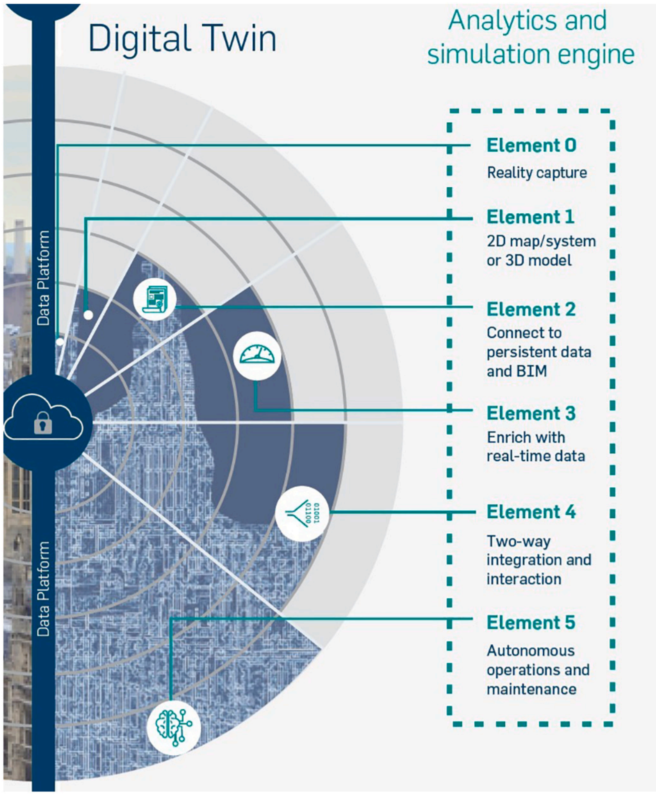

Fig. 1. Atkins/ITE Maturity levels Source: (Evans, 2024).

LDT concept, which is integrating of the social dimension into a traditionally industrial and technological framework Recent research proposes viewing digital twins of cities not just as digital replicas but also as dynamic cyber-physical-social ecosystems. This perspective emphasises the complex interactions between the digital, physical, and social realms (Batty, 2018; Tomko & Winter, 2018). (Batty, 2018; Tomko & Winter, 2018). The capacity to conceptualise and design urban digital twins as adaptive systems that accurately reflect local contexts and constraints is crucial for effective policy planning and implementation. This methodology emphasises the significance of involving older adults in cocreation processes (Buffel, 2018), facilitated by ongoing feedback mechanisms. Furthermore, it underscores the necessity of conducting post-implementation evaluations to address the diverse needs of the community and promote inclusivity (Nochta et al., 2020).

Several studies have used GIS-based tools to enhance the planning and evaluation of age-friendly cities. For instance (Bozdağ et al., 2017) explored the evaluation of accessibility and quality of urban green spaces and integrated these factors into a single indicator. Similarly, they conducted spatial analyses to assess how older individuals prioritised the accessibility of these services. Verschuur (Verschuur, 2014) employed GIS techniques to analyse the availability and accessibility of essential services for older adult populations in urban areas. Recent research has focused on quality-of-life assessment using a synergistic approach that combines GIS, database management, spatial analysis, and multicriteria analytical models. Similarly, (Jelokhani-Niaraki et al., 2019),(Yung et al., 2017) and (Stessens et al., 2017) proposed GIS-based models to measure older citizens' satisfaction with the planning and design of public parks and services. Additionally, tools such as the Multidimensional Assessment System of the Built Environment (MASBE) introduced by (Moyano et al., 2020), and site selection models for medical services (Kim et al., 2015) significantly contribute to the diagnosis of built environments and address the needs of an ageing population. (Padeiro et al., 2021) reviewed evidence for the influence of urban neighbourhood attributes on older adults' well-being.

However, GIS-based solutions encounter four critical challenges. First, older individuals are often insufficiently involved in the decision-making process, which can lead to overlooking their specific preferences and needs. Second, the effective use of extensive urban and citizen data is hindered by data gaps concerning older adults. These data gap, especially pronounced with new technologies, not only impedes the realistic analysis of patterns, trends, and real needs but also marginalises older adults, rendering them less visible and undervalued (Age Platform Europe, A, 2024). Third, the potential of the indicators generated for urban design and policymaking through scenario-based simulation workshops has not been fully exploited. Fourth, there is a need to represent three dimensions (physical, social, and service) while avoiding biases owing to subjective assessment factors.

In addition to GIS tools, commercial solutions for the microscopic simulation of mobility and traffic offer functionalities for accessibility assessment. Tools such as Aimsun Next 24 Editions and PTV Group's Mobility Solutions analyse how residents can access specific locations or services within a set time limit (Kučera & Chocholáč, 2021) Despite their advanced capabilities, these tools often fail to address the unique mobility challenges faced by older individuals. They tend to overlook critical comfort factors such as the availability of resting areas, toilets, drinking water spots, handrails, and vertical mobility infrastructure, which are essential for creating truly age-friendly urban environments.

Urban areas are complex ecosystems that evolve continuously due to diverse economic activities, creating significant challenges in the management and anticipation of these changes. The concept of a digital twin, which is essentially a digital replica of a physical system with ongoing information linkage throughout its life cycle, offers a promising solution. Although there is no universal definition of a digital twin, an IBM, 2014 proposal highlights their potential to integrate and analyse critical urban elements and activities using information and communication technologies. This integration supports efficient responses to urban needs, such as planning, resource management, safety, and transportation optimisation (IBM, 2014).

The theoretical foundation of urban digital twins involves encoding the semantic and geospatial properties of urban objects that provide substantial benefits to various stakeholders. Beyond simple replication, digital twins enable bidirectional interactions, allowing advanced analytical operations and simulations within virtual urban environments. Recent literature has expanded on this concept, focusing on the technological advancements and potential applications of digital twins in urban contexts (Lei et al., 2023; Shahat et al., 2021; Wang et al., 2023).

In 2018, the Centre for Digital Construction in Britain introduced the Gemini principles to foster agreement among individual digital twins (Bolton et al., 2018). These principles characterise a digital twin as a virtual ecosystem within a built environment. Gemini principles provide a framework for the development and application of digital twins, ensuring that they are trustworthy, effective, and beneficial. This framework advocates a decentralised strategy for the urban digital twin, envisioning it as an integrated system of federated systems that enhances real-world management and decision-making (Bolton et al., 2018). These principles are based on three main foundations: purpose, trust, and function. The Gemini principles emphasise the importance of a clear and beneficial purpose for digital twins; trust or trustworthiness includes data security, privacy, and ethics; and function emphasises the functionality and usability of digital twins.

Policymakers are increasingly recognising the crucial role of digital twins in urban planning (Batty, 2018; Gil, 2020; Lei et al., 2023). A city-scale digital twin offers the opportunity to digitally represent all urban domains and systems, thereby improving city visibility, understanding, and functionality. The use of sensors and Internet of Things (IoT) technologies enables real-time updates and simulations that enhance the actual environment (Hämäläinen, 2020). Nevertheless, challenges remain due to the nascent stage of LDT development and the absence of comprehensive implementations that encompass the environmental,

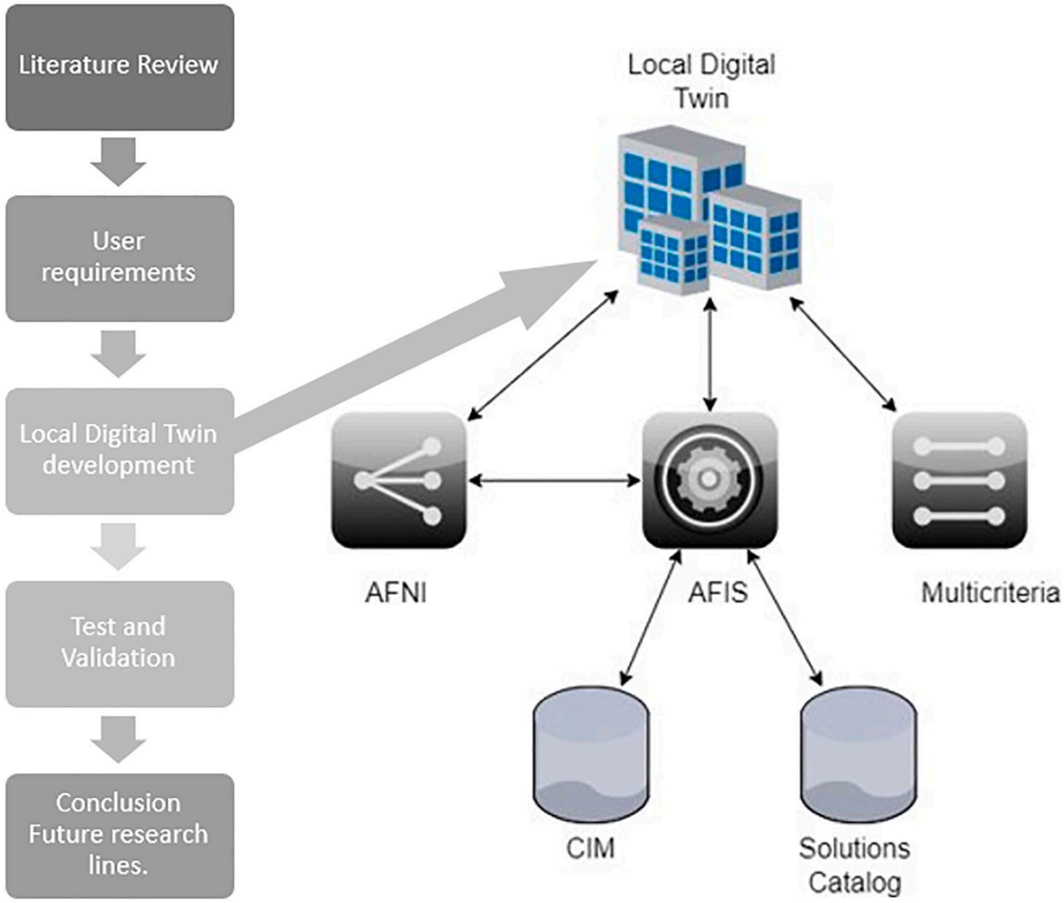

Fig. 2. Methodological approach and Components and Interconnections of the URBANAGE LDT. Source: Own elaboration.

social, and economic aspects of sustainable smart cities (Weil et al., 2023).

In this context, digital twin maturity levels serve as a framework for assessing the evolution and capabilities of a digital twin implementation. The concept of maturity levels helps organizations understand where they stand in terms of implementing and utilising digital twin technologies effectively (IBM, 2024). The Atkins/ITE Maturity Model (Evans, 2024). is a well-known framework for digital twins. Based on this maturity model, a comprehensive review of existing urban digital twins revealed that 90 % of the identified examples fall within maturity

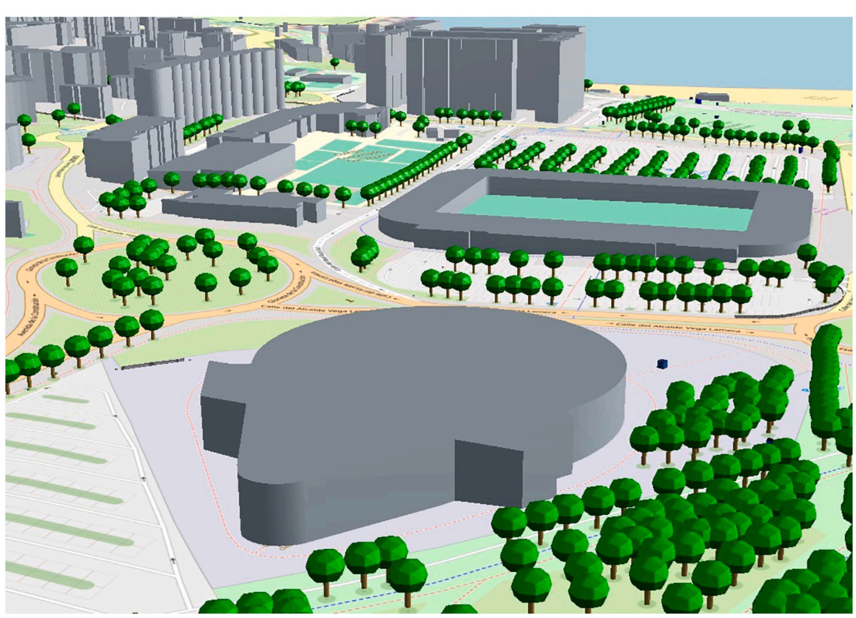

Fig. 3. Santander CityGML model. Source (URBANAGE, 2024).

levels 1–3, with no reference to Level 5 implementation (Masoumi et al., 2023) (Fig. 1).

In the realm of urban planning and digitalisation, the development of digital twins offers a transformative approach for managing the complexities of modern urban environments. (Lohman et al., 2023) highlighted how digital twins can support policymakers and urban planners by providing a scalable framework for constructing large-scale city models. This framework integrates data, simulation models, and visualisation systems to facilitate comprehensive urban analyses. Scenario-based simulations provide stakeholders with insights into traffic patterns, air quality, noise levels, and other critical factors, thereby supporting informed decision-making processes and enhancing urban planning efforts during the digital era.

This review highlights the dynamic advancements and potential benefits of urban digital twins while acknowledging significant challenges. Despite this progress, a major issue persists: the early stage of the development of urban digital twins and the lack of comprehensive implementations that fully integrate the social dimension in a traditional industrial framework. This study addresses these deficiencies by offering a practical, proven, and modular digital twin framework. This framework not only incorporates diverse data sources and stakeholder feedback but also provides a holistic view that integrates environmental and social factors. The integration of social dimensions signals a paradigm shift, enriching our understanding of digital twins in urban environments. Employing this comprehensive approach, this study delivers a robust tool for urban planning designed to enhance sustainability and inclusivity in smart cities.

The following sections detail the innovative features and implementation strategies employed by URBANAGE and provide valuable contributions to the evolving field of urban digital twins.

3. Materials and methods

This section presents the methodological approach, in Fig. 2, literature review, user requirements, local digital twin development, test and validation, conclusions and future research lines. and the components and interconnections of the URBANAGE LDT. The Santander URBANAGE LDT focuses on calculating the age-friendliness of neighbourhoods for older people by utilising the components illustrated in Fig. 2. The LDT assesses age-friendliness using several interconnected modules, and the City Information Model (CIM) is a database containing detailed information about urban elements in the CityGML format and serves as a foundational data source for the digital twin. The Age-Friendly Neighbourhood Index (AFNI) is the index used to evaluate neighbourhood age-friendliness by considering indicators related to accessibility, safety, and inclusivity for older adults. The Solutions Catalogue stores potential urban interventions to improve age-friendliness and offers strategies for urban planners based on AFNI-identified needs. The Age-Friendly Index Simulator (AFIS) module calculates the AFNI indicators by connecting to both the CIM and Solutions Catalogue, integrating dynamic data, performing simulations, and generating valuable insights for planners. Finally, multicriteria analysis allows users to refine indicator weights

Domains weights	Topics weights	Indicators weights	
0,25	D1: Outdoor spaces and buildings		
	0,24	T1.1: Neighbourhood walkability	
		0,17	1.1.1. Rest places
		0,15	1.1.2. Benches
		0,21	1.1.3. Public toilets
		0,11	1.1.4. Crosswalks
		0,23	1.1.5. Walkways
		0,13	1.1.6. Sheltered zones
	0,22	T1.2: Accessibility of public spaces and buildings	
		0,35	1.2.1. Accessible public spaces
		0,36	1.2.2. Accessible public buildings
		0,29	1.2.3. Accessible open space
	0,22	T1.3: Public safety	
		0,4	1.3.1. Rate of crimes against older people
		0,6	1.3.2. Phyisical incidents in public spaces
	0,32	T1.4: Environmental conditions	
		0,2	1.4.1. Location of public green and water
		0,21	1.4.2. Temperature
		0,21	1.4.3. Light areas
		0,16	1.4.4. "Quiet" zones
		0,23	1.4.5. Clean air
0,16	D2: Transport		
	0,32	T2.1. Access to public transport stops	
		0,65	2.1.1. Housing and public transportation
		0,35	2.1.2. Bus shelters
	0,18	T2.2. Access to priority vehicle parking	
		0,38	2.2.1. Priority parking in public buildings
		0,38	2.2.2. Special parking permits
		0,24	2.2.3. Maintenance in winter
	0,18	T2.3. Urban accessibility solutions	
		0,6	2.3.1. Urban accessibility solutions' infraestructures
		0,4	2.3.2. Short time parking lots
	0,32	T2.4. Traffic levels	
		0,52	2.4.1. Safe biking infraestructure
		0,48	2.4.2. Traffic volume
0,34	D3: Housing		
	0,62	T3.1. Availability and affordability of housing	
		0,57	3.1.1. Public housing options
		0,43	3.1.2. Protected flats for older people
	0,38	T3.2. Accessible housing	
		1	3.2.1. Accessible housing
0,24	D4: Social participation and communication		
	0,53	T4.1. Accessibility of participation opportunities	
		0,22	4.1.1. Access to community-based activities
		0,18	4.1.2. Access to community centers
		0,14	4.1.3. Access to cultural and educational facilities
		0,14	4.1.4. Access to sites of worship
		0,14	4.1.5. Access to leisure services
		0,1	4.1.6. Access to convenience stores
		0,08	4.1.7. Access to health services
	0,47	T4.2. Internet access	
		1	4.2.1. Internet access

Fig. 4. Domains, topics, and indicators of the AFNI and their corresponding weights Source: (Urra-Uriarte et al., 2024).

and visualise the AFIS results, facilitating a comprehensive understanding of the urban environment and supporting informed decision-making.

3.1. URBANAGE LDT components

The foundation of informed decision-making in urban planning lies in robust data collection and analysis coupled with the use of comprehensive indicators that encapsulate key aspects of city dynamics. This section presents three crucial components that form the bedrock of the URBANAGE Digital Twin data-driven approach: the CIM (Section 3.1.1), the AFNI (Section 3.1.2), and the Solutions Catalogue (Section 3.1.3).

The CIM serves as the spatial and semantic backbone of the digital twin, providing a detailed representation of the city's urban elements. This model facilitates data collection, simulation, and user interaction through 1D geospatial representation, which is vital for determining accessibility and age-friendliness.

Complementing the CIM, the AFNI offers a structured framework for evaluating the age-friendliness of neighbourhoods, incorporating a wide array of indicators across four domains: Outdoor Spaces and Buildings, Transport and Mobility, Housing, and Social Participation and Communication.

The Solutions Catalogue presents a curated collection of urban interventions aimed at enhancing age-friendliness within neighbourhoods, aligning with the domains identified in the AFNI.

Together, these components form a cohesive system for data-driven decision-making, empowering urban planners and policymakers with the insights needed to create inclusive and sustainable urban environments.

3.1.1. City Information Model (CIM)

A 1D city model of Santander was generated as foundational information for data collection, simulation, and user interaction through a 1D geospatial representation. The CIM refers to a data model for the representation of information within the URBANAGE Digital Twin, encompassing both the geospatial and semantic data of the 1D city model. The CIM primarily relies on the CityGML standard, which enables the modelling of key urban elements through thematic modules (Gröger et al., 2008) CityGML has been slightly tailored to the project requirements, modelling the most relevant city elements at *Level of Detail 1* (LoD1), as described in (Biljecki et al., 2014), ensuring a realistic representation without compromising computing or visualisation efficiency.

The modelling process begins with the generation of 1D geometries from primary two-dimensional (2D) representations using methods that vary based on the feature type. Buildings and polygonal structures, such as public facilities, are extruded based on height parameters, defaulting to 3 m if no height is provided. For trees represented as point features, separate geometries are created for the trunk and canopy, whereas other elements are dimensioned according to real-world proportions. Attribute management involves configuring or updating attributes to align with the CityGML model specifications, including the main parameters such as name, description, function, year of construction, and height, while retaining other attributes in a generic form for storage. Texture applications enhance visualisation by assigning appropriate textures to elements after geometry creation and selecting generic textures tailored to each asset type.

The resulting model contains key urban elements pertinent to improving accessibility and age-friendliness in the city, such as buildings; green areas, including street trees; mobility infrastructure, such as streets, bike lanes, parking, and escalators; and urban furniture, such as fountains, benches, public toilets, railings, and kiosks.

The data sources utilised to generate the CIM were primarily derived from publicly available open data (cadastre, OpenStreetMap, and municipal open data), predominantly comprising the 2D cartography of urban elements. This dataset was augmented with detailed information provided by the Santander municipality, including the location of urban furniture such as fountains, benches, or public toilets. Additionally, geospatial and aerial image processing were conducted to enhance the available information. Workflow processes were developed in the Spatial Extraction, Transform and Load (ETL) application for model generation (*FME Desktop, n.d.*). The model was stored within a spatial relational database, 3DCity (3DCityDB Database – Homepage, n.d.), to ensure compliance with CityGML specifications. For optimal online visualisation of the 1D model through a web application serving as the twin's user interface, FME was utilised to transform the CityGML model into an optimised format for large-scale 1D geospatial representation (3DTiles) (3D Tiles, 2024) (Fig. 3).

Table 1
URBANAGE Solutions catalogue and domains.

Name	Domain
Large Public Park 1000 m2	Domain 1
Medium Public Park 200 m2	Domain 1
Small Public Space	Domain 1
Accessible and safe bus stop	Domain 2
Social housing options for rental	Domain 3
Construction of protected flats for older people	Domain 3

3.1.2. Age-Friendly Neighbourhood Index (AFNI)

Indicators are becoming more prevalent in decision-making processes across all levels, offering a robust basis for evidence-based decision-making. They play a crucial role in constructing sustainable, self-regulated systems that seamlessly integrate various considerations (Rosales, 2011). Access to urban data allows citizens and decision-makers to explore novel possibilities, while the evaluation and comparison of cities based on their performance serves as a valuable tool for assessing policy effectiveness and fostering the exchange of best practices.

Taking this a step further, indicators enable not only city-to-city comparisons but also intra-city assessments, allowing distinctions among different neighbourhoods. This approach was adopted in the URBANAGE project with the explicit goal of providing urban planners and policymakers with effective tools for informed decision-making within cities (Fig. 4).

Based on the WHO age-friendly cities indicator framework (WHO, 2015) and a study focused on identifying metrics for assessing neighbourhood age-friendliness from an urban planning perspective, indicators were established through a co-creation process involving older adults and civil servants.(Urra-Uriarte et al., 2023) This led to the formulation of the Age-Friendly Neighbourhood Index (AFNI) within the URBANAGE project.(Urra-Uriarte et al., 2024) The purpose of this index is to contribute to the development of decision-support technologies, as described in subsequent sections. The AFNI, an urban index designed to assess the age-friendliness of diverse neighbourhoods within a single city, comprises four distinct domains: Outdoor Spaces and Buildings, Transport and Mobility, Housing, and Social Participation and Communication. Within each domain, 12 topics were measured through a comprehensive set of 36 indicators.

The AFNI was developed using the Delphi method, involving 18 professional experts from diverse fields such as sociology, gerontology, building environment, urbanism, architecture, and policy. Experts from seven countries validated the proposed structure and assigned weights to various domains, topics, and indicators. The weights assigned to the indicators, topics, and domains vary when assessing the age-friendliness of a neighbourhood in comparison to others. These evaluations provide valuable assistance to urban planners in establishing a baseline for age-friendliness in each neighbourhood.

When translated into a digital map, this index offers a direct overview of the age-friendliness status across various neighbourhoods in a city. This information can be cross-referenced with other pertinent urban indicators such as identifying neighbourhoods with a higher percentage of older residents. Once the baseline is determined, policy-makers and urban planners can make informed decisions regarding diverse urban interventions. The calculation of the AFNI for different neighbourhoods requires the measurement of indicators and the identification of the necessary data. These indicators are measured through various types of data, all derived from existing sources, included in the 1D city model, and do not rely on qualitative analyses such as surveys.

3.1.3. Solutions catalogue

The Solutions Catalogue is a set of pre-packaged urban interventions that can be readily simulated in selected neighbourhoods. It serves as a dynamic repository that can be expanded with additional solutions as necessary (see Table 1).

The built environment significantly affects health and overall well-being and establishes a distinct connection between surroundings and subjective feelings of wellness. Urban planning offers various strategies for enhancing subjective well-being, with one immediate approach being to create accessible and inclusive public spaces and communal areas. Designing pleasant buildings and public spaces according to resident preferences and needs is a straightforward strategy for improving overall well-being (Mouratidis, 2021). Both minor and major interventions have the potential to impact how individuals perceive the age-friendliness of urban environments. Urban planners should be able to model the effects of interventions at various scales and in different domains, contributing to the enhancement of age-friendliness within neighbourhoods. This simulation capability can inform decision-making processes. In line with this objective, the Solutions Catalogue was curated, with each proposed solution formulated by considering three key criteria: first, it falls within the competencies of urban planners; second, it aligns with one of the domains identified in the AFNI; and third, it has a discernible impact across multiple indicators, topics, or domains. Given that the simulation of the implementation aims to measure the potential impact of a solution when deployed, it is impractical to select simplistic interventions, such as planting a single tree or installing a new bench. These interventions carry minimal weight in the AFNI, result in a negligible impact, and create an imperceptible enhancement of age-friendliness in the neighbourhood. The design of the solutions must be a factor in these considerations. Using this approach, a catalogue with the first set of solutions is defined, always considering it as a dynamic repository.

An exemplary comprehensive solution involves the establishment of a *medium- or large-sized public park*. A public park can be defined as a public space with greenery where people can stay and rest, and usually consists of street furniture such as benches, fountains, public and accessible bathrooms, and sheltered areas that provide protection from the sun and rain. According to this definition, a medium- or large-sized public park adheres to specific surface area standards dictated by country regulations. These regulations also specify bench-to-person and bench-to-square-metre ratios. The implementation of a medium or large urban park directly influences the first domain of the AFNI, outdoor spaces and buildings, impacting several of its topics and indicators.

The *small public space* solution was conceived as a public area situated in a dense zone. Because of their reduced size and lack of greenery, public bathrooms, and sheltered zones, they differ from larger public parks. The influence of this solution would similarly affect the outdoor spaces and buildings domain, but to a lesser extent in terms of topics and indicators.

These two solutions directly contribute to Domain 3, Housing. These solutions include the *construction of protected flats for older people* and *social housing options for rental*. The former entails providing affordable multipurpose housing conducive to ageing, whereas the latter involves government-owned dwellings designated for social renting. Although these solutions influence only one topic in Domain 3, and each has a

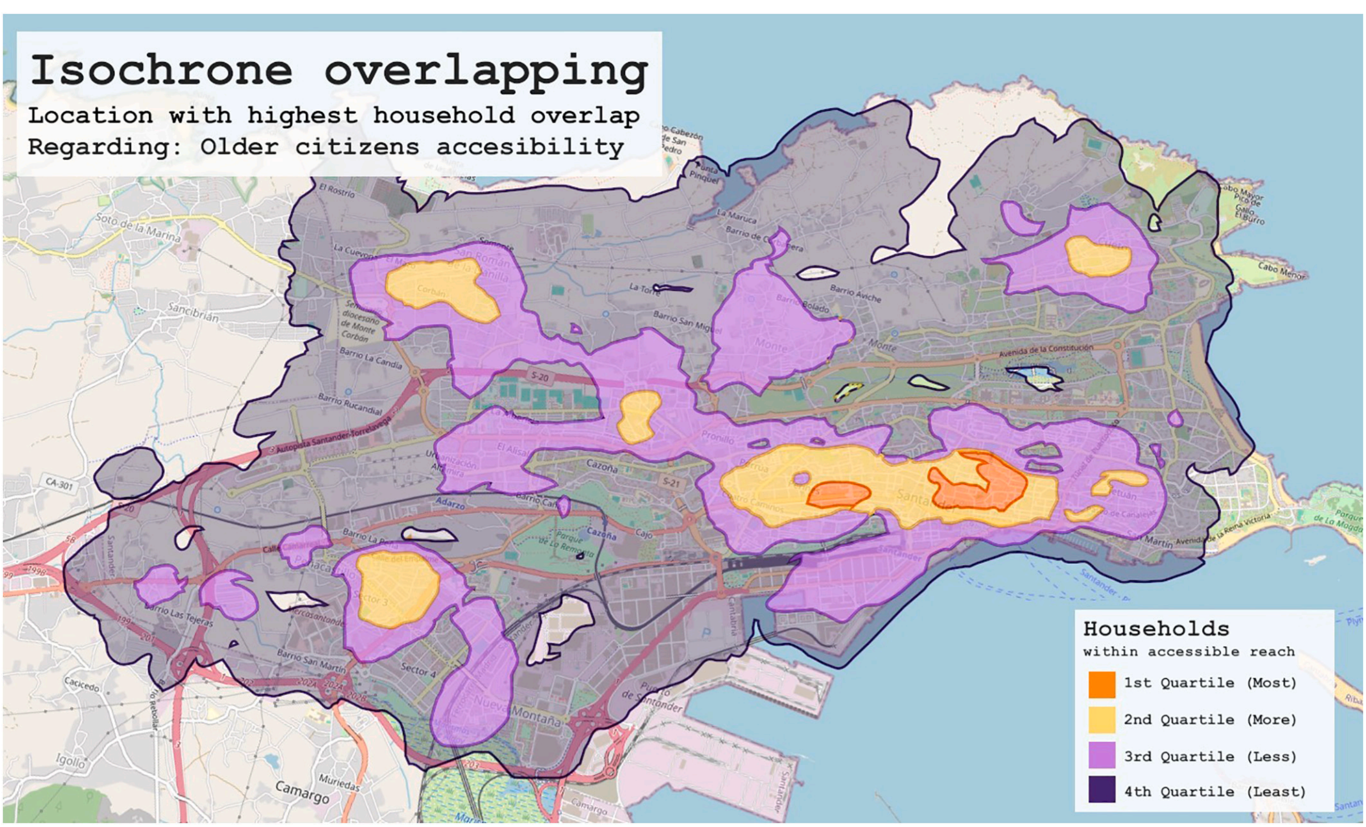

Fig. 5. Isochrone overlapping for older citizens walking configuration starting at their homes and traversing through an accessible path. Four quartiles are coloured to indicate the density of isochrone overlapping. Source: (URBANAGE, 2024).

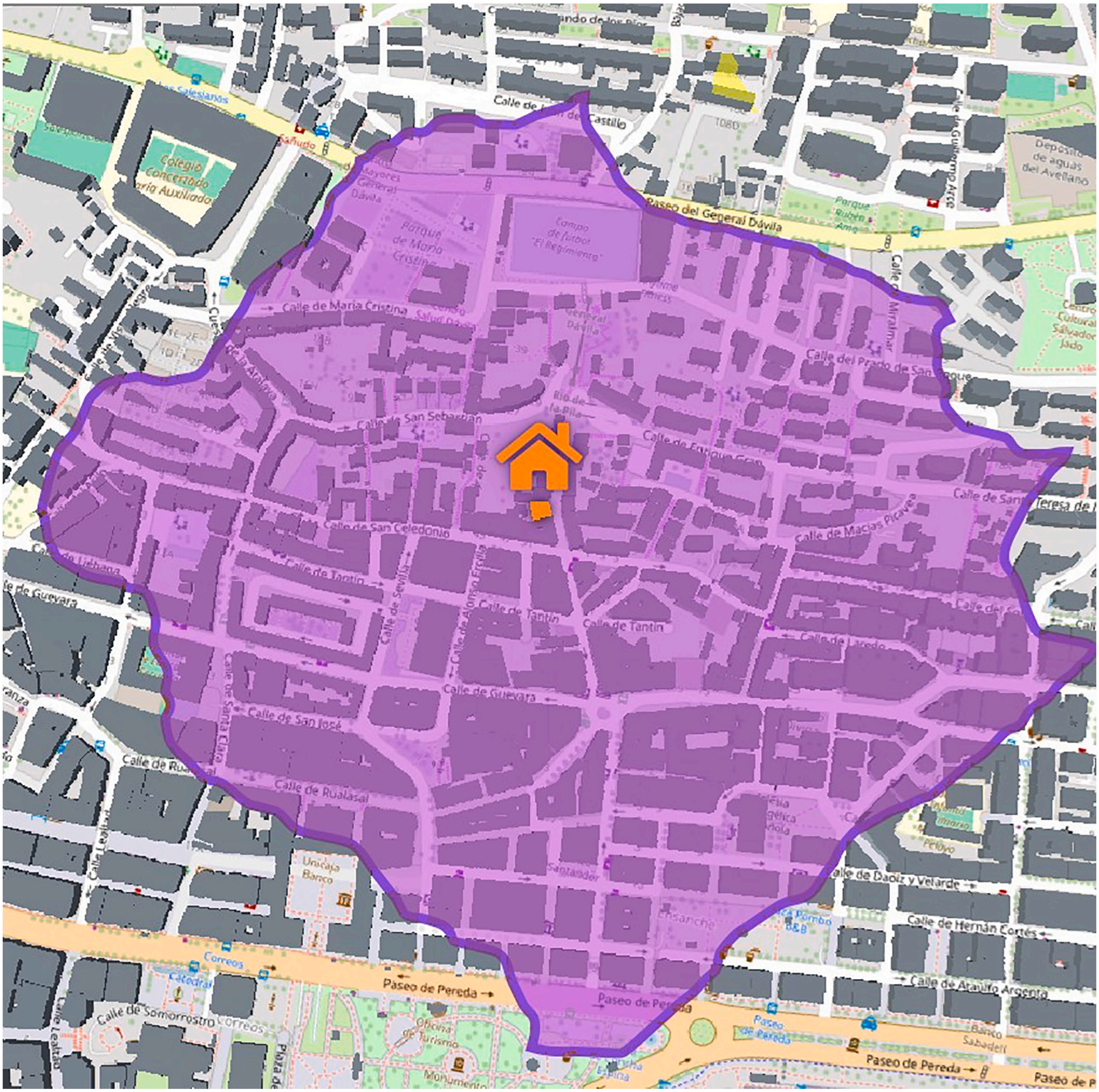

Fig. 6. The accessible isochrone polygon with a walking accessible configuration and a 10-minute trip coloured in purple that starts at the building highlighted in orange of "C. Río de la Pila, 21" in Santander. Source: (URBANAGE, 2024). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

single associated indicator, the substantial weight of these indicators in the AFNI renders these solutions highly impactful.

The final addition to this initial Solutions Catalogue involves the implementation of *accessible and safe bus stops*, characterised by secure and easily accessible bus stops or shelters (e.g. equipped with seating, well-lit, covered, with snow removal and in proximity to older people's residences). This solution affects Domain 2, Transport and Mobility and impacts one indicator and one topic. In contrast to the previous solutions, which, despite influencing only one topic, had a substantial impact on AFNI, this solution results in a very low impact due to the low weight assigned to the corresponding indicator.

3.2. Simulation and tools

The virtualisation of city geospatial data grows within the digital twin as quickly as new data exploitation requirements and opportunities emerge. To thoroughly evaluate the most complex scenarios, new technologies and methods must be designed in parallel from the Digital Twin. In this section, we present two modules: an AI simulation module and a decision-making tool involving multiple criteria. As described in the literature review, the necessity and implementation of AI solutions to solve urban challenges might be a sign of an LDT approaching the Level 3 Atkins maturity level.

Table 2
Available services within the accessible isochrone from building "C. Río de la Pila, 21" in Santander.

Service	Amount	AFNI indicator
Benches	188	1.1.1.
Public toilets	0	1.1.3.
Open spaces	54	1.2.3.
Public green and water areas	0	1.4.1.
Bus stops	9	2.1.1.
Community centers	2	4.1.2.
Convenience stores	9	4.1.3.
Cultural and educational facilities	0	4.1.6.
Sites of worship	3	4.1.7.

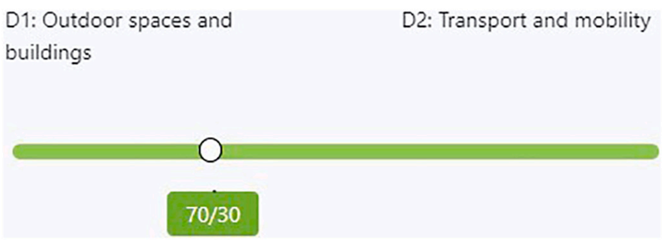

Fig. 7. Multicriteria Analysis sliders for prioritizing domains. *Source:* (URBANAGE, 2024).

3.2.1. Age Friendly Index Simulator (AFIS)

The AFIS is a simulation module that includes AI to evaluate the age-friendliness of a city. The evaluation was performed using the AFNI indicators described in Subsection 3.2.2. The diversity and singularities of some indicators prompted the need to devise an AI module as a complementary solution for LDT.

Notably, challenging indicators are those that evaluate a city's accessibility by measuring the percentage of households that have an accessible path to relevant services such as grocery stores. A conventional approach to evaluating them involves assessing services within a radius of each household in Euclidean or Manhattan distances (Bellot, 1988). However, these methods overlook crucial factors such as terrain elevation and accessibility for older citizens, who are precisely the demographic group that these tools are designed to assist.

To address these limitations and enhance the capabilities of LDT, the AFIS was integrated into the URBANAGE tool ecosystem. The AFIS is designed to ingest the geospatial information available in the digital twin, execute both AI simulations and optimisation processes, and provide output solutions in a consumable format for the LDT so that it can be visualised. Four AI algorithms have been implemented: 1) the *Age-Friendly Route Planner* (Aranguren et al., 2024) which enables computation of isochrones to measure accessible service for each household based on OpenStreetMap (OpenTripPlanner (OTP)) by computing an A* routing algorithm with accessibility concerns, and 2) the isochrone overlapping mobility analysis technique (Aranguren Ubierna, Laña, Osaba and Urra, 2024) utilised to identify and visualise optimal locations for new services comprehensively. 3) A metaheuristic optimisation algorithm selects the most rewarding solutions from the Solutions Catalogue taking into account the improvement they provide based on the isochrone overlapping data estimations. 4) Finally, a vertical infrastructure location optimisation model based on the approach proposed in (Delgado-Enales et al., 2022) offers a preliminary prescriptive analysis of the most rewarding areas for improving the AFNI.

These solutions were built on classic isochrones; however, their capabilities were improved. Isochrones are particularly useful because they can describe population mobility patterns. In this case, each citizen's household address for a set time and walking configuration can be described as a polygon that expands outwards from a particular point. In this case, time and configuration constraints were designed to portray the walking patterns and capabilities of older citizens (Aranguren Ubierna, Laña, Osaba and Urra, 2024; Willberg et al., 2023). Traditional isochrones do not consider terrain elevation; however, as our target group comprised older citizens, this factor was very important. To overcome this obstacle, an Age-Friendly Route Planner was used that prioritises vertical mobility infrastructure and avoids streets that exceed a particular steepness. Although this walking configuration is designed to resemble older citizens, it remains customisable to represent diverse citizen groups. Different configurations can be used to compare the needs and limitations of each citizen within a city (Fig. 5).

Taking full advantage of the AFIS, an urban planner within the LDT could check the exact area a person could traverse in an accessible manner (Fig. 6) and the number of services available inside that area for each building in the city (Table 2). Both data outputs can be requested for every building in the city and although this case study is based on

Fig. 8. URBANAGE LDT of Santander. Source: (URBANAGE, 2024).

older citizens, multiple configurations could be designed to portray, for example, teenager mobility, cyclists' mobility, or even multimodal transportation depending on the study urban planners want to conduct in the city.

Fig. 6 shows an example of the isochrone overlapping technique applied in Santander. This figure was created based on the walking configuration of older citizens described in (Aranguren Ubierna, Laña, Osaba and Urra, 2024). Orange represents the quartile with the highest number of overlapping isochrones. This orange polygon describes the areas that most citizens can reach, based on the configuration provided in a previously cited study. The yellow, light purple, and dark purple quartiles describe less dense areas. The central area of the city exhibits a higher percentage of isochrone concentration of households than the outskirts, which fell within the last quartile. Because of Santander's orography, the unevenness of the terrain creates spots with low coverage close to the locations with the highest coverage. This example demonstrates that simple Euclidean distances are not as useful when assessing cities with a steep orography, in contrast to an age-friendly routing algorithm. In addition, this mobility map could help urban planners in their decision-making process by, for example, being filtered to include only the households that do not already have access to a particular service, and thus, specific intervention locations from the Solutions Catalogue from Subsection 3.2.3 can be optimised.

3.2.2. Multicriteria analysis

A decision-support system (DSS) manages data and models, and assists managers in their decision processes for semi-structured and unstructured tasks to improve the quality of decisions (Taherdoost & Madanchian, 2023). Different decision model approaches exist, among which *multicriteria decision-making* (MCDM) deals with decision alternatives that are explicitly known from a discrete set of alternatives.

The use of the multicriteria methodology is especially useful in redefining the weights of the domains in the AFNI. Although the AFNI is based on European-level indicators and expert criteria, urban planners or policymakers who are aware of the situation in their cities may prefer to redefine the weights.

The adopted technique has been the Analytic Hierarchy Process (AHP) (Khazaii, 2016). Developed by Thomas L. Saaty in the 1970, the AHP is used to organise and analyse complex decisions based on mathematics and psychology.

The adoption of AHP-based multicriteria prioritisation facilitates weighting domains in the AFNI. Through an intuitive graphical interface featuring sliders, decision-makers can assess and compare each domain pair (see Fig. 7), thereby assigning relative priorities with precision and avoiding the pitfall of indiscriminate prioritisation across all domains.

Employing the AHP methodology translates pairwise comparisons into distinct weights for each domain and aligns with the priorities delineated by the user, as illustrated in Table 4.

Table 3
Santander less friendly neighbourhoods in Domain 1 (Outdoor spaces and buildings).

Neighbourhood	AFNI	Domain 1
Camarreal	5.99	9.55
La Albericia	7.62	12.59
Ciudad Jardín Porrua Cuatro Caminos	9.01	13.36
Monte	6.65	13.4
Vía Cornelia	10.22	13.49
Nueva Montaña	9.05	13.59
Castilla Hermida Pesquero	9.18	13.64
San Francisco Pronillo	9.54	13.7
La Torre	6.61	13.79
Peñacastillo Ortega y Gasset	8.02	14.01

4. Results

In this section, the outcomes of the research are presented, placing a

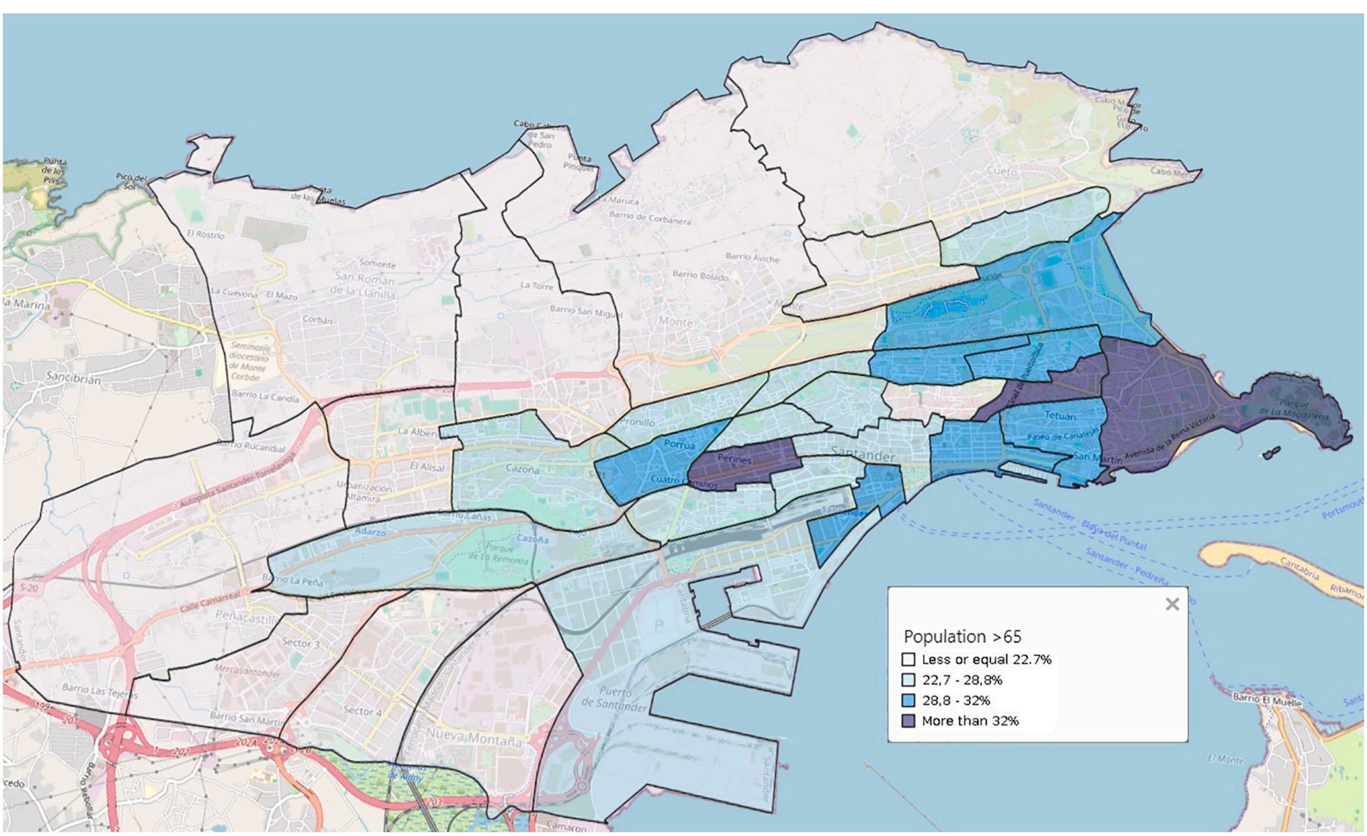

Fig. 9. Santander Population older than 65 map, Source (URBANAGE, 2024).

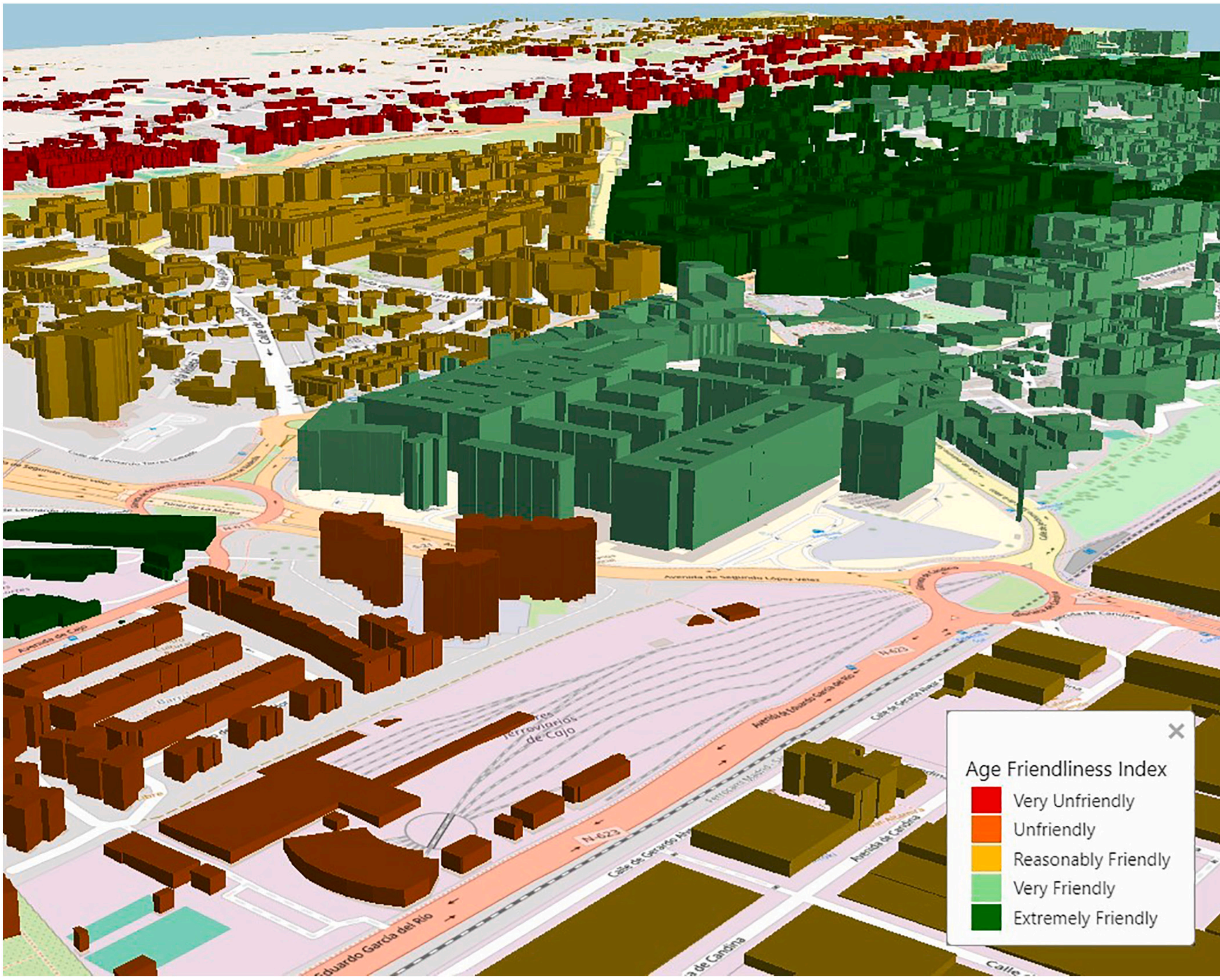

Fig. 10. Santander age friendly neighbourhood index at building level. Source:(URBANAGE, 2024).

spotlight on the application of the URBANAGE Digital Twin framework in Santander, where a comprehensive endeavour for long-term urban planning in age-friendly cities was developed.

Santander's URBANAGE LDT (see Fig. 7) focuses on calculating the age-friendliness of neighbourhoods for older people based on the AFNI described in Subsection 3.2.2. The digital twin can assess age-friendliness by performing the following actions. Within the LDT, there are multiple processed data sources, one of which, as mentioned in Subsection 4.3.1, is the AFIS module. The CIM is a database that contains the elements of the city in the CityGML format, which provides knowledge of the elements that are found in each neighbourhood. The Solutions Catalogue is a database in which possible interventions that can be carried out in a city are stored. Considering these two data sources, the AFIS, which is a service that calculates the indicators defined in the AFNI, calculates simulations by connecting itself to both sources. These data can be viewed from the digital twin itself. Finally, multicriteria analysis allows redefinition of the domain weights and visualisation of the results provided by the AFIS (see Fig. 7).

4.1. Study area

Santander, the capital of the autonomous community of Cantabria on the north coast of Spain, boasts a population that skews older; 26.28 % of its residents are aged 65 years or older as of 2022 (ICANE, 2022), surpassing the regional average of approximately 23.1 %. This places Santander among the regions with some of the highest proportions of older people in the country, where the overall figure hovers around 20 % according to the 2022 data (INE, 2022).

This demographic trend is expected to intensify in the coming years, placing a significant strain on municipal services. A closer examination of neighbourhood-level data (see Fig. 8) reveals that the city centre hosts the highest percentage of older residents, while peripheral neighbourhoods exhibit a lower proportion of individuals aged 65 and older. This distribution underscores the geographical challenges faced by older residents of Santander in terms of accessibility.

In response to the ageing population, the Santander City Council launched various initiatives to enhance older citizens' quality of life. Since December 2012, Santander is part of the WHO *Global Network of Age-Friendly Cities and Communities*. Through this membership, the city is committed to fostering participation, safety, and well-being across generations, thus enabling longer and more active lives filled with opportunities.

4.2. Long-Term Urban Planner (LTUP)

In the URBANAGE project, the Long-Term Urban Planner (LTUP) tool was developed by integrating the different elements mentioned in the methodology (AFNI, AFIS, multicriteria analysis, CIM, and Solutions

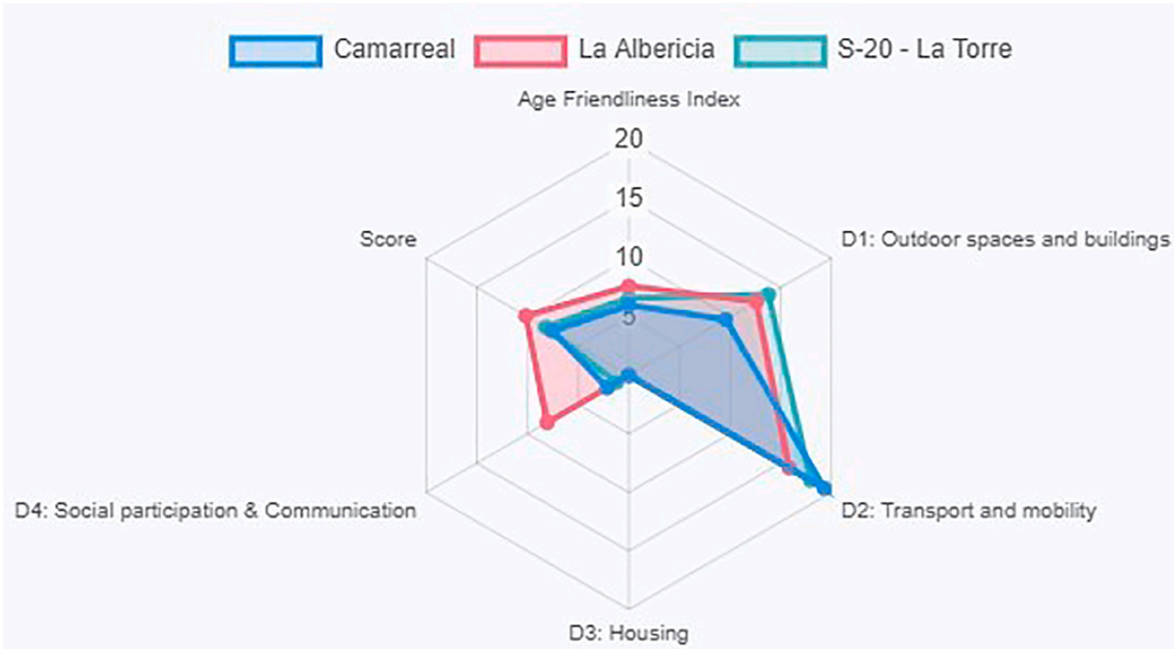

Fig. 11. Selected Neighbourhoods comparison in a chart. Source: (URBANAGE, 2024).

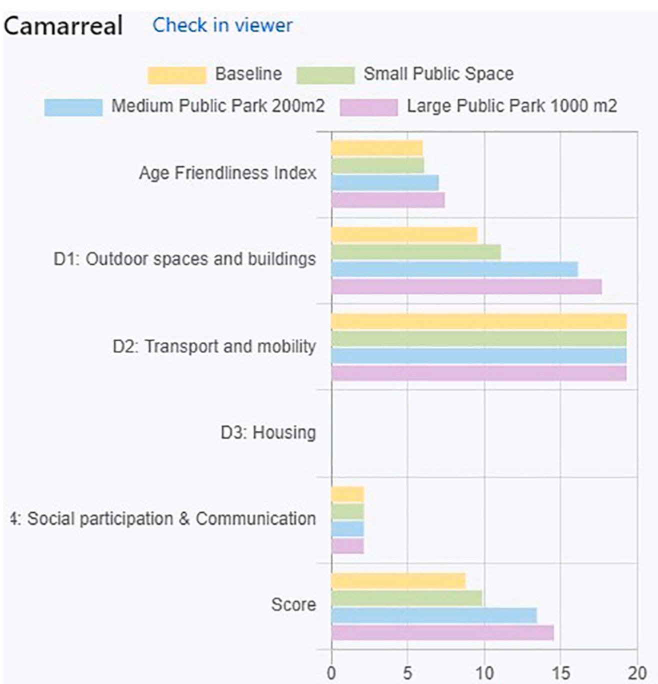

Fig. 12. Small, medium and large park simulation for Camarreal Neighbourhood. Source: (URBANAGE, 2024).

Catalogue). The primary objective of the Santander LTUP is to model the potential effects of various interventions on the age-friendliness of distinct neighbourhoods within urban areas. This assessment of age-friendliness draws upon the CIM and the AFNI, as described in Sections 3.2.1 and 3.2.2. The CIM is a 1D geospatial representation of the foundational information of city elements and processes. The AFNI provides insight into the factors influencing the well-being and quality of life of older residents from an urban planning perspective, highlighting areas for potential enhancement. Specific accessibility indicators are intrinsic to individual neighbourhoods and present challenges for targeted improvement initiatives.

The Santander LTUP seamlessly incorporates the Solutions Catalogue (Section 3.2.3), which delineates targeted interventions tailored to specific use cases in the urban context. These interventions influence diverse indicators and domains, necessitating a DSS endowed with multicriteria definition capabilities (Section 3.3.2). This comprehensive framework facilitates simulation and enables the comparative analysis and identification of optimal solutions through an AFIS.

The LTUP serves as a valuable tool for urban planners and policymakers and provides insights into the repercussions of decisions on the dynamics of the city. To illustrate its practical utility, two theoretical applications for Santander are presented from the perspective of two distinctive users: urban planners and municipal planning councillors.

4.2.1. *Use case 1: propose an intervention in public space*

Urban planners from the city of Santander are acutely aware of demographic shifts among citizens and the challenges associated with the built environment of the city. Therefore, they want to make informed decisions when proposing interventions for public spaces. With this objective, they aim to identify neighbourhoods that are less age-friendly, allowing them to propose urban solutions that would enhance the quality of life for older residents. Traditionally, the decision-making process relies on available land, visual map analysis, or simply prioritizing neighbourhoods with minimal historical investment (Fig. 10).

The tool enables urban planners to identify different AFNI scores and visualise them on a map or at the building level (see Fig. 9), providing a quick overview of the most disadvantaged neighbourhoods. In addition, it allows them to view the information segregated by domain in a tabular format that can be filtered and sorted. Suppose that neighbourhoods with the lowest scores in Domain 1 (outdoor spaces and buildings) are prioritised (Table 3).

Based solely on the score obtained from Domain 1, decisions are made regarding interventions in the Camarreal and La Albericia neighbourhoods.

Recognising that enhancing outdoor spaces and infrastructure positively impacts active ageing opportunities, urban planners acknowledge that this single criterion alone may not be sufficient for neighbourhood prioritisation. To address this limitation, they can employ a multicriteria tool (Section 2.3.2) that allows for the adjustment of weights assigned to

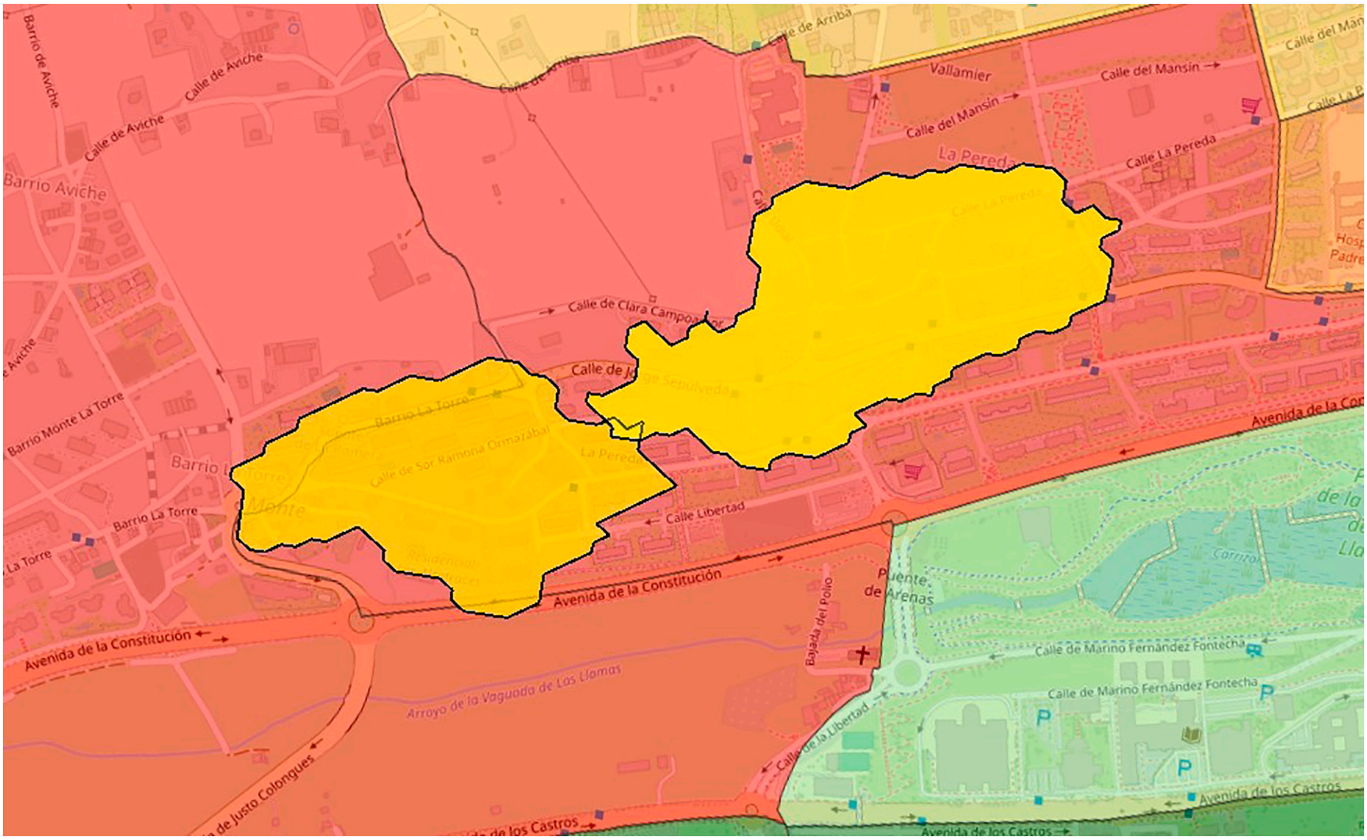

Fig. 13. In yellow small, medium, and large park simulation proposed places for La Torre Neighbourhood. Source: (URBANAGE, 2024). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

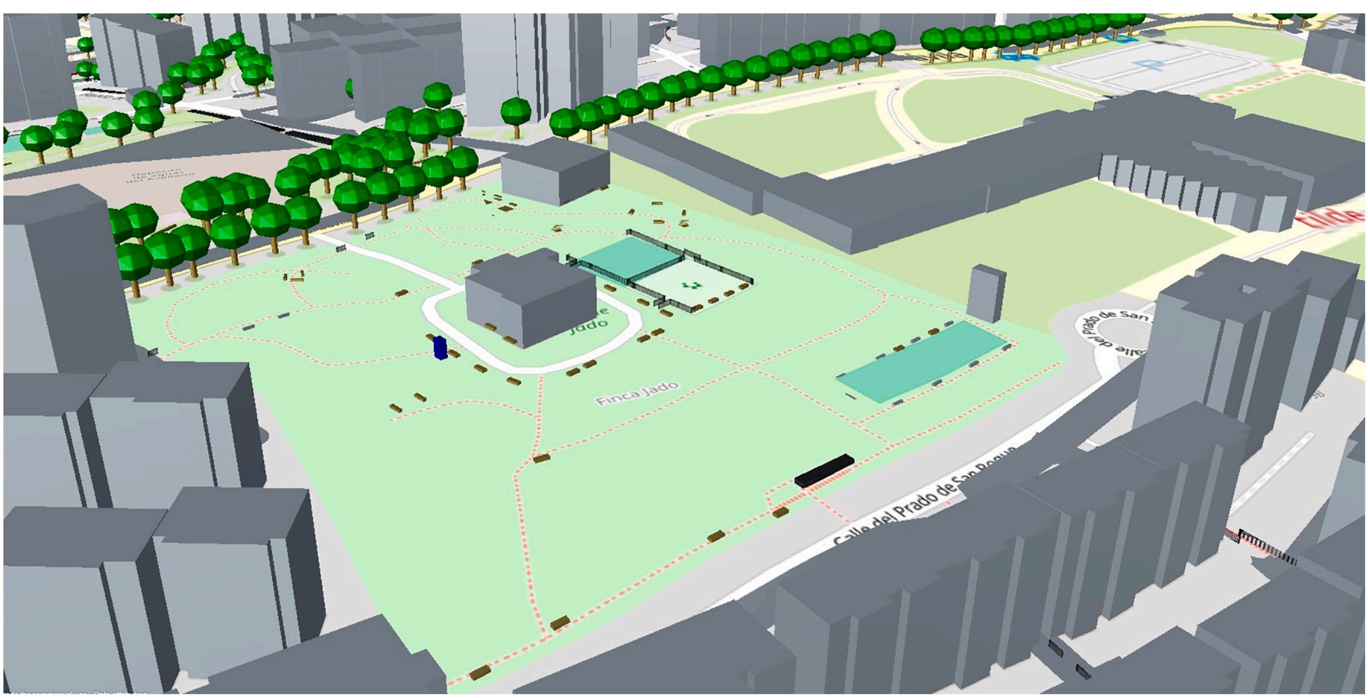

Fig. 14. Entrehuertas - Prado - San Roque digital twin 3d visualisation of hospital, park, and city elements. Source: (URBANAGE, 2024).

relevant domains. This functionality aids in the identification of priority areas. Consequently, they use the multicriteria tool to redefine weights, emphasising Domains 1 and 4 over Domains 2 and 3.

Despite the La Torre neighbourhood scoring higher in Domain 1, this insight prompts the prioritisation of interventions in that area. Subsequently, a comparative analysis is performed involving the three

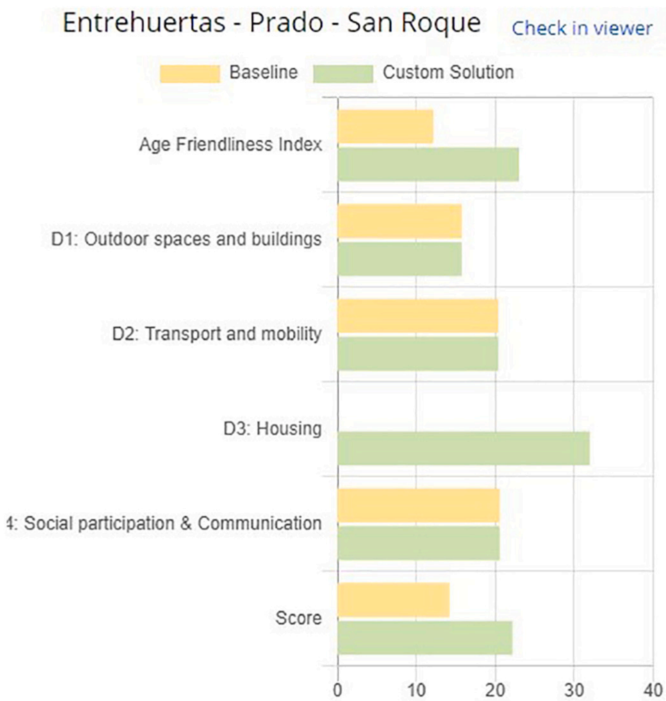

Fig. 15. Improvement simulating Construction of protected flats and social housing options for rental in a graph. Source: (URBANAGE, 2024).

Table 4
Camarreal, La Albericia, and La Torre neighbourhoods' age-friendliness index, multicriteria analysis values, and the percentage of population older than 65 and 80 years.

Neighbourhood	AFNI	Score	> 65	> 80
Camarreal	5.99	7.85	19.41	5.78
La Albericia	7.62	10.17	15.62	4
La Torre	6.61	8.22	21.21	7.56

neighbourhoods mentioned above.

In the subsequent phase, the selected neighbourhoods are visually represented both graphically and in a tabular format. This representation includes the following components: the AFNI value, a parameter defined as a multicriteria metric (score); the four domains, each contributing to the overall assessment; and, in the table, an Additional Information column displaying the percentage of residents aged over 65 and 80 years in each neighbourhood. Based on this comprehensive analysis, it can be concluded that La Albericia lacks a significantly older population. Consequently, the other two neighbourhoods were prioritised.

The objective is to add a new urban park to the city. As described in Section 3.1.3, urban parks are multifaceted solutions that affect various indicators, including benches, fountains, and green zones.

Leveraging the predefined solutions allows for rapid calculations, which are typically completed within three minutes. These calculations use precalculated isochrones and the baseline state of the indicators. Consequently, urban planners can simulate the feasibility of constructing small, medium, or large parks independently for the two selected neighbourhoods of Camarreal and La Torre.

During the simulation, it is observed that a small park did not have a significant impact. Furthermore, the difference between medium and large parks is not substantial relative to their associated costs (see Fig. 11). This observation arises from the indicators reaching their maximum scores, and even exceeding them in the case of a large park. Based on this information, the choice is made to proceed with the construction of two medium-sized parks.

The subsequent step involves determining the optimal locations for these medium-sized public parks (Fig. 12). Guided by an indicator stipulating that open spaces should be conveniently accessible to older adults, the tool calculates suitable areas within the neighbourhood.

In the context of Camarreal, which is situated on the periphery of the city, the proposed park location presents relatively straightforward considerations. However, in the case of La Torre, a central neighbourhood characterised by uneven topography, the optimal locations, while suitable from the standpoint of indicators and population coverage, may not align seamlessly with the viability criteria (Fig. 13).

Thus, the expertise of urban planners is pivotal. By cross-referencing data from the digital twin with their intimate knowledge of the city, the planner can discern the most suitable placement within the options established by the digital twins. Nevertheless, as the ultimate decision-maker, the urban planner must weigh additional factors, including existing building occupancy and adherence to urban regulations, to arrive at the final choice of location.

4.2.2. *Use case 2: address demographic trends*

In this theoretical case, a municipal planning councillor is committed to addressing future demographic trends within specific city neighbourhoods. Specifically, the councillor is concerned about the projected increase in the proportion of older residents and recognises the importance of anticipating these demographic shifts and their implications. To address this issue, the councillor intends to use LTUP tools to assess how the city can proactively prepare for these circumstances. By doing so, the aim is to identify necessary interventions that align with the needs and expectations of citizens residing in these neighbourhoods. This informed approach guides the decision-making process and enables the strategic allocation of resources for future urban planning investments.

As explained in Section 4.1, the central urban areas of Santander exhibit a higher concentration of older residents, whereas the peripheries predominantly harbour younger populations. This phenomenon reflects the city's evolutionary trajectory; the outwards expansion of housing offerings has led to an observed demographic stratification. However, the neighbourhoods of El Sardinero and Cueto diverge significantly in terms of age distribution. El Sardinero boasts a substantial 33.34 % of residents aged 65 years and older, while Cueto, mere metres away, registers a modest 17.13 % in the same age group (Table 5).

Of particular interest to policymakers is the analysis of the Entrehuertas–Prado–San Roque neighbourhood, a central neighbourhood of Santander with a much younger population than its surroundings. The intervention in this neighbourhood would have been difficult to discover from the AFNI, because it has the third-best score in Santander. This is because it is a central neighbourhood with access to services, two parks, and one hospital.

Policymakers are deeply attuned to the potential ageing trends within this neighbourhood. With the municipality poised to initiate new tenders for the construction of residential buildings—both public and private—it is proactively considering measures to address the needs of Santander's ageing population. To this end, the councillor proposes explicitly reserving a portion of the housing units for older residents. Specifically, some units will be allocated for the *construction of protected flats for older people* to ensure their safety and comfort. Other units are designated as *social housing options for rental*, promoting affordability and inclusivity.

To operationalise this strategy, a simulation tool is employed in this specific neighbourhood and intervention. Unlike the approach described in the first use case, where the input of data is manual, in this case, the neighbourhood is directly selected from the map interface. The simulation then generates graphical and tabular results that guide the decision-making process (Fig. 15).

Housing was particularly significant. Although Santander currently offers social rental housing and protected housing, a critical gap persists

Table 5
El Sardinero, Cueto and Entrehuertas Prado San Roque neighbourhoods AFI and population ageing comparison.

Neighbourhood	AFNI	> 65	> 80
El Sardinero	10.54	30.9	10.54
Cueto	9.77	17.13	4.77
Entrehuertas Prado San Roque	12.15	22.68	6.99

Table 6
Entrehuertas - Prado - San Roque neighbourhood AFNI before and after adding construction of protected flats and social housing options for rental.

Domain	Baseline	Simulation
Domain 1	15.76	15.76
Domain 2	20.42	20.42
Domain 3	0	32
Domain 4	20.58	20.58
Total	12.15	23.03

in the absence of dedicated housing options tailored specifically for older adults. Therefore, the value observed in the baseline of Domain 3 is zero (Fig. 14). The prevailing criteria for existing housing units hinge primarily on financial capacity, thereby overlooking the unique needs of the ageing population. In this context, this indicator assumes heightened relevance. Addressing this housing deficit is paramount to enhancing the city's age-friendliness. Strategic interventions aimed at creating age-appropriate housing alternatives play a pivotal role in fostering inclusive and supportive environments for older residents.

Should the proposed intervention be implemented, the AFNI for the neighbourhood would experience substantial enhancement, from its current value of 12.15 % to 23.03 % (see Table 6).

4.3. Evaluation of the tool

The digital twin and its diverse functionalities, designed for long-term urban planning, were developed for use by urban planners and policymakers, specifically targeting civil servants as end users. As an integral part of the URBANAGE project, the functionality of the tool was rigorously evaluated by a group of civil servants in Santander. This assessment encompassed not only technical validation and current functionality, but also user perceptions, utility, and potential added value to their work (Molina & Luc, 2022).

This evaluation yielded interesting results. In terms of trustworthiness, civil servants expressed growing confidence in the digital twin, which incorporates a diverse set of features. As a result of this effort, civil servants can now visualise urban elements and their associated data, manipulate the age-friendliness index and simulate enhancements using a curated catalogue of solutions. Notably, users emphasised the critical link between trustworthiness and the quality and currency of the underlying data, suggesting that including data update timestamps enhances the tool's value.

Regarding inclusiveness, all civil servants concurred that pretraining sessions on using the tool were highly advisable. In addition, domain-specific expertise is essential for maximising tool efficiency. Soliciting user feedback at the outset of development and involving it in testing various intermediate versions before the final release significantly contributes to tool adaptation and acceptance. End users perceive substantial value in the tool, recognising its utility and the effort invested in its development. The acceptance level of digital twins among the consulted civil servants was also notably high. They not only recommend its use for urban planning but also find it intriguing as a solution for daily management.

In summary, the assessment results affirm that the developed digital twin and functionalities effectively meet end-user needs through a user-friendly interface and provide reliable results.

5. Discussion

The development of the LDT in the Santander use case provides a comprehensive platform for integrating various services and technologies. By constructing a digital twin from the ground up, seamless integration of data and analytics has been achieved, offering evidence-based support to urban planners and policymakers in Santander in their decision-making processes. This implementation adheres to the Gemini principles, ensuring that the LDT is purposeful, trustworthy, and functional, thereby aligning with the best practices in digital twin development. Regarding *Purpose*, in this study, the primary purpose of the LDT was to enhance urban planning for inclusive neighbourhoods, focusing on age-friendliness and social integration. This aligns with the principle of ensuring that digital twins are used to create public good and improve citizens' quality of life. Related to *Trust*, URBANAGE LDT implementation follows data protocols to ensure data integrity and protect sensitive information. It has also been identified as a main contributor to robust data governance. Regarding *Function,* URBANAGE LDT integrates advanced technologies such as GIS data, computational intelligence, and data analytics to provide practical tools for city planners. This functional integration allows for comprehensive analysis and informed decision-making, aligning with the focus of the Gemini principles on effective and usable digital twins.

However, the reliance on publicly available data and 2D cartography can impact the accuracy of the CIM. Although large European cities often have up-to-date digital cartography and georeferenced urban information, this is less common in medium or small cities. Furthermore, open data may not always be updated or made accessible to users. To address these limitations, various data sources were combined and additional data were generated through image processing and advanced analytics. Despite these efforts, fieldwork remains crucial for collecting valuable data that would otherwise be unavailable. The Santander CIM exemplifies advancements in integrating geospatial data but highlights that relying solely on open data and municipal information may not ensure a complete and accurate representation. Future research should focus on incorporating more current and detailed data, and adapting methodologies to specific urban contexts to improve model precision.

It is also important to highlight that the use of indicators such as the AFNI helps stakeholders make informed decisions based on more objective criteria and real-time insights. However, obtaining all the data required for the calculation of the AFNI has proven to be complex, leading to some indicators being left unmeasured. In some cases, predefined indicators from WHO (*World Health Organization (WHO), n.d.*) were difficult to measure in the specific context of Santander. These challenges highlight the dynamic nature of urban environments and the need for adaptable methodologies in digital twin development.

In terms of the tools and methods used, the AFIS module has been validated as a valuable tool for urban planners. However, to make it accessible to civil servants with limited digital expertise, its integration with a digital twin is essential, and an application programming interface (API) endpoint or dashboard might not be sufficient. The gradual integration of AI solutions within the digital twin will enable urban planners to assess the real-life implications of urban interventions. The AHP combined with the AFNI empowers stakeholders to make informed choices by leveraging both quantitative and qualitative factors within a mathematically complex yet user-friendly system. The AHP was chosen for its simplicity of use for non-expert users, although it is only feasible for a limited set of indicators because the combinations grow exponentially with the number of indicators.

On the other hand, the isochrone overlapping technique shows potential for representing diverse population groups; however, further testing should be conducted to determine the suitability of this proposal, because it has not been tested outside of this first use case. Additionally, a key limitation of the Age-Friendly Route Planner is its inability to adjust walking speed according to street steepness, which must be addressed to accurately capture the pedestrian experience.

Regarding the Atkins/IET maturity model, URBANAGE LDT goes a step further by proposing a digital twin that reaches Level 3. Levels 0, 1, and 2 were addressed in URBANAGE by developing a CIM based on CityGML. Level 0 captures the reality and reading of different sources, Level 1 captures the creation of semantic 1D models, and Level 2 connects the models with persistent data.

At Level 3, URBANAGE connects the 1D model to the dynamic data within the data management layer. This integration includes real-time information on parking occupancy, escalator status, and other dynamic urban elements. Geospatial queries and specialised algorithms related to urban comfort and accessibility exploit existing data and provide valuable insights to users. At this level, the URBANAGE LDT data model goes a step further by integrating an AI module that facilitates route planning and mobility analyses for the optimal location of services for citizens. These algorithms are employed to diagnose intervention needs in the decision-making phase, enabling the simulation of what-if scenarios. Taking a step toward Level 4, URBANAGE prioritises human-machine interaction, particularly emphasising 1D visualisation, navigation, and user engagement with the digital twin for comprehensive reality analysis and informed decision-making. The URBANAGE Digital Twin facilitates interaction with static information, allowing users to select and manipulate the information layers. Additionally, it incorporates dynamic information such as real-time shadows and simulation results generated by decision-making algorithms.

Addressing data gaps and refining indicator definitions to better suit the local context are crucial for enhancing the effectiveness of digital twins. Collaborative efforts among stakeholders, data providers, and researchers are essential to overcome these challenges and further advance the capabilities of the URBANAGE LDT. Continuous refinement and iterative improvements are essential to maintain the efficacy of the digital twin, and perpetuate its status as a valuable tool for evidence-based decision-making not only in this case but also in other urban contexts. Moreover, adequate training of end users and domain-specific expertise play pivotal roles in unlocking the full potential of this powerful resource.

6. Conclusions

The implementation of the URBANAGE LDT in Santander to enhance the city's age-friendliness highlights the critical role of long-term urban planning. This tool provides valuable insights into the relationships between demographics, spatial distribution, and quality of life. A trend seen in many European cities, including Santander, reveals a high concentration of older adults in city centres, which requires solutions to address this social challenge. Strategic interventions can enhance the quality of life of older residents by evaluating the age-friendliness of the neighbourhood and identifying areas that need improvement. The URBANAGE digital twin presents an innovative solution that enables cities to address age-related challenges and create inclusive and resilient communities that adapt to demographic shifts.

The URBANAGE LDT modular approach, incorporating the CIM, AFNI, Solutions Catalogue, AFIS, and AHP-based multicriteria analysis, represents a step forward in the field of urban planning digital tools for creating inclusive and sustainable environments.

The CIM provides a comprehensive 1D representation of urban elements, facilitating a better understanding and visualisation of accessibility and infrastructure. The use of CityGML standards and the inclusion of both open data and specific municipal information enriches the model and provides a robust foundation for simulations and analyses. The AFNI is essential for evaluating and comparing age-friendliness across neighbourhoods. Its structured framework based on domains and indicators offers a clear assessment of the areas requiring intervention. This index aids in both inter-city comparisons and intra-city evaluations, helping urban planners identify high-need neighbourhoods and prioritise effective interventions. The Solutions Catalogue offers a dynamic repository of urban interventions tailored to improve age-friendliness. From creating public parks to enhancing bus-stop accessibility, these solutions can be simulated and visualised within a digital twin, thereby providing a powerful tool for urban planning. AFIS- and AHP-based multicriteria analyses are crucial for evaluating complex scenarios and adjusting planning priorities. These tools enhance the precision and relevance of assessments, ensuring that the proposed solutions align with specific urban contexts and priorities. The seamless integration of these components enables informed decision-making by urban planners and policymakers, allowing detailed assessments of accessibility and age-friendliness in urban areas. The development of user-friendly environments for visualisation and interaction with representative information and simulation results provides urban planners and policymakers with an effective means of evaluating and comparing different urban intervention scenarios.

This study makes a noteworthy contribution to the current smart cities literature by demonstrating the practical applications of LDTs in urban planning for inclusive neighbourhoods. This study presents a LTUP tool that allows comprehensive analysis and modelling of the effects of various interventions. Through two use cases, one suggesting a public space intervention and another addressing the needs derived from future demographic trends, this study advances in the understanding of how LDTs can enhance social integration in smart cities. Assessing neighbourhood age-friendliness informs targeted urban interventions, whereas practical testing underscores the importance of robust data governance. This study represents a step forward in exploring the potential of urban digital twins to integrate the social dimension within smart cities, offering a proven implementation of a holistic approach (environmental, social, and economic) toward achieving a sustainable smart city. An evaluation by civil servants in Santander revealed high trust and value in the digital twin, emphasising the importance of data quality and user training. The tool's user-friendly interface and reliable results have led to its acceptance and recommendation for urban planning purposes, highlighting its potential to create age-friendly, inclusive communities.

The implementation of the LDT highlights the necessity for robust data governance structures in cities to fully exploit the potential of urban technologies. Effective governance requires comprehensive frameworks that include institutional structures, defined roles, regulatory guidelines, procedural methodologies, and technical infrastructure, all of which ensure reliable and valuable data sharing. Consequently, high-quality planning decisions depend on accessible data, preferably obtained from public sources or platforms. Civil servants play a pivotal role in continuously improving open data by regularly updating and sharing internal datasets, thereby enhancing the precision and relevance of the dependent tools. Furthermore, integrating AI into urban planning necessitates the long-term storage and annual aggregation of substantial datasets to develop robust machine learning models. A centralised approach to data sharing is essential, particularly for smaller municipalities that may lack resources for open data strategies. Collaboration among various city departments, including civil servants, urban planners, IT, local law enforcement, and cultural and sports departments, is vital for the development of age-friendly urban environments. Ultimately, ensuring precise and relevant data in digital tools is critical with a focus on accuracy and direct applicability to user needs.

Future studies in this area can explore the possibility of adding real-time data not only to the visualisation in the digital twin but also taking it into account in different simulations that can be carried out. It would also be within this area of study that future scenarios defined by a simulation affect other simulations or the state of the digital twin itself. From a technological perspective, it would be beneficial to increase the digital twin's level of maturity, allowing it to interact with reality from the digital twin and eventually carry out predictive actions and propose or take actions. Regarding the use of these tools, future studies will consider the possibility of opening a digital twin to the public. The data generated and displayed are relevant to a wide audience, transcending technical boundaries. Ensuring equitable access to digital technologies for all individuals is essential to achieve the true potential of smart cities (Dragan et al., 2024). However, achieving this goal necessitates a redefinition interface. A more user-friendly design is essential, particularly when engaging in non-technical or non-specialised profiles. Simplifying certain aspects of the process or selectively exposing the visualisation of results can enhance accessibility and democratise the benefits of digital twins.

CRediT authorship contribution statement

Asel Villanueva-Merino: Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Investigation, Conceptualization. **Silvia Urra-Uriarte:** Writing – original draft, Methodology, Investigation. **Jose Luis Izkara:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Sergio Campos-Cordobes:** Writing – review & editing, Supervision, Data curation. **Andoni Aranguren:** Writing – original draft, Methodology. **Patricia Molina-Costa:** Writing – review & editing, Validation, Supervision.

Statement

During the preparation of this work the author(s) used ChatGPT 3.5 and Copilot in order to improve readability and language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no conflicts of interest relevant to this research study. No financial or non-financial interests have influenced the design, conduct, analysis, or reporting of this research. The authors have no affiliations with organizations or entities that could be perceived as influencing the objectivity, integrity, or validity of the research findings presented in this manuscript.

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Data availability

The authors do not have permission to share data.

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