

A Moving Toward Robot Friendly Cities A Five-Dimensional Framework for Urban Planning and Design

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Abstract

Advances in artificial intelligence, autonomous navigation, sensing, and robotics are accelerating the deployment of autonomous robots in streets, buildings, and public spaces. Yet existing research remains fragmented across robotics, human-robot interaction, architecture, engineering, and policy, leaving an integrated urban planning framework for human-robot coexistence underdeveloped. This study conceptualizes the Robot-Friendly City as an urban environment capable of accommodating autonomous robots while supporting safe, inclusive, and responsible coexistence with humans. Through a systematic literature review and thematic analysis, the study identifies and synthesizes key considerations for integrating autonomous robots into urban environments. The analysis identifies five interdependent dimensions: (1) physical and spatial environment, (2) environmental sustainability, (3) digital and technological environment, (4) social and human-robot interaction, and (5) governance and institutional arrangements. Together, these dimensions provide an integrated framework for understanding the urban conditions and design considerations associated with human-robot coexistence. By shifting the focus from adapting individual robots to existing environments toward considering how urban environments should accommodate robots, this study positions robotic integration as a multidimensional urban planning challenge and provides a conceptual foundation for future planning strategies and urban design guidelines for Robot-Friendly Cities.

Keywords: Smart Cities, Smart City Innovation, AI for Cities, Artificial Intelligence for Urban Policing, Urban Governance.

1. Introduction

Recent advances in artificial intelligence, autonomous navigation, sensing, and robotics are rapidly expanding the role of robots beyond traditional industrial settings. Autonomous and service robots are increasingly entering everyday built environments, performing tasks such as delivery, cleaning, security, information assistance, inspection, and mobility support (International Federation of Robotics [IFR], 2026). As robots move from controlled environments such as factories and warehouses into streets, buildings, public spaces, and residential areas, their successful deployment increasingly depends not only on technological capabilities but also on the characteristics of the urban environments in which they operate (Farkas et al., 2021; Elara et al., 2014; Fong et al., 2003).

Cities, however, have long been planned and designed primarily for people and vehicles rather than autonomous robots. Sidewalk conditions, street layouts, building entrances, and other elements of the built environment can constrain robot mobility and operational accessibility. At the same time, the growing presence of robots in shared urban spaces raises broader social and institutional questions concerning human-robot interaction, public acceptance, safety, privacy, accessibility, liability, and regulation, extending the challenge beyond physical design (Savela et al, 2024; Bu et al., 2023). The integration of autonomous robots into cities should therefore be understood not simply as a robotics or technological challenge, but as a multidimensional urban planning challenge involving the interaction of robots with physical

space, digital infrastructure, people, and institutions.

Existing research provides important foundations for understanding individual aspects of this transition. Human-robot interaction (HRI) research has examined how people perceive, communicate with, trust, and respond to robots (Hancock et al., 2011; Campagna & Rehm, 2025). Studies of urban robotics and service robots have explored the deployment and operation of autonomous robots in public and semi-public environments (Savela et al, 2024; Bu et al., 2023). Research on robot-built environment interaction and robot-compatible environments has increasingly considered how spatial configurations and architectural features influence robot navigation, accessibility, and performance (Plank et al., 2022; Hwang & Elara, 2026). Other studies address the regulatory, ethical, environmental, and governance implications of autonomous systems in urban and public spaces (Kovacic et al, 2024; Thomasen, 2024).

However, these research streams remain relatively fragmented across robotics, architecture, urban design, engineering, human-computer interaction, and policy studies. Existing studies tend to focus on particular relationships—such as robot-human interaction, robot navigation, robot-building compatibility, or robot regulation—rather than examining the city as an integrated environment for human-robot coexistence. Consequently, an urban-scale framework that brings together the physical, technological, social, and institutional conditions required to accommodate autonomous robots remains underdeveloped.

This gap becomes increasingly important as autonomous robots evolve from experimental technologies into potentially routine participants in everyday urban systems. Adapting cities to robotics requires consideration of the relationships among technology, infrastructure, space, people, and institutions. From an urban planning perspective, robots can therefore be understood not merely as technological devices or service-delivery tools, but as emerging users and actors of urban space whose operation creates new requirements for the built environment, infrastructure, public-space management, and governance.

This study aims to identify and conceptualize the key factors that cities should consider in transitioning toward Robot-Friendly Cities from an urban planning and design perspective. It addresses the central research question: What dimensions constitute a Robot-Friendly City from an urban planning and design perspective? By identifying these factors and organizing them into key dimensions, this study seeks to establish a conceptual foundation for planning and designing Robot-Friendly Cities and provide a framework for reconsidering how urban environments should be planned, designed, and governed to enable safe, inclusive, and responsible human-robot coexistence.

2. Literature Review and Conceptual Foundations

Research on the integration of autonomous robots into urban environments spans multiple disciplines and research domains, including robotics, human-robot interaction (HRI), architecture and the built environment, smart cities and Urban AI, and urban planning and governance. Drawing on these interdisciplinary foundations, four broad research streams are particularly relevant to understanding the integration of autonomous robots into urban environments: (1) robots in urban and built environments; (2) human-robot interaction and coexistence in public spaces; (3) digital and environmental conditions for urban robot operation; and (4) policy, regulation, and governance of urban robots. The following sections review these four research streams, beginning with studies that examine how robots interact with and operate within urban and built environments.

2.1. Robots in Urban and Built Environments

Historically, robotics standards and safety regulations have been heavily rooted in industrial robotics, where machines operate within highly controlled, predictable, and isolated environments (International Organization for Standardization[ISO], 2020; IFR, 2026). However, the rapid advancement of service and mobile robotics has prompted their deployment directly into dynamic, everyday human environments (Savela et al, 2024). Unlike industrial settings, these urban and built environments are inherently unstructured or semi-structured, presenting a multitude of spatial, physical, and cognitive challenges for autonomous operations (Farkas et al., 2021; Elara et al., 2013; Hwang and Elara, 2026).

Early approaches to these challenges largely focused on improving the capabilities of robots

themselves to adapt to existing environments. Research has advanced sensing, sensor fusion, mapping, localization, and locomotion to enable autonomous robots to navigate increasingly complex spaces (Elara et al., 2014; Borusu et al., 2024). Nevertheless, even technologically advanced mobile robots remain sensitive to physical characteristics of the built environment, including uneven surfaces, thresholds, slopes, and other barriers that can affect navigation and operational reliability (Farkas et al., 2021; Borusu et al., 2024). These limitations suggest that improving robot-side capabilities alone may not fully address the challenges of deploying robots in human-centered built environments.

In response, a complementary research perspective has emerged that shifts attention from adapting robots to existing environments toward adapting environments to better accommodate robots. The “Design for Robot” (DfR) approach conceptualizes the built environment not merely as a passive setting for robot operation, but as an environment that can be deliberately designed to facilitate robotic accessibility and performance (Elara et al., 2014). Related concepts such as Robot Compatible Environments (RCE) and Robot Inclusive Spaces further integrate spatial design with robotic operational requirements, emphasizing considerations including observability, accessibility, manipulability, activity, and safety (Ezhilarasu et al., 2024; Farkas et al., 2021). More recently, this environment-oriented perspective has been extended toward systematic approaches to Robot-Friendly Buildings. The Robot-Friendly Buildings Level of Service (RFB-LOS) framework evaluates the extent to which built environments can support autonomous robots through architectural planning, accessibility, infrastructure, observability, and safety (Hwang & Elara, 2026).

These studies indicate an important evolution in robotics research—from asking primarily how robots can adapt to human-centered environments toward considering how built environments themselves can be designed and managed to accommodate autonomous operation.

2.2. Human–Robot Interaction and Coexistence in Public Spaces

Human–Robot Interaction (HRI) provides an established research foundation for understanding how people perceive, communicate with, respond to, and develop trust in robots. As autonomous robots move from controlled environments into shared public spaces, however, HRI extends beyond intentional or task-oriented interactions between a robot and a specific user toward interactions involving diverse and often unintended urban users (Fong et al., 2003). Unlike industrial environments, where trust is strongly associated with functional performance and reliability, public environments introduce relational, behavioral, and contextual factors that influence how people perceive and respond to robots (Campagna and Rehm, 2025).

This broader context makes spatial behavior and communication particularly important for human–robot interaction in public spaces. Studies of pedestrian–robot interaction demonstrate that lateral distance, robot speed, pedestrian movement, and external human–machine interfaces (eHMI) can significantly affect perceived safety, discomfort, and avoidance behavior (Jung et al., 2026). These findings suggest that successful interaction depends not only on collision avoidance but also on maintaining socially acceptable distances and communicating robot intentions in understandable and predictable ways. Related research further indicates that perceived intent, politeness, and communicative cues can shape how people interpret and respond to robots in shared environments (Inbar & Meyer, 2019; Sumartojo et al., 2021). Importantly, public-space robots interact not only with direct users but also with pedestrians, cyclists, and other bystanders who may encounter them unintentionally (Duboz et al., 2025). Their presence can therefore influence not only individual interactions but also how public space itself is experienced and used. Research suggests that robots can alter pedestrian movement and spatial practices, while their presence may generate concerns related to obstruction, surveillance, privacy, and the appropriation of shared space (Marcu et al., 2023; Perrem, 2026; Shin et al., 2024).

These developments broaden the focus from conventional HRI toward human–robot coexistence in public space. Successful urban integration cannot therefore be evaluated solely by whether robots navigate safely or complete assigned tasks. It must also consider whether robot behavior is understandable and predictable, whether diverse urban users can safely and comfortably share space with robots, and whether public spaces remain accessible and human-centered.

2.3. Digital and Environmental Conditions for Urban Robot Operation

Autonomous robot operations are increasingly contingent on factors outside the machine itself, shifting the research paradigm from purely onboard computational intelligence toward greater integration with intelligent digital and physical environments (Borusu et al., 2024). While autonomous robots rely on onboard sensors and computational capabilities for navigation and decision-making, studies have increasingly examined how these capabilities interact with external communication networks, spatial information, and digitally represented environments. Building Information Modeling (BIM), spatial data models, and real-time digital twins, for example, can provide updated representations of operating environments that support localization, path planning, and adaptation to changing spatial conditions (Chen et al., 2024, 2025; Ding et al., 2026). Research on 5G and emerging 6G technologies similarly explores how advanced communication networks can support reliable data exchange, low-latency communication, and positioning for mobile robotic systems (Krejci et al., 2025; Oruma and Petrovic, 2023). Together, these studies reflect growing research interest in the interdependence between autonomous robots and digitally enabled environments.

Research has also examined how physical and ambient environmental conditions affect autonomous robot operation, particularly as robots move beyond controlled indoor environments. Surface materials, unevenness, slopes, weather, and changing illumination can influence robot mobility, sensing, localization, energy consumption, and operational reliability (Borusu et al., 2024; Plank et al., 2022). Such environmental variability is particularly relevant to urban robotics because streets and public spaces cannot be controlled or standardized to the same degree as industrial environments. This body of research therefore extends the robot-environment relationship beyond spatial accessibility to include the dynamic environmental conditions under which autonomous operation occurs.

A further strand of research considers the relationship between robots and urban information systems as bidirectional. Robots consume spatial, communication, and environmental information to support autonomous operation, while simultaneously functioning as mobile sensing platforms that can generate data on sidewalk conditions, pedestrian density, accessibility, and environmental quality (Tong et al., 2026). Related studies examine how heterogeneous robotic systems can interact with broader smart-city infrastructure through interoperable data interfaces and service architectures, particularly as robotic services move beyond individual pilots toward larger-scale deployment (Puig-Pey et al., 2025; Ruess et al., 2026).

Collectively, this literature shows an expanding research perspective in which urban robots are examined not as isolated autonomous machines, but as increasingly interconnected components of digitally enabled urban environments.

2.4. Policy, Regulation, and Governance of Urban Robots

The proliferation of autonomous systems in shared environments has prompted a critical shift in urban governance, moving beyond basic traffic management to address broader socio-technical, institutional, and spatial implications (Infocomm Media Development Authority [IMDA], 2020; Kovacic et al., 2024). Historically, the introduction of street-level robots, such as sidewalk delivery robots (SDRs), has occurred within a regulatory vacuum, resulting in fragmented municipal responses ranging from prohibition to permissive, developer-driven codes (Kovacic et al., 2024). This uneven regulatory geography illustrates what the literature describes as the “pacing problem,” in which technological development advances faster than corresponding regulatory and institutional adaptation (Kovacic et al., 2024).

At the core of this debate is the changing publicness of shared urban space. Legal and geographical scholarship suggests that robot regulation is not socially or spatially neutral but participates in defining who and what can access, occupy, and use public space (Thomassen, 2024). Regulations accommodating robotic mobility may consequently reshape access to urban commons and, in some cases, contribute to their commercialization or de facto privatization (Thomassen, 2024; Mintrom et al., 2022, 2025). Security robots used to discourage unauthorized encampments and ordinances restricting “loitering,” for example, illustrate concerns that robot-oriented spatial governance may disproportionately affect vulnerable populations, including people experiencing homelessness (Thomassen, 2024).

The literature further identifies tensions between existing regulatory instruments and more

adaptive forms of governance. Safety standards such as ISO 13482 and data-protection frameworks such as the General Data Protection Regulation (GDPR) address different dimensions of robotic operation, but may not fully capture the interconnected safety, privacy, and real-time data-governance challenges of public-facing robots (Oruma et al., 2026; Mintrom et al., 2022, 2025). Privacy perceptions also appear to be context-dependent, varying across public, workplace, and domestic environments (Lin et al., 2026).

Regulatory choices may also shape the technological trajectories of urban robotics through morphological lock-in and path dependence. Urban environments designed around human physical dimensions may implicitly favor humanoid or human-compatible robotic forms, potentially constraining alternative morphologies despite their functional advantages (Ozcan, 2026). Accordingly, emerging scholarship contrasts morphology-specific prescriptions with technology-neutral, performance-based approaches that evaluate measurable outcomes, such as force limits and operational safety, rather than predetermined robotic forms (Kovicic et al., 2024; Ozcan, 2026).

Urban robot governance is also expanding to encompass software lifecycle security and infrastructural interoperability. Connected robots introduce cybersecurity, data-integrity, and system-integration risks, while proprietary interfaces can create vendor lock-in across heterogeneous robots and urban infrastructure (Oruma et al., 2023; Verma et al., 2025, Macrorie et al., 2021; Nagenborg, 2020).

Overall, the literature reflects an evolution from device-specific regulation toward multidimensional urban robot governance that encompasses public-space rights, adaptive regulation, technology neutrality, lifecycle security, and interoperability.

2.5. Synthesis: Fragmented Perspectives on Urban Robotics

The literature reviewed above demonstrates that substantial knowledge already exists concerning particular aspects of robots and urban environments. Research on mobile and service robots examines operation beyond controlled settings; built-environment studies reveal spatial and infrastructural requirements; HRI and public-space research addresses human encounters, safety, trust, and acceptance; digital and environmental research considers external conditions supporting robot operation; and policy research examines public-space rights, regulation, responsibility, privacy, security, interoperability, and public value.

However, these issues have largely been examined from the perspective of individual disciplines, technologies, applications, or interactions. Consequently, the literature provides considerable knowledge about individual conditions affecting urban robot deployment, but relatively limited understanding of how these conditions interact as part of an integrated urban system. What remains comparatively underdeveloped is an urban planning perspective capable of considering robots within the broader complexity of cities.

This gap becomes increasingly important as robots move from experimental applications toward routine participation in urban services and everyday environments. Robots can no longer be considered solely as subjects of technological innovation. As they move through buildings, streets, sidewalks, transportation systems, and public spaces, they increasingly become components of complex urban systems, interacting with people, physical environments, and digital infrastructure, environmental conditions, and institutional arrangements. These interactions are inherently interdependent: physical design influences robot mobility and accessibility; digital infrastructure enables navigation and coordination; human behavior shapes operational uncertainty and social acceptance; environmental conditions affect technical performance; and governance determines the rules, responsibilities, and rights through which these interactions are managed. Viewed collectively, urban robotics therefore emerges as a socio-technical and spatial planning challenge rather than simply a robotics problem.

The conceptual challenge therefore shifts from asking simply how robots can operate in cities toward asking how urban planning and design can understand and respond to environments in which humans and robots increasingly coexist. This study uses the concept of the Robot-Friendly City to address this gap. The concept provides an integrative urban lens through which previously fragmented research streams can be examined as interconnected conditions of human-robot coexistence. The systematic literature review and thematic analysis described in the following section identify recurring conditions and considerations across these existing research streams and synthesize them into an integrated urban planning and design framework for understanding robot readiness at the city scale.

3. Research Methodology

This study employed a systematic literature review (SLR) and thematic analysis to develop a conceptual framework for Robot-Friendly Cities from an urban planning and design perspective. The systematic literature review was used to identify and organize existing knowledge concerning the integration of robots into urban and built environments through a transparent and structured review process (Snyder, 2019; Page et al., 2021), while thematic analysis was employed to identify recurring concepts and synthesize them into broader dimensions relevant to urban planning and design (Braun & Clarke, 2006, 2021).

Research on robots in cities is distributed across several disciplines, including robotics, human-robot interaction (HRI), architecture, urban planning and design, engineering, environmental studies, and governance. Systematic and integrative approaches are particularly useful for synthesizing knowledge across fragmented and interdisciplinary research domains and for developing conceptual models from existing literature (Snyder, 2019). Rather than beginning with predetermined dimensions, this study therefore adopted an iterative analytical process in which relevant factors were identified from the literature, coded, grouped into broader themes, and subsequently interpreted from an urban planning (Braun & Clarke, 2006).

The overall research process consisted of four stages: (1) literature identification, (2) screening and selection, (3) coding and thematic analysis, and (4) conceptual framework development. The identification and screening stages were structured with reference to the PRISMA 2020 framework (Page et al., 2021), while the coding and thematic synthesis followed an iterative process of identifying, reviewing, and interpreting recurring patterns across the selected literature (Braun & Clarke, 2006, 2021).

3.1. Literature Search and Identification

Relevant academic publications were identified using Web of Science (WoS) and Scopus, two multidisciplinary citation databases widely used for systematic literature searches across science, engineering, and the social sciences (Falagas et al., 2008; Mongeon & Paul-Hus, 2016). The two databases were used complementarily to broaden disciplinary coverage and reduce potential database-specific selection bias, as previous comparative studies have demonstrated differences in their journal coverage and indexing characteristics (Mongeon & Paul-Hus, 2016; Martín-Martín et al., 2018).

The literature search was conducted in August 2026. No lower publication-year limit was imposed, while the upper publication-year limit was set at 2025 to ensure that only complete publication years were included in the review.

The literature search focused on studies examining robots operating in, interacting with, or being shaped by built and urban environments. Search terms were organized into three broad conceptual domains: (1) robotics and human-robot interaction, including robots, robotics, service robots, autonomous robots, mobile robots, human-robot interaction, and robot-environment interaction; (2) built and urban environments, including built environments, urban environments, urban spaces, public spaces, streetscapes, sidewalks, pedestrian environments, architecture, urban planning and design, and urban infrastructure; and (3) urban systems, policy, and governance, including smart cities, digital infrastructure, regulation, standards, policy, governance, safety, accessibility, and social interaction. Boolean operators (AND and OR) were used to systematically combine relevant terms within and across these conceptual domains.

Exclusion terms and research-area filters were applied to reduce studies primarily related to industrial, manufacturing, surgical, and agricultural robotics, as well as unrelated fields such as agriculture, chemistry, and other basic sciences.

The database searches and initial data-cleaning process identified 235 records from Web of Science and 256 records from Scopus, yielding 491 records in total. Publication titles were compared across the two databases to identify duplicate records. A total of 185 duplicate records were removed, resulting in 306 unique publications for title and abstract screening.

3.2. Screening and Selection

The titles and abstracts of the 306 unique publications were screened to assess their relevance to the objective of conceptualizing Robot-Friendly Cities. Studies were considered relevant when they addressed autonomous or service robots in relation to the urban or built environment, public spaces, human interaction, environmental conditions, or institutional and governance issues.

Studies were excluded when they focused primarily on robot-level technological development or domain-specific applications without substantive implications for urban or built environments. Studies in which robots or robotics appeared only as peripheral concepts were also excluded.

ChatGPT was used as an AI-assisted screening tool to rank the publications based on their conceptual relevance, built-environment implications, human–robot coexistence, infrastructure requirements, and policy or governance contributions. The AI-generated assessments were reviewed and verified by four researchers, particularly for studies near the inclusion–exclusion threshold. Final decisions were based on researcher judgment rather than AI-generated rankings alone.

Following title and abstract screening and researcher validation, 86 publications were excluded, and 220 publications were retained as candidate studies for further analysis. The retained publications formed the preliminary evidence base for identifying recurring factors associated with the integration of robots into urban environments. Because relevance could not always be determined from titles and abstracts alone, the candidate studies were subsequently examined in greater detail to assess their substantive contribution to developing the Robot-Friendly City conceptual framework.

To ensure a transparent and standardized literature selection process, this study adhered to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The entire identification, screening, and inclusion process is structured in the PRISMA flow diagram presented in Figure 1:

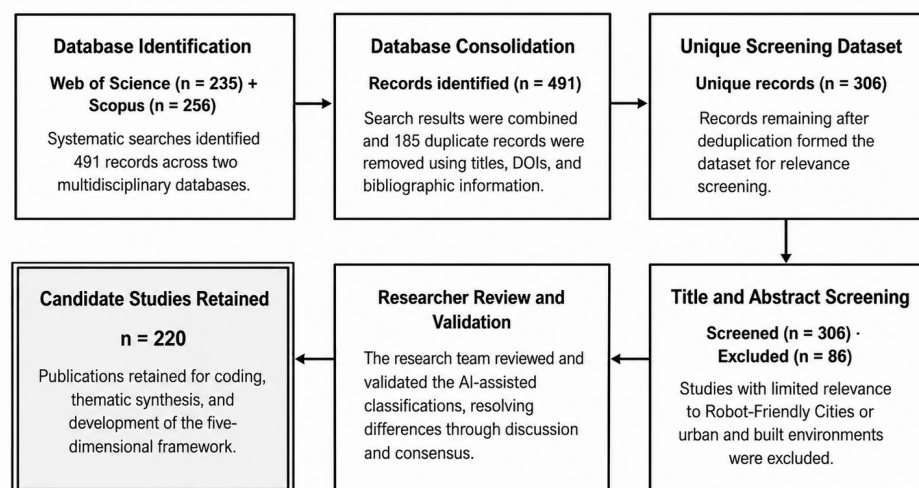


Figure 1. Literature Screening & Selection for Robot-Friendly Cities Research

3.3 Coding and Thematic Analysis

The 220 retained publications were analyzed using thematic synthesis following Thomas and Harden (2008). A hybrid inductive–deductive coding strategy combined research-informed categories with concepts emerging from the literature (Fereday & Muir-Cochrane, 2006), while theme development and refinement followed Braun and Clarke (2006).

The analysis proceeded in three stages. First, relevant concepts were extracted and coded, including spatial accessibility, streets, buildings, mobility, environmental conditions, connectivity, sensing, data, human–robot interaction, acceptance, safety, sustainability, regulation, liability, privacy, and institutional responsibility. Second, conceptually related codes were consolidated into descriptive themes. Third, these themes were reviewed and synthesized into five analytical dimensions: physical and spatial environment, environmental quality, digital and technological infrastructure, social and human–robot interaction, and governance and institutional framework.

Because individual studies frequently addressed multiple aspects of robot integration, cross-coding was permitted. Table 1 presents the number of publications associated with each dimension and representative publications.

Table 1. Five-Dimensional Classification of the Retained Literature

Dimension	Principal classification criteria	Studies (n)	Representative Publications
Physical and Spatial Environment	Streets, sidewalks, buildings, public spaces, mobility, accessibility, and physical infrastructure	104	Arntz et al. (2023), Ezhilarasu et al. (2024), Farkas et al. (2021), Franchi et al. (2025), Gehrke et al. (2023), Kim et al. (2024), Plank et al. (2022), Weinberg et al. (2023), Wijayathunga et al. (2023), Yu et al. (2024), etc.
Environmental Quality	Weather, lighting, terrain, surface conditions, energy consumption, emissions, resource use, and sustainability	39	Amante et al. (2024), Arntz et al. (2023), Choi et al. (2024), Garus et al. (2024), Haddeler et al. (2022), Rasmussen et al. (2021), Roldán-Gómez et al. (2022), Schnieder et al. (2021), Tong et al. (2026), Tran et al. (2025), Vecchio et al. (2024), Vepsäläinen (2022), Yeo et al. (2021), etc.
Digital and Technological Infrastructure	Connectivity, sensing, positioning, data, digital twins, intelligent systems, cybersecurity, and interoperability	84	Ezhilarasu et al. (2024), Glas et al. (2012), Lee et al. (2024), Lu et al. (2023), Merino et al. (2012), Oruma et al. (2025), Oruma and Petrovic (2023), Pauwels et al. (2023), etc.
Social and Human-Robot Interaction	Human-robot interaction, pedestrian behavior, public acceptance, trust, inclusion, safety, and coexistence	74	Hetherington et al. (2021), Jiang et al. (2019), Joosse et al. (2013), Mavrogiannis et al. (2023), Satake et al. (2013), Savela et al. (2024), Wang et al. (2023), Weinberg et al. (2023), Yu et al. (2024), etc.
Governance and Institutional Framework	Policy, regulation, standards, liability, privacy, governance, and institutional responsibility	60	Kovacic et al. (2024), Mintrom et al. (2022), Mintrom et al. (2025), Oruma et al. (2023), Oruma et al. (2025), Salvini et al. (2010), Salvini et al. (2021), While et al. (2021), etc.

3.4. Development of the Five-Dimensional Framework

The five analytical dimensions identified through the thematic synthesis were subsequently integrated into a conceptual framework for the urban planning and design of Robot-Friendly Cities as shown in Table 2.

Table 2. Five Dimensions of the Robot-Friendly City Framework

Dimension	Central planning question	Definition
Physical and Spatial Environment	How should urban spaces and infrastructure be designed or adapted to accommodate robots?	Physical and spatial conditions enabling robots to access, navigate, and operate within urban environments
Environmental Quality	How can robots operate safely and sustainably under changing urban environmental conditions?	Dynamic environmental conditions affecting robot performance, safety, energy use, and sustainability
Digital and Technological Infrastructure	What digital infrastructure and data systems are required to connect robots with broader urban systems?	Digital infrastructure and information systems supporting robot perception, connectivity, navigation, and integration with urban systems

Social and Human–Robot Interaction	How can cities ensure safe, inclusive, and socially acceptable coexistence between humans and robots?	Human and societal conditions necessary for safe, inclusive, and publicly acceptable human–robot coexistence
Governance and Institutional Arrangements	How should cities regulate, coordinate, and assign responsibility for urban robot deployment and operation?	Policy, regulatory, organizational, and governance arrangements guiding robot deployment and operation

These dimensions were conceptualized as interdependent rather than mutually exclusive. For example, safe robot mobility may simultaneously require accessible physical infrastructure, reliable digital connectivity and positioning, adaptation to changing environmental conditions, predictable interactions with pedestrians, and appropriate regulatory standards.

Rather than defining robot-friendliness solely in terms of technological readiness or robot performance, the framework adopts a systems-oriented urban planning and design perspective. It provides an analytical basis for assessing how cities should plan, design, manage, and govern environments in which autonomous robots coexist with humans and become integrated into broader urban systems.

The methodological progression of this study is summarized in Figure 2 as follows:

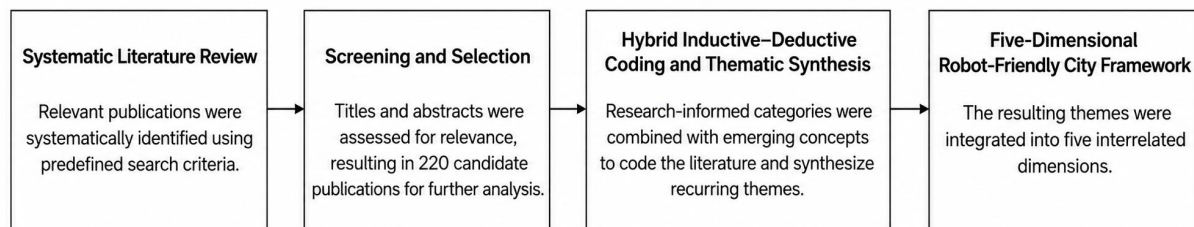


Figure 2. Development Process of the Five-Dimensional Robot-Friendly City Framework

4. A Five-Dimensional Framework for Robot-Friendly Cities

The systematic review and thematic analysis identified five major dimensions that shape the capacity of urban environments to accommodate autonomous robots: physical & spatial environment, environmental quality, digital & technological infrastructure, social & human–robot interaction, and governance & institutional arrangements. These dimensions extend the discussion of urban robotics beyond the technological capabilities of individual robots toward the broader conditions under which robots operate and coexist with humans as components of complex urban systems.

4.1 Physical & Spatial Environment

The first dimension concerns the physical and spatial conditions required to support robot operation in urban environments. Unlike controlled environments such as factories and warehouses, urban environments contain complex and unstructured spatial conditions that autonomous robots must continuously interpret and navigate (Wijayathunga et al., 2023). Sidewalk width and quality, curbs, slopes, surface materials, street furniture, temporary obstacles, crossings, building entrances, and vertical circulation can all be targets for physical adjustment to improve robot mobility and accessibility (Plank et al., 2022; Arntz et al., 2023; Franchi et al., 2025).

Delivery robots are among the most widely studied types of robots in relation to physical urban environments (Weinberg et al., 2023; Yu et al., 2024; Gehrke et al., 2023). Existing studies demonstrate that sidewalks are particularly challenging because they are unstructured spaces shared by pedestrians and other users including children, dogs and cyclists (Weinberg et al., 2023; Yu et al., 2024). In real-world observations, Yu et al. (2024) found that robots encounter slopes they cannot negotiate, scooters or other objects blocking their routes, and situations requiring assistance from pedestrians (Yu et al., 2024). Gehrke et al. (2023) similarly identify obstruction and accessibility challenges associated with the deployment of robots on public

sidewalks. Existing studies also provide or apply measurable criteria for assessing physical conditions, including a 2-meter sidewalk width for robot operation (Corno & Savaresi, 2020; Arntz et al., 2023), while accessibility standards applied in robot-based assessments include a maximum running slope of 5% and a maximum level change of 6.4 mm (Ahmadi et al., 2026). Such findings illustrate how the performance of autonomous robots is partly determined by the physical characteristics of the environment rather than by robotic capability alone (Yu et al., 2024; Weinberg et al., 2023).

Recent research has extended the assessment of physical conditions toward broader measures of urban suitability for robot deployment and navigation. Arntz et al. (2023) propose “roboreadiness,” which considers both robot performance in the traffic environment and social acceptance, while Franchi et al. (2025) introduce the “Robotability Score” to evaluate how built-environment characteristics, pedestrian activity, connectivity, and other urban conditions support robot navigation. Studies have identified sidewalk width, slopes, level transitions, surface conditions, curb accessibility, and physical discontinuities as important spatial factors affecting robot navigation and accessibility (Plank et al., 2022; Arntz et al., 2023; Franchi et al., 2025; Tong et al., 2026). Franchi et al. (2025) identify sidewalk slope, sidewalk condition, sidewalk width, and curb-ramp accessibility as relevant features for evaluating the suitability of urban environments for wheeled robot navigation. Farkas et al. (2021) also emphasize adequate maneuvering space, accessible ramps and entrances, negotiable thresholds, even floor surfaces, and accessible docking areas as key requirements of a robot-compatible environment.

The building–street interface is particularly critical because urban robots must navigate continuously across public sidewalks, building entrances, internal circulation spaces, vertical transitions, and final destinations. Hwang and Elara (2026) highlight architectural planning, accessibility, active infrastructure, building intelligence, and safety as interconnected requirements for robot-ready buildings. Ng et al. (2022) show that inadequate clearance, narrow circulation spaces, poor furniture layout, and other built-environment constraints can directly reduce robot mobility and operational efficiency.

Taken together, these studies suggest that robot-ready built environments require coordinated attention to spatial accessibility, circulation continuity, surface and level conditions, maneuvering space, and supporting infrastructure across streets and buildings. From a Robot-Friendly City perspective, planning and design strategies therefore extend beyond individual streets or buildings to address continuity across the broader urban system, including robot-ready streets and coordinated building–street interfaces. Importantly, the objective is not to redesign urban space primarily for robots, but to reduce critical spatial and operational barriers while enabling safe and effective human–robot coexistence. Such interventions should preserve pedestrian priority, universal accessibility, and the quality of public space while improving the mobility and operational performance of urban robots.

4.2 Environmental Sustainability

The second dimension concerns the environmental conditions that influence robot performance and the environmental consequences of robot deployment. Unlike the Physical and Spatial Environment dimension, which focuses primarily on relatively fixed characteristics of the built environment—such as sidewalks, streets, buildings, accessibility, and spatial configurations—Environmental Sustainability addresses dynamic natural and ambient conditions and the environmental consequences of robot operation.

Urban robots operate outdoors under conditions substantially different from controlled indoor environments. Rain, snow, extreme temperatures, surface water, heat, vegetation, terrain, lighting, and seasonal changes can affect sensing, navigation, battery performance, mobility, and operational reliability. Reflecting these characteristics and the emerging literature, three interconnected issues can be identified within the Environmental Sustainability dimension: (1) how natural and urban environmental conditions affect robot performance; (2) how robot deployment affects human settlement environments and urban ecosystems; and (3) how robots can contribute to environmental sensing and monitoring.

First, a substantial strand of the literature has shown how natural and urban environmental conditions affect robot performance and operational reliability. Vegetated and uneven terrain can challenge outdoor navigation because vegetation and irregular surfaces interfere with sensing and the identification of traversable ground (Jian et al., 2024; Yeo et al., 2021). Studies of

outdoor robot operation also demonstrate the influence of weather and seasonal conditions. Sidewalk delivery robots in Tallinn, for example, have become immobilized in snow, requiring pedestrian or operator assistance (Dobrosovestnova et al., 2022). Terrain, slopes, and surface unevenness can further affect traversability and navigation (Haddeler et al., 2022; Vecchio et al., 2024), while changes in lighting and visibility can affect perception and sensing (Kim et al., 2024). Environmental complexity and obstacle density can also increase navigation difficulty, travel time, and energy requirements (Choi et al., 2024). Collectively, this body of research suggests that robot operability is therefore determined not only by technological capability but also by the dynamic environmental conditions through which robots move (Arntz et al., 2023; Garus et al., 2024).

A second strand of the literature shifts attention from how the environment affects robots to how robot deployment affects human and ecological settlement environments. Research identifies both potential environmental benefits and negative externalities associated with urban robots. Robotic waste collection can generate noise affecting nearby residents alongside broader environmental impacts (Amante et al., 2024). Research on interactions between animals and autonomous mobility systems has also raised concerns regarding multispecies coexistence (Tran et al., 2025), while robotic lawn mowers have been shown to pose direct risks of injury to wildlife such as European hedgehogs (Rasmussen et al., 2021). Conversely, electrically powered delivery and service robots may reduce some environmental externalities associated with conventional vehicles, while robots for waste management and green-infrastructure maintenance may contribute to cleaner urban environments. These potential benefits, however, need to be assessed against fleet-level energy demand, carbon emissions, land occupation, and lifecycle impacts (Choi et al., 2024; Garus et al., 2024; Schnieder et al., 2021; Vepsäläinen, 2022). These studies indicate that the environmental sustainability of urban robots cannot be assessed solely in terms of operational efficiency or direct emissions but requires consideration of their broader impacts on human well-being, ecosystems, resource consumption, and urban space (van der Schoor & Göhlich, 2023).

A third, emerging strand of research highlights the potential of robots to contribute directly to urban environmental monitoring. Robots can function not only as actors within urban environments but also as mobile platforms for observing them. Equipped with cameras, LiDAR, positioning systems, and environmental sensors, robots can collect spatially distributed data while performing their primary tasks. Aerial robotic swarms have been used to monitor traffic, climate, and pollution in real time (Roldán-Gómez et al., 2022), while sidewalk robots can support the collection of spatially distributed data relevant to pedestrian environments and walkability (Tong et al., 2026). Connected to digital twins and urban monitoring platforms, mobile robots could complement fixed sensor networks by generating fine-grained data on terrain, vegetation, cleanliness, and environmental anomalies along their routes. This literature suggests an emerging role for urban robots as mobile environmental sensing platforms and as potential components of broader urban environmental monitoring systems.

Robot-Friendly Cities require climate- and environment-adaptive approaches that support robot operation while managing the environmental consequences of deployment. Planning should consider energy use, noise, land occupation, wildlife disturbance, green-infrastructure compatibility (Yeo et al., 2021), and lifecycle impacts, while exploring opportunities to use existing robot fleets as mobile environmental sensing platforms. The Environmental Sustainability dimension therefore captures a reciprocal relationship between robots and urban environments: environmental conditions shape robot operation; robots can positively or negatively affect human and ecological environments; and robots can become new sources of environmental knowledge for cities.

4.3. Digital and Technological Environment

The digital and technological environment refers to the networked digital infrastructure, sensing systems, spatial data, communication networks, and computational capabilities that enable robots to perceive, interpret, navigate, and interact with urban environments. This dimension extends beyond individual robots toward a digitally connected and machine-readable urban environment.

Studies consistently have indicated that relying solely on robots' onboard sensing and computational capabilities is insufficient for reliable operation in complex and dynamic urban environments. Occlusion, clutter, lighting variation, and changing pedestrian environments can

constrain robot perception and navigation (Merino et al., 2012). Connecting robots with distributed environmental sensors, spatial data, and networked information systems can extend perception, support multi-robot coordination, and enable remote human supervision (Glas et al., 2012; Lu et al., 2023).

Urban navigation presents similar challenges, as GPS signal degradation or blockage in urban environments can undermine localization and navigation (Lee et al., 2024; Trulls et al., 2011). Digital maps, environmental sensing, real-time localization, and machine-readable representations of urban environments can therefore complement onboard intelligence and provide a shared layer of digital intelligence for more reliable autonomous navigation and operation (Pauwels et al., 2023).

Within this context, digital twins are particularly relevant as a planning and design tool for robot-friendly cities (Ezhilarasu et al., 2024; Zeng et al., 2024). By integrating spatial models with real-time and semantic information, digital twins can provide machine-readable representations of urban environments that support robot navigation and operation (Lu et al., 2023; Pauwels et al., 2023). Beyond operational support, they can serve as virtual environments for assessing robot accessibility, navigation, and interaction before physical implementation, allowing potential design conflicts to be identified and addressed in advance (Ezhilarasu et al., 2024).

Connectivity is another critical requirement. Urban robots depend increasingly on wireless networks for real-time sensing, localization, coordination, and remote intervention, making reliable and low-latency communication essential (Oruma & Petrovic, 2023). Greater connectivity, however, increases cybersecurity and privacy risks, including misuse of robot-generated data (Oruma et al., 2025; Oruma & Petrovic, 2023). Digital infrastructure should therefore incorporate secure communication, data protection, and resilience.

These findings suggest a shift from designing for autonomous robots to designing digitally legible environments for connected robotic systems. Urban planning should therefore address digital robot-readiness from the planning and design stage, including interoperability with urban data and infrastructure, machine-readable spatial information, reliable connectivity, cybersecurity and data governance, and real-time coordination. Digital twins can further provide a platform for the ex-ante simulation and evaluation of robot-friendliness. The digital and technological environment thus constitutes a shared layer of urban intelligence connecting robots with the broader urban system.

4.4. Social and Human-Robot Interaction

The Social and Human-Robot Interaction (HRI) dimension concerns the social norms, behavioral principles, and interaction protocols needed to shape how humans and robots interact and coexist in shared urban spaces. Unlike the preceding dimensions, which primarily address the conditions necessary for robots to operate effectively in cities, this dimension shifts the focus to the social relationship between humans and robots, asking how they should behave toward, respond to, and interact with one another as they increasingly share everyday urban spaces.

An emerging body of literature demonstrates that the presence of robots in public spaces can influence how people perceive, experience, and emotionally relate to urban environments (Oruma et al., 2022). Rather than functioning merely as technological objects, robots become visible elements of the social environment and participate in everyday encounters in streets and other shared spaces. Studies show that pedestrians may ignore, observe, approach, accommodate, or actively engage with robots, indicating that robot presence itself becomes part of the social experience of urban space (Satake et al., 2013; Weinberg et al., 2023). Public responses are also influenced by robot behavior and appearance. Expressive visual features can affect perceived sociability, while polite behavior can influence perceptions and willingness to cooperate (Wang et al., 2023; Yu et al., 2024). At a broader urban scale, Savela et al. (2024) demonstrate that the visual presence of robots can affect urban belonging and anxiety. These findings suggest that robot deployment can influence not only mobility but also the psychological and social experience of urban public space.

A second stream of research examines how humans and robots modify one another's behavior while moving through shared environments. Human-robot coexistence can therefore be understood as a reciprocal spatial relationship rather than a one-sided navigation problem.

Robots can interpret pedestrian movement, body orientation, and intention to anticipate human behavior and adapt their movement accordingly (Mavrogiannis et al., 2023; Satake et al., 2013). Conversely, robot behavior can influence pedestrian movement and comfort. Robot motion and positioning can communicate intentions such as yielding and help pedestrians interpret how to respond during spatial encounters (Mavrogiannis et al., 2023). At the collective level, robots can affect pedestrian flow, spacing, congestion, and movement patterns in shared environments (Jiang et al., 2019). These findings demonstrate that robots are not simply moving objects within pedestrian environments but increasingly participate in reciprocal spatial interactions with people.

Human-robot interactions are also shaped by social context and emerging norms. Research demonstrates that people evaluate robot behavior in relation to normative expectations and personal space, and may respond differently when these expectations are violated (Joosse et al., 2013). Socially acceptable operation therefore requires more than collision avoidance: robots need to communicate their intentions in understandable ways, respect socially meaningful distances, and adapt to different interaction contexts (Mavrogiannis et al., 2023). Nonverbal motion cues can make robot intentions more legible to pedestrians and improve the social acceptability of spatial interactions (Hetherington et al., 2021). Social norms for urban robots may therefore emerge through repeated interactions among robot behavior, individual responses, group behavior, and expectations regarding appropriate conduct in shared spaces.

The growing presence of robots in shared urban spaces requires attention to social interaction alongside physical accessibility and technological performance. Robot-Friendly City planning should consider pedestrian comfort, interaction distance, yielding behavior, communication cues, crowd movement, and diverse user needs (Joosse et al., 2013; Mavrogiannis et al., 2023; Tomitsch & Hoggenmueller, 2021; Weinberg et al., 2023). Attention should be given to vulnerable users and accessibility, as real-world robot deployments can create different challenges for people with diverse mobility and accessibility needs (Weinberg et al., 2023). Pilot deployments, citizen feedback, and real-world observation can help identify unexpected interaction patterns, social conflicts, and emerging behavioral expectations (Weinberg et al., 2023). The planning objective therefore extends beyond enabling robots to operate safely and efficiently toward creating urban environments in which humans and robots can coexist safely, comfortably, predictably, and socially acceptable. These findings can also provide an empirical basis for the governance and institutional arrangements addressed in a separate dimension of the Robot-Friendly City framework.

4.5. Governance and Institutional Arrangements

Governance and institutional arrangements encompass the rules, policies, standards, institutional responsibilities, and coordination mechanisms required to ensure the safe, responsible, and accountable integration of robots into urban environments. The significance of this dimension lies in establishing an institutional environment for managing robot deployment and operation within shared urban spaces, with particular attention to public safety, liability and compensation, accountability, and the protection of citizens and public interests.

The rapid deployment of robots challenges conventional incremental and reactive approaches to policymaking. Mintrom et al. (2025) highlight the limitations of “muddling through,” whereby policy responses emerge incrementally after new technologies and associated problems have already appeared. They argue instead for anticipatory policy design that considers the possible social implications of robots before their widespread deployment (Mintrom et al., 2025). Early sidewalk delivery robot deployment in California illustrates this challenge, as municipalities experimented with regulatory approaches ranging from prohibition to permissive and collaborative forms of governance (Kovacik et al., 2024). Experiences across different cities and countries similarly demonstrate diverse pathways of institutional and regulatory experimentation in integrating robots into existing urban systems (While et al., 2021).

Despite these developments, significant institutional and regulatory gaps remain in governing robots operating in public environments (Mintrom et al., 2025; Salvini et al., 2021). Existing safety standards, including ISO 13482:2014, have limitations in addressing the safety of pedestrians and bystanders in complex public settings (Salvini et al., 2021). The increasing sensing and data-collection capabilities of robots also raise unresolved concerns regarding privacy, personal information, cybersecurity, and broader data governance (Mintrom et al., 2022; Oruma et al., 2023; Oruma et al., 2025). Moreover, increasing robot autonomy

complicates existing legal and liability frameworks by raising questions about the legal status of autonomous robots and the attribution of responsibility when accidents or damage occur (Salvini et al., 2010).

For urban planning, the central institutional question is therefore not simply how robots should be regulated, but how decisions concerning their urban integration should be made, coordinated, and held accountable. This requires clear mandates across government agencies, coordination mechanisms across institutional boundaries, explicit allocation of responsibilities among public and private actors, and transparent procedures for liability, compensation, data governance, public complaints, and dispute resolution. Such arrangements also require attention to stakeholder roles and interactions across technical systems, service providers, public-space managers, and other actors involved in robot deployment (Oruma et al., 2025). Participatory mechanisms are also needed to incorporate citizens and affected groups into decision-making, while anticipatory policy design can help institutions address potential societal impacts before large-scale deployment (Mintrom et al., 2022, 2025).

The five dimensions suggest that robot-friendliness cannot be reduced to the technical performance of robots or the provision of isolated robot infrastructure. Instead, it concerns whether the broader urban environment can appropriately accommodate autonomous robots across physical, environmental, digital, social, and institutional conditions.

The framework therefore shifts the analytical focus from robots as objects of technological innovation toward robots as emerging components of complex urban systems. From an urban planning perspective, the central challenge is not simply how to introduce more robots into cities, but how to plan, design, and govern the relationships among robots, humans, infrastructure, data, institutions, and the urban environment. This systems perspective provides the conceptual foundation for moving from individual robot deployment toward the development of Robot-Friendly Cities.

5. Discussion

This study proposes the Robot-Friendly City as an emerging urban planning concept for understanding how cities may need to adapt to the increasing presence of autonomous robots. The five-dimensional framework—physical & spatial environment, environmental quality, digital & technological infrastructure, social & human-robot interaction, and governance & institutional arrangements—suggests that robot integration cannot be adequately addressed through technological development or infrastructure provision alone. Rather, robot-friendliness emerges from the interaction among multiple urban systems. This perspective extends the discussion of robotics from the performance of individual machines toward the capacity of cities to accommodate robots as part of everyday urban environments.

5.1. From Smart Cities to Robot-Friendly Cities

The concept of the Robot-Friendly City can be understood in relation to the broader evolution of smart cities. Smart-city development has traditionally focused on integrating information and communication technologies, sensors, data platforms, and intelligent systems into urban infrastructure and services. Robotics introduces an additional dimension to this evolution because intelligent systems increasingly acquire a physical presence within the city. Unlike digital applications that primarily operate through screens, platforms, or background information systems, autonomous robots move through physical space, interact with people, encounter architectural and infrastructural constraints, and potentially make operational decisions in real time.

Robot-Friendly Cities should therefore not be interpreted as an alternative to Smart Cities. Rather, they represent an emerging planning perspective responding to the physical manifestation of AI and autonomous systems in urban environments. Existing smart-city infrastructure—including connectivity, IoT networks, urban data platforms, and digital twins—may provide important foundations for urban robotics. However, digital intelligence alone does not ensure robot compatibility. Sidewalks, crossings, entrances, elevators, public spaces, and other physical elements must also enable safe and reliable robot operation. The Robot-Friendly City thus connects digital intelligence with physical, social, environmental, and institutional readiness.

5.2. Robots as Emerging Urban Actors

A second implication concerns how urban planning conceptualizes robots themselves. Most cities are planned around human residents, pedestrians, vehicles, buildings, infrastructure, and organizations. As autonomous robots increasingly perform delivery, cleaning, inspection, security, information, and mobility-related functions, they become active participants in urban systems rather than isolated technological devices.

Considering robots as emerging urban actors changes the planning question. The issue is no longer limited to whether a particular robot can technically navigate an existing environment. Instead, planners must consider how repeated and large-scale robot operations affect pedestrian movement, public-space use, accessibility, infrastructure demand, safety, and service delivery. Urban space may increasingly become a shared operational environment involving pedestrians, conventional vehicles, autonomous vehicles, drones, and different categories of service robots.

However, recognizing robots as urban actors does not imply granting them equivalent status to human users of the city. Robot-friendly planning should remain oriented toward public value and human well-being. Accommodating robots should improve urban services and quality of life rather than reorganizing public space primarily around technological efficiency. This distinction is particularly important where robot optimization could conflict with pedestrian priority, universal accessibility, privacy, or equitable access to public space.

5.3. Theoretical Contributions

The primary theoretical contribution of this study is to reposition robot deployment as an urban planning and design challenge. Existing research provides substantial knowledge concerning human-robot interaction, autonomous navigation, service robotics, robot-compatible environments, and the regulation of autonomous systems. However, these research areas often examine particular relationships or operational contexts independently. The Robot-Friendly City framework integrates these fragmented perspectives at the urban scale.

The five dimensions provide an analytical structure for this integration. The physical (spatial) dimension addresses spatial configuration, accessibility, mobility, buildings, streets, and other elements of the built environment. The environmental dimension considers robots' climate vulnerability, environmental impacts, and explore their potential role as moving sensors for urban environmental monitoring. The digital dimension concerns connectivity, sensing, positioning, data, and digital systems supporting autonomous operation. The social dimension addresses human-robot interaction, trust, acceptance, inclusion, and coexistence. Finally, the governance dimension incorporates regulation, safety standards, liability, privacy, institutional responsibilities, and operational rules.

Importantly, these dimensions should not be understood as independent categories. Their interactions may ultimately determine the degree of robot-friendliness of an urban environment. For example, improving physical accessibility without reliable digital connectivity may still constrain robot operations, while technological and spatial readiness without public acceptance or appropriate regulation may prevent large-scale deployment. Robot-friendliness should therefore be understood as a system-level urban capacity emerging from the alignment of the five dimensions.

This framework also contributes to expanding the conventional understanding of urban accessibility. Accessibility has traditionally focused appropriately on enabling people with different physical and cognitive abilities to use urban environments. The emergence of autonomous robots introduces an additional operational layer. Future planning may need to consider how robot accessibility can be incorporated without compromising universal human accessibility. This creates a new research agenda concerning how cities can simultaneously remain human-centered and become compatible with autonomous systems.

5.4. Limitations and Future Research

This study has several limitations. First, the proposed framework is conceptual and derived from the synthesis of existing literature. The five dimensions therefore require empirical validation across different urban contexts and robot applications. Second, urban robots vary considerably in size, mobility, autonomy, function, and operational requirements. Delivery robots, cleaning robots, security robots, mobility-support robots, and other systems may require different spatial and infrastructural conditions. Future studies should examine whether the

relative importance of the five dimensions varies across robot types and urban settings. Third, cities differ substantially in density, urban form, infrastructure quality, regulatory systems, technological readiness, and social attitudes toward automation. Comparative case studies are therefore necessary to determine how Robot-Friendly City principles should be adapted to different contexts. Future research could also operationalize the framework into measurable indicators and develop a Robot-Friendly City assessment framework or index.

Finally, longitudinal research will be important because both robotics and urban environments continue to evolve rapidly. Rather than establishing fixed design requirements around current technologies, planning should seek adaptable principles capable of responding to future generations of autonomous systems. The Robot-Friendly City should therefore be understood not as a predetermined urban model, but as an evolving planning framework for managing the long-term integration of robots into cities while protecting human-centered, inclusive, and sustainable urban values.

6. CONCLUSION

This study argues that the growing presence of autonomous robots in cities requires a shift in how urban planning and design conceptualize robotics. Robots have largely been approached as subjects of technological innovation, with research and policy focusing on their technical performance, functionality, and deployment. As autonomous robots increasingly move into streets, buildings, public spaces, and neighborhoods, however, this technology-centered perspective becomes insufficient. Robots should increasingly be understood as emerging components of complex urban systems, operating within environments already shaped by people, physical space, infrastructure, digital systems, institutions, and environmental conditions.

From this perspective, the challenge of creating Robot-Friendly Cities is not simply to make urban environments more accessible to robots or to accelerate the deployment of robotic technologies. Rather, it is to understand how robots can be incorporated into existing urban systems without disrupting the values, functions, and relationships that sustain urban life. This requires a systems perspective that considers robots in relation to the broader urban environment and a governance perspective that addresses how their roles, operations, responsibilities, and impacts should be managed as their presence becomes increasingly embedded in everyday city life.

The five-dimensional framework proposed in this study—physical (spatial), environmental, digital, social, and governance—provides a foundation for this broader understanding. The framework shifts attention from the robot as an individual technological object toward the conditions surrounding its integration into the city. It highlights that robot-friendly planning involves not only spatial accessibility and digital readiness but also social acceptance and interaction, environmental sustainability, and appropriate institutional and governance arrangements. Robot-friendliness should therefore be understood as a broader urban planning capacity to accommodate robotics within the physical, social, technological, environmental, and institutional realities of cities.

This shift also raises a more fundamental question for future urban planning: how can robots coexist with humans and the urban environment? As robots increasingly share sidewalks, buildings, transportation facilities, workplaces, residential environments, and public spaces with people, planning must move beyond the question of whether robots can technically operate in these environments. Greater attention will be required to how their presence affects human behavior, accessibility, safety, public space, existing infrastructure, environmental sustainability, and everyday urban experience. Human-robot coexistence should therefore become an important planning and governance issue rather than remaining primarily a concern of robotics and human-robot interaction research.

Importantly, recognizing robots as components of urban systems does not imply reorganizing cities around the needs of machines. Human priority and public value should remain fundamental principles of Robot-Friendly City planning. The objective should be to determine how autonomous robots can contribute to urban services and quality of life while respecting the social, spatial, environmental, and institutional conditions of cities. This requires planning approaches capable of balancing technological opportunities with accessibility, safety, inclusiveness, sustainability, and public interest.

The Robot-Friendly City should consequently be viewed not as a technological endpoint, but as an evolving urban planning and governance concept for managing the integration and coexistence of robots within complex urban systems. Future research should examine how this perspective can be translated into planning principles, design standards, governance mechanisms, and evaluation frameworks across different robot types and urban contexts. As autonomous robots become an increasingly ordinary part of urban life, the critical question will no longer be simply how cities can support robots, but how humans, robots, and urban environments can coexist within the same complex urban system.

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