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Review

Autonomous Mobile Robots Inclusive Building Design for Facilities Management: Comprehensive PRISMA Review

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Abstract: The increasing adoption of advanced technologies and the growing demand for automation have driven the development of innovative solutions for smart Facilities Management (FM). The COVID-19 pandemic accelerated this trend, highlighting the need for greater automation in FM, including the use of Autonomous Mobile Robots (AMRs). Despite this momentum, AMR adoption remains in its early stages, with limited knowledge and research available on their practical applications in FM. This study seeks to explore the challenges that hinder the successful integration of AMRs in the FM industry. To achieve this, a systematic literature review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology, encompassing three phases: identification, screening, and inclusion. The review covered 80 full-text articles published from 1994 to 2024, reflecting the growing interest in technological advancements for FM and the increased focus on AMR research. The study identified five key barriers specific to FM that affect AMR adoption: diverse operational contexts, poorly designed indoor environments, varying building occupants, multi-faceted FM functionalities, and differences in building exteriors. These findings provide a comprehensive understanding of the unique challenges faced by FM professionals, offering valuable insights for organizations and AMR developers to consider during the adoption process. The research contributes to the field by providing a foundation for FM practitioners, policymakers, and researchers to develop strategies for overcoming these barriers and advancing the adoption of AMR technologies in FM.

Keywords: autonomous mobile robots (AMR); facilities management (FM); smart FM; challenges; advantages; applicability; PRISMA review; poorly designed indoor environments; diverse operation context

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1. Introduction

The world is experiencing a profound shift towards digitalization, fueled by rapid advancements in robotics and Artificial Intelligence (AI) across various sectors, with the built environment being no exception. In this context, digital technologies are revolutionizing how we design, construct, and manage buildings and infrastructure. AI-driven design tools enable architects and engineers to create more efficient and sustainable structures, leveraging data-driven insights to optimize everything from energy use to material selection [1,2]. Autonomous construction robots are taking on tasks ranging from bricklaying to site surveying, reducing labor costs, enhancing precision, and minimizing waste [3]. Furthermore, smart building systems are becoming integral to modern infrastructure, with AI and the Internet of Things (IoT) enabling real-time monitoring and control of energy consumption, security, and indoor environmental quality [4]. The integration of robotics, AI, and digital technologies is not only streamlining processes but also enabling the development of adaptable and resilient urban spaces that can more effectively meet the needs of occupants. This capability has become particularly critical in the post-pandemic era, where the flexibility and adaptability of spaces are of heightened importance.

As cities and buildings become increasingly interconnected and intelligent, the built environment is poised to become more sustainable, efficient, and responsive, reflecting the broader digitalization trend reshaping industries worldwide. A radical shift in the spatial design shift in the indoor built environment will underscore the critical role of AMR technology in shaping the future of urban living, driving innovation in construction practices, and paving the way for smarter, more resilient cities.

However, it is essential to recognize that a key gap in current research and industry practices is that buildings have traditionally been designed with human needs as the primary focus, often without consideration for robotic integration or inclusivity [5]. This human-centered design approach presents challenges when integrating AMRs, as the built environment does not inherently support or facilitate robotic movement and operational needs.

To bridge these advancements in the built environment, it is crucial to recognize the developments occurring within FM. Traditionally, FM has been characterized by manual processes, routine maintenance schedules, and reactive management approaches. However, with the advent of digitalization, FM is increasingly embracing innovative technologies that promise to enhance efficiency, sustainability, and responsiveness in managing facilities [6]. Among these emerging technologies, AMRs are gaining attention for their ability to automate and optimize various FM tasks, from routine cleaning and maintenance to complex security operations. Despite the clear potential of AMRs, their adoption in FM has been slower compared to other sectors, such as manufacturing and logistics, where automation is more established [7]. This slower pace can be attributed to the unique challenges posed by the FM environment, which often involves diverse and dynamic conditions that require adaptable and robust robotic solutions. This reflects a notable research gap in understanding how the unique FM environments can effectively integrate with AMR technologies, and what specific factors will influence their adoption in this context.

In this regard, this study contributes to the literature by providing a comprehensive review of the challenges associated with the implementation and adoption of AMRs in FM, with a particular focus on identifying organizational and operational obstacles that hinder AMR adoption. By systematically analyzing the literature, this research offers valuable insights for both researchers and practitioners into the specific requirements for integrating AMRs into FM environments, which are distinct from those in other industries. Additionally, this study emphasizes often-overlooked aspects, such as organizational readiness, workforce training, and interoperability with existing systems, thereby bridging the gap between technical research and practical application. This fresh perspective on the potential difficulties in adopting AMRs within FM not only fills a critical gap in the current literature but also sets the stage for future research aimed at developing strategies and frameworks to facilitate more effective AMR integration into various FM operational contexts.

Given these challenges and the ongoing digital transformation in the built environment, it is essential to thoroughly examine the unique challenges in FM that hinder AMR adoption. Section 2 of this study presents a systematic literature review, focusing on FM context, current AMR applications, and the challenges associated with AMR adoption in FM. Section 3 introduces the PRISMA methodology, while Section 4 presents the results. This study centers on literature examining the unique challenges of technology adoption in FM, with a particular focus on AMRs. As this research is a systematic review rather than an empirical study, it does not include original data from interviews or case studies; this limitation is discussed in Section 5, alongside other limitations and recommendations for future research. Finally, Section 6 offers a summary of the study. Ultimately, the study aims to enrich the broader conversation on FM digitalization by providing insights and strategies to encourage wider AMR adoption, thereby enhancing the overall efficiency and sustainability of FM practices.

2. Literature Background

2.1. Historical Background of FM

FM began gaining recognition as a distinct field in the late 20th century, largely driven by the growing need to effectively oversee and maintain increasingly complex building systems and infrastructures [8]. Prior to this, building maintenance was primarily a technical, task-focused role, centered on addressing immediate operational needs. However, as buildings and facilities grew in scale and complexity, there arose a need for a more organized, strategic approach to managing these assets effectively and sustainably [9].

The formalization of FM as a recognized profession took shape in the 1980s, beginning with the establishment of institutions like the International Facility Management Association (IFMA) in 1980. This was a pivotal moment for the field, marking a transition from traditional maintenance practices to a comprehensive, multi-faceted approach that includes strategic planning, operational efficiency, and sustainable practices. This new approach emphasized not only the upkeep of physical assets but also the optimization of space, energy use, and the overall working environment, aligning with broader organizational goals [10].

One of the first significant research contributions to FM was by Becker (1990), who examined how FM could enhance organizational performance through better space management, which is a concept that recognized FM's potential impact beyond technical maintenance alone [11,12]. Research over the following decades continued to expand FM's scope, delving into its critical role in improving productivity, supporting environmental goals, and integrating technology into building operations. In the 2000s, the rise in digital and smart technologies further transformed FM, leading to the adoption of building information modeling (BIM), automation, and data analytics to drive efficiency and predictive maintenance [4,13].

Today, FM is recognized as a multi-disciplinary field that goes beyond traditional facility upkeep to encompass functions such as asset management, environmental sustainability, energy management, occupant health, and well-being [14]. It plays a strategic role in ensuring that buildings and infrastructures not only meet functional needs but also support broader objectives like sustainability and organizational productivity [15].

2.2. Shifts in FM Industry

The FM industry is undergoing a significant transformation as it shifts from traditional methods to smart technology-driven management. Traditionally, FM has relied on manual processes and reactive approaches to maintain and manage buildings and infrastructure [16,17]. This conventional model often involved routine inspections, scheduled maintenance, and reliance on human oversight, which could lead to inefficiencies, higher operational costs, and delayed responses to issues. However, the advent of smart technologies, including the Internet of Things (IoT), AI, and advanced data analytics, is revolutionizing the way facilities are managed, offering more proactive, efficient, and sustainable solutions.

One of the most profound changes brought about by smart technology in FM is the transition from reactive to proactive maintenance. Traditional FM practices often addressed issues only after they occurred, leading to unplanned downtime, higher repair costs, and potential safety risks. In contrast, smart technology enables predictive maintenance, where IoT sensors and AI-driven analytics continuously monitor the condition of equipment and infrastructure. These systems can predict when a component is likely to fail, allowing for timely intervention before a breakdown occurs. Studies have shown that predictive maintenance can reduce maintenance costs by about 25% and reduce downtime by about 70%, highlighting the tangible benefits of this shift [18–20].

Smart technology is also driving significant improvements in energy management within the FM industry. Traditionally, energy management practices often relied on manual meter readings and static schedules, which could lead to energy wastage. With the integration of IoT sensors, AI, and advanced building management systems (BMS), facilities can now dynamically adjust lighting, heating, ventilation, and air conditioning (HVAC) systems based on real-time occupancy data and environmental conditions [21]. For example, AI algorithms can analyze data from various sources to optimize energy use, reducing consumption during non-peak hours and adjusting settings based on predictive weather patterns. This not only leads to significant cost savings but also contributes to sustainability goals by reducing the carbon footprint of buildings [22,23].

Essentially, the shift from traditional methods to smart technology management in the FM industry represents a fundamental change in how facilities are going to be operated and maintained. The general benefits of this transformation are clear, with improvements in maintenance efficiency, energy management, occupant experience, and safety [24]. However, realizing these benefits requires overcoming significant challenges, particularly in the areas of integration, and workforce development and training. As the FM industry continues to evolve, the adoption of smart technologies will be crucial in driving efficiency, sustainability, and innovation in FM practices.

2.3. Autonomous Mobile Robots (AMRs)

AMRs are robots equipped with advanced sensors, Artificial Intelligence, and machine learning algorithms that enable them to navigate and operate independently without human intervention [25]. Unlike non-autonomous robots, which typically follow pre-programmed paths or require direct human control, AMRs can perceive their surroundings, make real-time decisions, and adapt to changes in their environment [26]. AMRs are increasingly utilized across various industries, including logistics, manufacturing, healthcare, and retail [27]. In logistics and warehousing, for example, AMRs are employed to transport goods, manage inventory, and optimize supply chain operations. In healthcare, they assist in delivering medication, supporting patient care, and maintaining hygiene standards.

Beyond these sectors, AMRs are gaining traction in fields such as agriculture, hospitality, and additional service industries. In agriculture, for instance, AMRs perform tasks like crop monitoring, planting, and harvesting while navigating unstructured terrains, a challenge often addressed through advanced path-planning algorithms, such as kinematically constrained bi-directional rapidly exploring random tree (RRT) approaches, to ensure efficiency and adaptability in complex settings [28,29]. In the hospitality industry, AMRs are now utilized in customer service roles, such as delivering room service in hotels or guiding guests through large venues, enhancing the customer experience and reducing dependence on human staff [30]. Other applications include infrastructure monitoring and structural health assessments in civil engineering, where AMRs are employed in tasks such as bridge inspection, applying both data-driven and knowledge-driven methodologies to improve the accuracy and timeliness of assessments [31,32].

These applications underscore the versatility and adaptability of AMRs, making them suitable for a wide range of uses. As AMR technology advances, especially in areas like obstacle avoidance and dynamic path planning, the robots are positioned to tackle increasingly complex tasks [33]. This trend is part of a broader shift toward smart automation and intelligent systems across sectors, where AMRs are likely to play an integral role. Their autonomy, coupled with advancements in AI and machine learning, will drive their continued integration across industries seeking enhanced efficiency, safety, and innovation in their operations. Consequently, AMRs are central to the future of automation, representing critical areas of study as industries pursue more advanced solutions to operational challenges.

2.4. Brief Overview of AMR in FM

Without a doubt, AMRs are also increasingly becoming integral to the evolution of FM, offering a modern solution to the complex demands of maintaining and operating large-scale facilities. As mentioned before, FM relies heavily on manual labor and static systems to perform tasks such as cleaning, security, and routine maintenance. However, the integration of AMRs is transforming these processes by introducing automation, efficiency, and flexibility that traditional methods cannot match. Theoretically, AMRs equipped with advanced navigation systems, sensors, and Artificial Intelligence, can autonomously navigate facility environments, performing a variety of tasks with minimal human intervention.

In FM, robotics are being adopted for several key functions. One of the primary applications is in cleaning and sanitation, where robots are deployed to clean floors, disinfect surfaces, and manage waste, ensuring that environments are maintained to a high standard of hygiene [34]. This has become particularly important in sectors like healthcare, where maintaining sterile conditions is critical. Robots are also used in security, patrolling premises, monitoring for intrusions, and providing real-time alerts, thereby enhancing the safety and security of the facility without the need for continuous human oversight. Furthermore, robotics also contribute to the efficiency of logistics management within facilities by transporting materials, managing inventory, and optimizing the supply chain processes, particularly in large industrial complexes or warehouses [35,36].

The adoption of robotics in FM represents a significant leap forward from traditional methods, offering several advantages. However, most robots deployed for FM purposes are still largely non-autonomous or partially autonomous where the system requires a fixed infrastructure or follows pre-defined paths. AMRs on the other hand can adapt to dynamic environments, avoid obstacles, and re-route themselves as needed. This flexibility will allow the AMRs to operate more efficiently in environments that are constantly changing or where human activity is prevalent. Moreover, the ability of AMRs to collect and analyze data in real-time also provides facilities managers with valuable insights, enabling predictive maintenance and more informed decision-making [37].

As the FM industry increasingly embraces digitalization and smart technologies, the role of AMRs is expected to grow even further. They not only enhance operational efficiency but also contribute to creating safer, cleaner, and more sustainable environments. The integration of AMRs into FM practices is a clear alignment with the industry's shift towards more intelligent, automated solutions that can meet the complex needs of modern facilities in the future. As research and development in robotics continue to advance, AMRs will likely become a standard component of FM, driving the future of the industry toward greater automation and innovation. This transition underscores the broader trend of digital transformation within FM, where technology-driven solutions are becoming essential for managing the increasing complexity and demands of modern facilities.

2.5. Lag in AMR Implementation Within FM

Although AMRs have shown considerable potential in the FM industry, particularly in areas such as cleaning, security, and logistics, their adoption has been comparatively slow and limited when measured against other sectors like manufacturing and logistics. This slower pace of adoption can be attributed to the unique challenges posed by the diverse and often unpredictable environments within the FM industry, which demand more sophisticated and adaptable robotic solutions. Additionally, there is a discernible research gap regarding the specific factors that influence AMR adoption in FM. Few studies have investigated how AMRs can be effectively aligned with the specific needs of FM. This gap underscores the necessity for targeted research on the barriers and facilitators of AMR adoption in FM, as well as the study of case studies and pilot projects that can offer practical insights for broader implementation across the FM industry. To address this gap, the following section outlines a research methodology that involves conducting a systematic bibliographic literature review of existing studies. This approach aims to identify general trends as well as the challenges associated with the adoption and implementation of AMR in the FM industry.

3. Methodology

This research seeks to explore the unique challenges in the FM industry that complicate the implementation of AMRs. FM encompasses a wide range of tasks, and the adoption of AMRs in this sector presents several barriers that are distinct from those in other industries. To achieve these objectives, a systematic scoping literature review was conducted, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol [38]. The research study would be carried out with a three-phase methodological approach, adhering to the PRISMA protocol (access on 12 Agust 2024: https://www.prisma-statement.org/scoping) [39] and utilizing the PRISMA flow diagram (Figure 1), as outlined in the PRISMA 2020 Statement, for both high-level and detailed reporting in the systematic review [40].

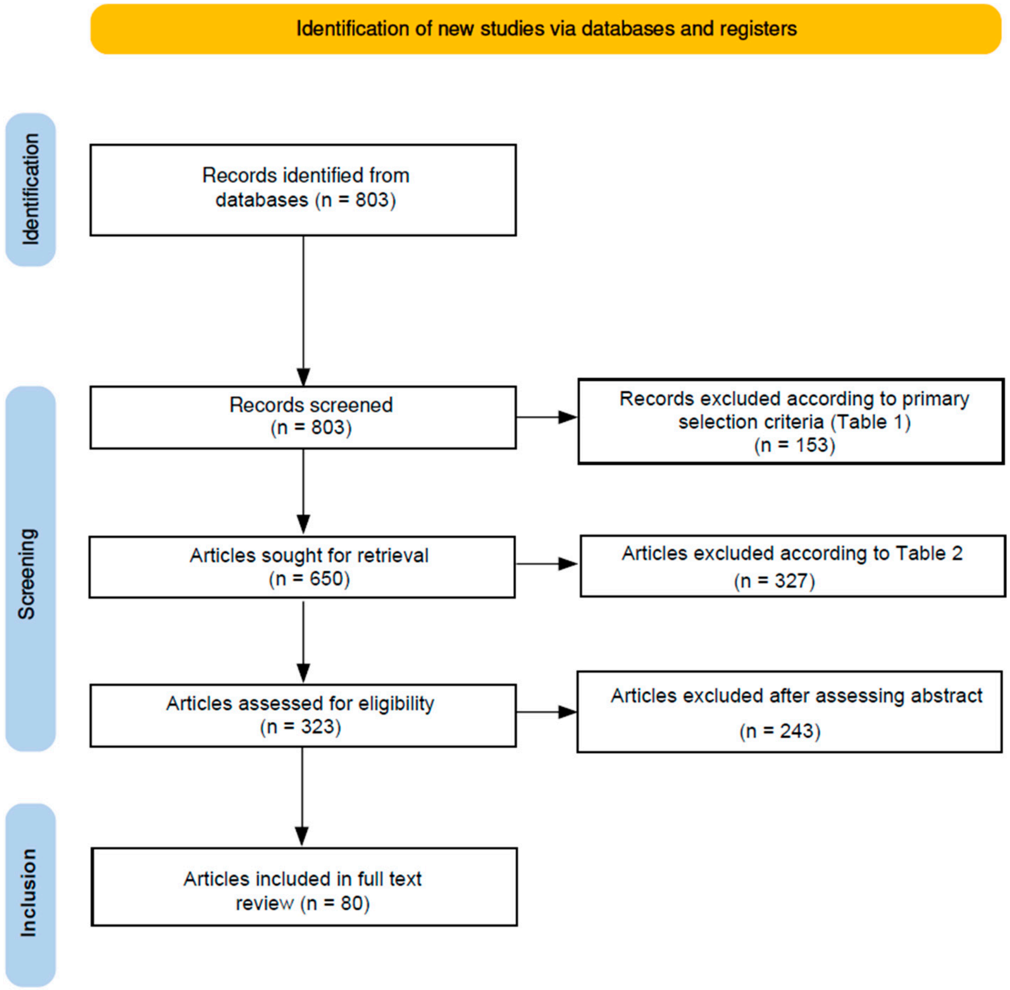

Figure 1. Adapted PRISMA flow diagram [41].

The rigorous and transparent approach of the PRISMA protocol for conducting this literature review was a key reason in adopting this methodology technique as it ensures a more structured and comprehensive synthesis of the literature [42]. PRISMA is widely recognized for its methodical process that includes clear guidelines on identifying, screening, and including relevant studies, making it well-suited for synthesizing extensive bodies of research and ensuring replicability [43].

Compared to other methodologies, such as the scoping review or narrative review, PRISMA offers several distinct advantages. Unlike scoping reviews, which provide broad overviews and are more exploratory, PRISMA is tailored to systematic reviews that seek to answer specific research questions through a structured, reproducible methodology [38]. Additionally, while narrative reviews provide flexibility in selecting and synthesizing studies, they can introduce greater subjectivity and potential bias, as they lack the step-by-step rigor that PRISMA offers [44]. PRISMA's stepwise approach and explicit reporting guidelines reduce such biases by emphasizing transparency in study selection and exclusion criteria.

However, this research also acknowledges that PRISMA also has its limitations. Its highly structured nature can sometimes limit the flexibility to explore emerging themes or less-studied areas, which scoping or narrative reviews may better capture [45]. Moreover, PRISMA may require more extensive time and resources due to its detailed documentation and screening processes, making it more demanding than alternative approaches. Nevertheless, PRISMA was selected because its benefits in ensuring transparency, rigor, and reproducibility align well with the objectives of this systematic review, providing a solid foundation for synthesizing findings within the research scope [46].

3.1. Phase 1: Identification

Phase 1 involves identifying relevant research papers that align with the research objective of understanding the unique FM industry challenges affecting the implementation of AMRs. A scoping review of the literature was conducted using academic databases such as IEEE Xplore, Science Direct, Scopus, and Web of Science, with keywords including "Autonomous Mobile Robots in Facilities Management", "AMR challenges FM", "robotics in FM operations", and "digitalization of FM".

The initial search retrieved 803 papers, which included research on AMR adoption across various industries as well as FM-specific challenges. All searches were accurate as of the time of the research, conducted in August 2024. No date restrictions were applied to ensure a comprehensive understanding of the foundational concepts explored in the context of FM and AMRs. To conduct the initial analysis of the extensive body of literature, VOSviewer (version 1.6.18) was employed as a bibliometric analysis tool, enabling the visualization and mapping of relationships between keywords. VOSviewer (version 1.6.18) was instrumental in sorting and identifying keyword co-occurrences across the relevant literature related to AMRs. In Figure 2, the different colors represent distinct clusters of related keywords, with each cluster indicating a specific theme within the research area. Larger nodes signify keywords that appear more frequently, showing their importance, while lines between nodes indicate co-occurrence, with thicker lines suggesting stronger relationships. The closer two nodes are, the more often they appear together in the same documents. This visualization highlights key themes and connections within the literature, helping to map out relationships between concepts in robotics, human interaction, and facilities management. The analysis revealed that the top ten most frequently co-occurring terms, including "robotics", "human", "architectural design", and "procedures", were prominent issues in the literature (Figure 2 and Table 1).

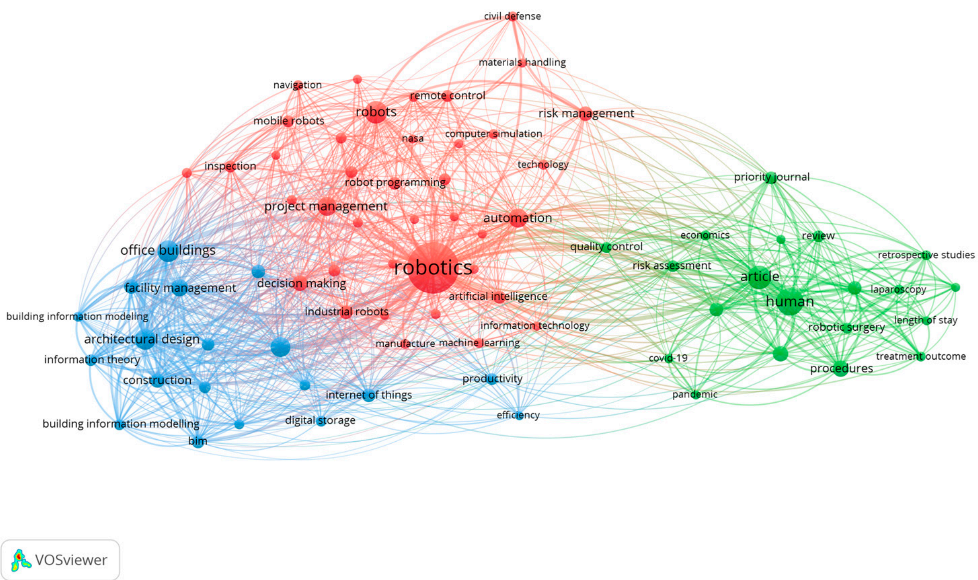

Figure 2. Bibliometric networks of AMRs research for co-occurrence of keywords using VOSviewer.

Table 1. Top 10 occurrences of keywords.

No	Keyword(s)	Occurrences	Total Link Strength
1	Robotics	439	1598
2	Human	128	954
3	Architectural Design	76	480
4	Procedures	45	391
5	Information management	421	286
6	Automation	62	231
7	Decision-Making	40	178
8	Personnel Training	15	75
9	Navigation	17	63
10	Optimization	16	31

A co-authorship analysis was also performed using VOSviewer, with countries serving as the unit of analysis. Figure 3 shows the result generated where each colour represents a cluster of countries with strong interconnections, highlighting regional or collaborative groupings. For example, blue nodes connect the United States with closely associated countries like Canada and Australia, while red nodes represent European countries such as Germany, France, and Spain. Green nodes highlight East Asian connections, including China, South Korea, and Taiwan. The line colours correspond to relationships within each cluster, with cross-cluster lines (e.g., between the United States and Germany) illustrating international collaborations. The findings showed that most research on FM challenges related to AMR implementation is concentrated in the United States and European countries, with only a small cluster of research emerging from Asia. Given that FM practices may vary significantly across different regions and countries, this further emphasizes the relevance of this study in addressing this gap.

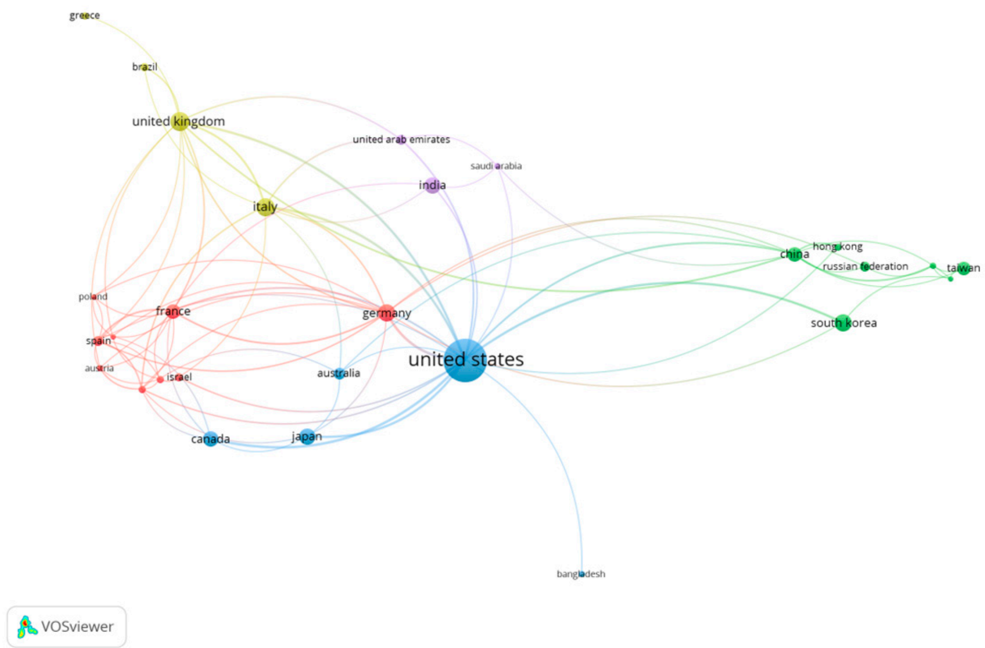

Figure 3. Bibliometric networks of AMRs research for co-authorship analysis by countries.

3.2. Phase 2: Screening

In Phase 2, the search was refined to narrow down in terms of date, language, and document type. The 30-year timeframe (1994–2024) was chosen for this systematic review because it captures the critical period during which AMRs transitioned from emerging technologies to widely researched and applied systems (Table 2) [47]. This period reflects significant technological advancements, increased academic and industry attention, and key milestones that have shaped the evolution and adoption of AMRs. By focusing on these three decades, the review provides a comprehensive overview of the field's development, from early innovations to the current state of the art [48]. Additionally, only papers written in English were selected, as it is the primary language in the region where this research is being conducted. Lastly, to avoid publication bias, the document types included are conference papers, articles, and journal papers, whether published or unpublished. This reduces the number of publications from 803 to 650. Table 2 below presents a summary of the primary selection criteria [39,49].

Table 2. Primary selection criteria.

Included	Excluded
Timeframe 1994–2024 Journal papers Articles Conference papers Complete text online Published in English Published and registers	Book chapters Report Conference review

The secondary screening process involved an in-depth review of abstracts to ensure that the selected papers specifically addressed the challenges related to the implementation of AMRs within the FM industry. This stage of the review was critical in filtering out papers that were not directly relevant to FM-related issues (Table 3).

Table 3. Secondary selection criteria.

Included.	Excluded
Non-technical research articles Qualitative research Challenges in adopting AMRs Challenges of FM unique environment AMR adoption case studies	Articles that focus on development and optimization of AMR technologies such as advanced algorithms and multi-sensor fusion techniques AMR related to water or underwater studies AMR related to aerospace

During this phase, papers that focused on overly technical aspects, such as the development and optimization of AMR algorithms and multi-sensor fusion techniques, were excluded. The intention was to maintain the focus on practical, industry-related challenges rather than on purely technical innovations. For instance, studies dedicated to algorithmic improvements or specialized AMR-use cases in fields like aerospace, underwater applications, or extreme environments were also excluded, as these were outside the scope of FM. By applying these criteria, the review remained centered on the core goal of understanding the specific challenges FM professionals face when integrating AMRs into their operations (Table 3).

3.3. Phase 3: Inclusion

In Phase 3, all 80 articles selected for this research will be analyzed through full-text content analysis. The primary themes emerging from these papers include varied building exteriors, diverse operational contexts, different building occupant types, poorly designed indoor environments, and the multi-faceted functionalities of FM. Section 4 of this paper will present these findings.

By employing this methodological approach, the study provides a comprehensive understanding of the challenges that FM professionals face in diverse operational contexts. This research will form the basis for future recommendations on improving FM practices by addressing these unique challenges.

4. Results

4.1. General Observations

The distribution of articles published over the years, as shown in Figure 4, reveals an increasing trend in research focused on the unique challenges of the FM environment. From 1994 to 2010, there were relatively few papers published, with sporadic peaks in the early 2000s. However, a noticeable rise in publications occurred after 2010, with a significant spike around 2020. This sharp increase coincides with the onset of the COVID-19 pandemic, which likely heightened the need for automated solutions such as AMRs in FM to minimize human contact, ensure safety, and maintain operational efficiency in facilities. The pandemic likely accelerated the industry's interest in leveraging robotics to overcome labor shortages and health-related restrictions hence increasing the related research to study the unique challenges of FM when adopting smart technologies.

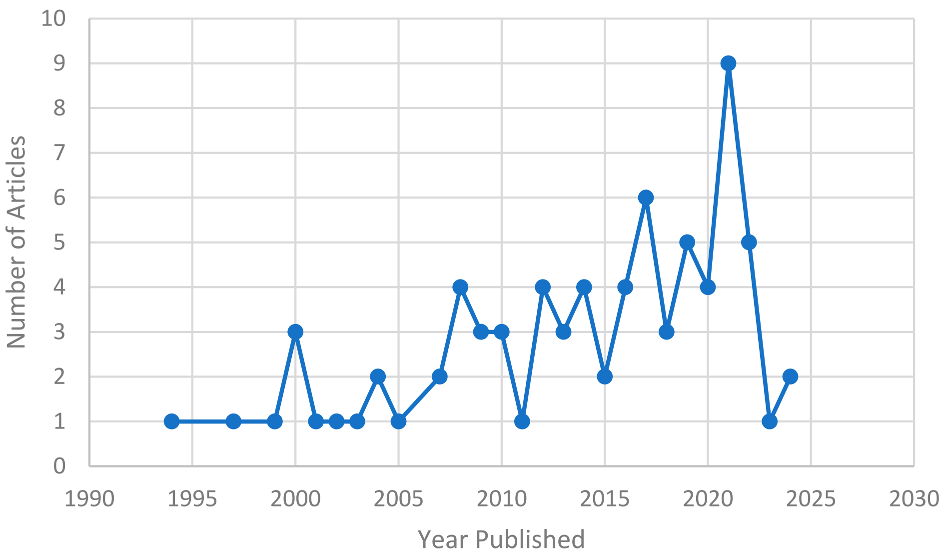

Figure 4. A distribution of the articles published over the years.

Although there was a slight dip in the number of publications after 2020, the overall number remains higher compared to earlier years, indicating continued research attention. However, the sharp decline in publications after this peak may indicate a temporary saturation of interest or challenges in sustaining research funding and resources, as well as the potential complexity of real-world AMR adoption in FM environments. As initial enthusiasm wanes and challenges in implementation become apparent, research efforts may have pivoted towards more practical applications and fine-tuning existing technologies rather than introducing new studies. This decrease may also be due to a reallocation of research focus towards integrating AMRs with other emerging technologies, such as AI and IoT, in more specialized studies, which may not fall strictly under the same research category. The sustained growth in publications before the decline suggests that the FM industry's challenges in adopting AMRs have become increasingly significant, especially as smart technologies evolve and the post-pandemic world seeks more resilient, tech-driven FM solutions.

4.2. Challenges in Adopting AMRs

In the following section, the 80 articles were reviewed and categorized in Table 4. The table will help to identify patterns and trends across the literature and will be helpful to understanding the frequency and significance of each challenge in the context of FM.

Table 4. Categorization of reviewed articles.

Article	Citation	Building Exterior	Diverse Operational Context	Varying Building Occupants	Poorly Designed Indoor Environment	Multi-Faceted FM Functionalities
1	[50]	√				
2	[51]		√		√	
3	[52]	√	√			
4	[53]	√				
5	[54]		√	√		√
6	[55]		√	√		√
7	[56]		√			
8	[3]				√	
9	[57]				√	
10	[58]			√	√	
11	[59]				√	
12	[60]			√		√
13	[61]			√		
14	[62]					√
15	[63]		√	√		√
16	[64]		√	√		
17	[65]		√			√
18	[66]		√			√
19	[67]		√			√
20	[68]					√
21	[69]		√			
22	[24]		√	√		√
23	[70]		√			√
24	[71]		√			
25	[72]		√	√		√
26	[73]		√			√
27	[74]					√
28	[75]		√			
29	[23]			√		
30	[76]		√	√		
31	[77]			√		
32	[78]		√			√

Table 4. *Cont.*

Article	Citation	Building Exterior	Diverse Operational Context	Varying Building Occupants	Poorly Designed Indoor Environment	Multi-Faceted FM Functionalities
33	[79]		√			
34	[80]		√	√		√
35	[81]		√	√		√
36	[82]		√			
37	[83]			√		
38	[84]			√		
39	[85]					√
40	[86]	√	√			
41	[87]				√	
42	[88]				√	
43	[89]				√	
44	[90]				√	
45	[91]				√	
46	[92]				√	
47	[93]		√		√	
48	[94]				√	
49	[95]				√	
50	[96]				√	
51	[97]				√	
52	[98]				√	
53	[99]		√		√	
54	[100]		√	√	√	
55	[101]		√		√	
56	[102]		√		√	
57	[103]				√	
58	[104]				√	
59	[105]	√		√	√	
60	[106]		√	√	√	
61	[107]		√		√	
62	[108]			√	√	
63	[109]		√	√		√
64	[110]		√			
65	[111]			√		
66	[112]	√				
67	[113]	√	√			
68	[114]	√	√	√		√
69	[115]	√		√		√
70	[116]	√	√			√
71	[117]		√	√		√
72	[118]		√			√

Table 4. *Cont.*

Article	Citation	Building Exterior	Diverse Operational Context	Varying Building Occupants	Poorly Designed Indoor Environment	Multi-Faceted FM Functionalities
73	[119]		√	√		√
74	[120]		√		√	
75	[121]		√	√	√	√
76	[122]			√	√	
77	[123]				√	√
78	[124]			√	√	
79	[17]		√	√		√
80	[125]	√				

The analysis of the reviewed articles highlights that the diverse operational context (n = 42) and poorly designed indoor environments (n = 32) are the most frequently identified challenges. These factors emphasize the complexity of FM settings, where variability in spatial layouts, occupant behaviors, and multiple functions create obstacles for smooth AMR deployment. Varying building occupants (n = 30) also pose significant challenges, as AMRs must be capable of adapting to the dynamic interactions between humans and robots within these spaces. The multi-faceted FM functionalities (n = 28) further complicate adoption, as FM operations often involve diverse tasks that require flexible AMR systems. Lastly, building exterior considerations (n = 11) present additional challenges, particularly when AMRs are required to operate in both indoor and outdoor environments.

5. Discussions

5.1. Key Findings

This section will discuss the key findings from the results presented in Section 4 and how they contribute to a deeper understanding of the potential impact and relevance of the various research objectives explored in the field of FM.

The results of this review highlight several critical challenges that FM may face in adopting AMRs. Among these, the diverse operational context emerged as the most prominent challenge, followed by poorly designed indoor environments, varying building occupants, multi-faceted FM functionalities, and building exterior considerations. These findings underline the complex, dynamic, and multifaceted nature of FM settings, where standardization is often lacking, and the adaptability of AMRs to unpredictable conditions is vital for successful implementation.

5.1.1. Diverse Operational Context

The diverse operational context (n = 42) ranked as the highest challenge due to the inherent complexity of FM environments. Unlike controlled, static industrial settings, FM environments are highly variable, with different types of facilities requiring distinct operational approaches. These can range from corporate offices, healthcare facilities, and shopping malls to manufacturing plants and data centers, each having unique spatial layouts, occupant interactions, and operational priorities. The FM industry also deals with highly dynamic conditions, with fluctuating daily activities, shifts in facility usage, and the need for AMRs to adapt in real-time to unforeseen changes. This level of variability makes it difficult for AMRs to operate consistently without sophisticated perception, learning, and navigation capabilities.

Moreover, FM operations often involve diverse tasks, including cleaning, security, maintenance, and waste management. Each task has different requirements, demanding a high degree of versatility from AMRs. The lack of standardized facility structures and the diversity of tasks make FM environments more challenging compared to other industries such as manufacturing, where processes are more predictable and structured. As a result, the AMRs must be flexible enough to handle these variable conditions, making the diverse operational context a significant challenge for implementation.

5.1.2. Poorly Designed Indoor Environments

Poorly designed indoor environments (n = 32) also pose substantial obstacles to AMR adoption. Many FM environments were not originally designed with automation in mind, leading to issues such as narrow corridors, stairs, obstacles, and clutter that complicate navigation. Historically, building environments have been designed with human needs and behaviors as the primary focus, often prioritizing comfort, esthetics, and human mobility. However, this approach does not always align with the requirements of automation. The physical constraints of many older facilities—such as tight spaces, irregular layouts, and infrastructure designed for human use rather than robotic integration—pose significant challenges to AMRs, which must navigate in a way that humans typically do not. This mismatch between the design of built environments and the operational needs of autonomous systems further complicates their deployment, often requiring substantial retrofitting or redesigning to accommodate AMRs effectively.

5.1.3. Varying Building Occupants

Varying building occupants (n = 30) represent another considerable challenge. FM environments are dynamic due to the constant movement of people—staff, visitors, and residents—throughout the facilities. AMRs must safely navigate these unpredictable interactions, ensuring not only operational efficiency but also safety. The need for AMRs to be aware of and responsive to human behavior adds another layer of complexity, particularly in crowded or high-traffic areas like hospitals, malls, or airports.

5.1.4. Multi-Faceted FM Functionalities

Multi-faceted FM functionalities (n = 28) highlight the variety of tasks that AMRs are expected to handle. This diversity includes janitorial services, security patrols, and even minor maintenance tasks. Each of these functions requires specific configurations, programming, and real-time adaptability from the AMRs. For example, a robot used for cleaning may need different operational requirements from one used for security patrols, necessitating flexibility in design and programming.

5.1.5. Building Exterior Considerations

Lastly, building exterior considerations (n = 11) further complicates AMR implementation in FM. Many FM operations are not confined to indoor spaces alone. For AMRs to be fully effective, they need to operate both indoors and outdoors, adapting to different lighting, weather conditions, and terrain, which adds to the technical complexity and operational challenges. Variations in building exteriors, such as differences in entrances, exits, and facade configurations, can disrupt AMR navigation, particularly in managing tasks across multiple sites. The presence of architectural complexities like stairs, uneven surfaces, and other obstructions complicates the mapping and mobility of AMRs. Additionally, exposure to environmental factors such as rain and wind, particularly in sustainable building designs like net-zero structures that incorporate open layouts to promote natural airflow, can impact the durability and functionality of AMRs during operations. This increases operational risks and heightens maintenance demands in FM contexts.

5.1.6. Unique and Combined Challenges in FM

While the top five challenges identified from the PRISMA review are significant, they do not encompass the full spectrum of issues FM managers may face when adopting AMRs. The complexity of FM operations means that each facility may present its own unique set of challenges or combinations of these factors. For instance, a facility may struggle with both architectural complexities and the need for highly flexible AMR task allocation, while another might face issues related to both occupant interaction and weather conditions in outdoor spaces. This variability underscores the highly individualized nature of FM challenges and helps explain why AMR adoption in the field remains low.

Moreover, while the adoption of AMRs offers numerous benefits, such as enhanced efficiency and cost savings over time, improper integration into the FM environment can lead to decreased productivity and operational inefficiencies. If AMRs are not seamlessly incorporated into existing workflows and infrastructure, they can create more problems than they solve, resulting in significant costs that FM managers would prefer to avoid. This potential for negative outcomes further emphasizes the importance of addressing the unique challenges within each facility to ensure successful AMR implementation.

5.2. Research Contributions

5.2.1. Academic Contributions

This study provides a systematic review that addresses a significant research gap by exploring the practical challenges within FM settings that impact AMR adoption. Through a comprehensive analysis of collected data, the findings underscore that the built environment is evolving to serve not only human occupants but also robots and emerging technologies. The core challenges in FM's integration of AMRs highlight a larger issue: the built environment has not been designed to be inclusive of such technologies, indicating a need for more adaptable infrastructure. The identification of FM's unique operational challenges forms a foundation for future research aimed at developing frameworks and strategies to support more inclusive AMR integration.

Moreover, this research contributes to the broader body of knowledge on digital transformation and smart technology adoption within the built environment, offering insights into the changing demands of contemporary FM and the increasing need for spaces that accommodate both human and technological occupants.

5.2.2. Industrial Contributions

For the FM industry, this study provides actionable insights into the effective integration of AMRs to improve operational efficiency, reduce labor costs, and enhance service delivery. By systematically examining the specific challenges FM professionals encounter, this research offers practical guidance for practitioners and decision-makers seeking to adopt AMRs. The findings underscore the importance of addressing key factors to increase the likelihood of successful AMR implementation, paving the way for smarter FM practices.

Additionally, the unique challenges identified in this study could inform future policy development or certification standards for AMR-friendly built environments, establishing criteria that recognize and certify buildings for their inclusivity toward autonomous systems. This perspective contributes to a growing body of knowledge on smart technology adoption within the built environment, emphasizing the need for spaces that are adaptable to both human and technological occupants.

5.3. Research Limitations and Future Research Directions

This study has several limitations that should be acknowledged.

Firstly, the scope of the literature review was constrained by the selection criteria, which excluded highly technical studies focusing on aspects like algorithmic improvements or niche applications outside of FM. As a result, the review may not have captured all relevant challenges associated with AMR adoption in FM, potentially leading to an incomplete understanding of the barriers.

This study exclusively relied on qualitative data obtained through a systematic review of existing literature, without incorporating empirical research. Consequently, this dependence on secondary sources may not fully capture the real-world operational challenges encountered by FM professionals. The absence of practical data from case studies, interviews, or surveys restricts the generalizability of the findings to actual FM practices. Future research could enhance this by incorporating empirical methods, such as case studies, interviews, experiments, or surveys, to provide more concrete evidence and actionable recommendations.

While this review draws on a robust base of sources, it does have certain limitations. Notably, the inclusion and exclusion criteria, as detailed in Tables 2 and 3, focused the review on practical challenges in AMR adoption specific to the FM industry by excluding highly technical studies and niche applications outside of FM. While this targeted approach allowed for a clearer understanding of FM-specific operational and environmental factors, it may have inadvertently limited the breadth and depth of the review. Additionally, restricting sources to English-language publications may have narrowed the scope to FM practices prevalent in English-speaking regions, potentially affecting the generalizability of findings to other global contexts. Similarly, focusing on specific databases might have restricted the overall comprehensiveness of the review. Future studies could address these limitations by including multilingual sources and expanding the range of databases consulted, which would enhance the applicability of the findings across diverse FM environments and provide a more globally representative view of AMR adoption challenges.

Additionally, while the review identified key barriers to the adoption of AMRs in FM, the challenges and benefits may not be uniformly applicable across different FM contexts or industries. The nature of FM varies significantly from one facility to another, with distinct operational requirements and environmental conditions, which could influence the relevance of the findings.

Lastly, the study concentrated on identifying and categorizing the challenges without addressing potential solutions or strategies for overcoming these barriers. Future research should seek to bridge this gap by exploring the best practices, technological advancements, and policy measures that could facilitate more seamless AMR integration in the FM sector. One promising solution that the research team is working on is the Robot-Inclusive Built Environment framework, combined with the Robot Building Compatibility Index, which could help address the poorly designed indoor environment challenge identified in this paper.

6. Conclusions

This research offers a comprehensive review of the distinct challenges the FM industry faces in adopting AMRs. The findings reveal that the primary barriers to successful AMR integration in FM are diverse operational contexts, poorly designed indoor environments, varying building occupants, multi-faceted FM functionalities, and building exterior considerations. The dynamic and unpredictable nature of FM settings, along with the wide range of tasks AMRs must perform, requires advanced capabilities in adaptability, navigation, and real-time decision-making. These are areas where many current technologies are still evolving.

The study emphasizes that FM environments are far more complex than industries such as manufacturing, where processes and conditions tend to be standardized and predictable. The results suggest that developing and deploying AMRs in FM will demand robust and flexible solutions capable of navigating unpredictable environments, interacting seamlessly with human occupants, and handling a variety of tasks simultaneously.

By shedding light on these operational challenges, this research contributes to the growing body of literature on the digital transformation of FM and smart buildings. It provides a foundation for further research aimed at addressing these challenges and facilitating the broader adoption of AMRs in FM. The study also serves as a call to action for AMR developers, FM professionals, and policymakers to collaborate on strategies to overcome these barriers and unlock the full potential of robotics in FM.

While the study provides valuable insights, it does have limitations. Future research should include empirical investigations, such as real-world case studies and interviews with FM professionals, to further explore potential solutions. By focusing on overcoming these challenges, the FM industry can advance toward greater automation and efficiency, leveraging AMRs as an integral part of its operations.

The rapid advancement of digital technologies, including AMRs and Artificial Intelligence, is transforming industries by enhancing efficiency, accuracy, and sustainability [126]. However, FM has been slower to adopt these innovations. To remain competitive and effective, FM and other sectors must accelerate the integration of smart technologies [127]. Embracing these advancements will enable industries to harness their full potential, drive operational improvements, and achieve long-term success. Ultimately, while technological progress is a powerful catalyst for change, it is up to industries to embrace and adapt to these changes collectively.

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