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SURVEY

State of the Art and Future Directions of Healthcare 4.0: A Systematic Literature Review

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ABSTRACT This article explores the emerging field of Healthcare 4.0, which integrates advanced technologies from Industry 4.0 to enhance decision-making processes in the healthcare context. As the healthcare landscape evolves, there is a pressing need to understand how these innovations can support clinical and operational management, ultimately improving patient outcomes and healthcare efficiency. This study employs a systematic literature review (SLR) methodology to investigate the current state of research on Healthcare 4.0 solutions, focusing on their applications across various healthcare sectors. The main scientific databases were considered and we evaluated peer-reviewed articles published in scientific journals until July 2024. The review identifies key themes, trends, and gaps in the literature, revealing that while the field is still in its infancy, there is a notable increase in publications, indicating growing interest and potential for future research. The findings categorize applications into several areas, including hospital general facilities and specific environments, highlighting the diverse contexts in which Healthcare 4.0 technologies are being implemented. Additionally, the study examines the geographical distribution of research, with a significant emphasis on developments in Asia and Europe. Regarding the decision objectives, we highlight the use of Healthcare 4.0 solutions to improve the performance of activities related to data exchange, diagnosis, and patient monitoring. Furthermore, considering the main techniques and tools adopted by the authors, Artificial Intelligence, Internet of Things, and Blockchain stand out, as well as hybrid approaches which integrate different solutions. By synthesizing these insights, the article contributes to a deeper understanding of how Healthcare 4.0 can transform decision-making in health facilities, offering directions for future research and practical implications for healthcare researchers and professionals.

INDEX TERMS Healthcare 4.0, emerging technologies, systematic literature review.

I. INTRODUCTION

The concept of Healthcare 4.0 emerges as an extension of the principles of Industry 4.0. This term refers to what is considered the fourth industrial revolution, proposing the integration of emerging technologies to revolutionize industrial processes with a focus on more efficient decision-making [1], [2], [3], [4]. In the healthcare context, the same technologies can be adapted to optimize diagnostics, treatments, and the management of hospitals and clinics, providing more personalized and efficient care. This approach transforms healthcare systems, which have historically faced

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challenges related to service capacity, rising costs, and accessibility, into a more sustainable and patient-centered model [5], [6].

In recent years, Healthcare 4.0 has played a crucial role, particularly in the face of an ageing population, the rise in chronic diseases, and the need for rapid responses to global emergencies such as pandemics [7]. The ability to monitor patients in real-time or near real-time not only improves individual care, but also the performance of healthcare systems [8]. Furthermore, advanced systems can analyze medical data, such as test results and symptom descriptions, assisting physicians in identifying diseases at early stages and increasing the chances of successful diagnosis and treatment [9], [10].

Beyond benefits primarily related to the efficiency of patient care and treatment, there is also a significant impact on hospital operational management. By automating administrative processes and leveraging technologies for secure health data management, hospitals can operate more efficiently, reducing waste, lowering operational costs, and improving process performance [11], [12], [13]. Additionally, automation minimizes human error, enhancing safety and precision in healthcare environments [14], [15].

Lastly, it is essential to highlight that Healthcare 4.0 represents not only a technological revolution but also a cultural one. Despite its numerous advantages, the use of these technologies raises critical issues regarding data privacy, equitable access, and the impact on the doctor-patient relationship [16], [17]. Thus, the success of this transformation depends on a careful balance between innovation, regulation, and education, ensuring that the benefits of Healthcare 4.0 are widely distributed while potential risks are mitigated.

Finally, it is worth noting that the adoption of Healthcare 4.0 faces various challenges and barriers. Among the main challenges are the initial costs associated with acquiring and implementing advanced technologies. Additionally, there is a lack of adequate digital infrastructure, such as high-quality connectivity and robust cybersecurity, which hinders technological integration. Finally, the lack of technical qualifications among healthcare professionals also poses a significant obstacle, as operating these technologies requires specialized training [6], [18].

Although it is a promising approach, we highlight that the adoption and advancement of Healthcare 4.0 also call for robust theoretical studies that thoroughly describe its current applications since new solutions and technological developments emerge year after year, significantly impacting the healthcare systems management. Some theoretical reviews addressed Healthcare 4.0 in the last years. Ahsan and Siddique [19] reviewed 47 works to explore the Industry 4.0 solutions applied in the Healthcare context. They considered papers available in the Scopus and Web of Science databases and the focus was on current applications and future paths. Moreover, Tlapa et al. [18] investigated the impact of digital technologies on healthcare, considering five databases, PubMed, Ebsco, The Cochrane Library, CINAHL, and Web of Science. The authors reviewed 28 papers. Tortorella et al. [20] also reviewed papers that explore Healthcare 4.0 solutions. They investigated 78 papers from five databases, Scopus, Web of Science, Science Direct, and Pubmed, and the focus was to answer questions about the use of Information and communication technologies in healthcare applications. Other reviews available in the literature need to present a systematic research protocol, such as the works proposed by Paul et al. [7] and Jayaraman et al. [5]. Finally, Mwanza et al. [6] reviewed 72 articles from Scopus, Pubmed, and Science Direct databases, but they focused on the impact of Industry 4.0 in healthcare systems considering low- and middle-income countries. Thus, this work complements the current literature with a more comprehensive review considering different databases and research questions.

Therefore, since the current literature reviews did not address relevant aspects related to Healthcare 4.0, we highlight that it is crucial to investigate the tools and technologies being employed, the objectives driving decision-making in healthcare settings, as well as the advantages, barriers, and future perspectives in this field. Understanding these dimensions can provide valuable insights into how Industry 4.0 solutions can support healthcare environments. Furthermore, these investigations can guide the development of frameworks and strategies to address the current challenges, fostering a more seamless integration of advanced tools into the healthcare ecosystem while maximizing their potential benefits.

To fill this gap in the literature, the main objective of this article is to develop a Systematic Literature Review (SLR) addressing the state of the art regarding the use of Healthcare 4.0 solutions. We considered the main scientific databases and a systematic procedure to select and evaluate the main papers in this field. In this way, this paper intends to answer the following research questions: (i) In which health area/sector and in what region did the work focus? (ii) What were the objectives regarding decision-making? (iii) What techniques and tools were adopted/proposed?, and (iv) What are the advantages, open issues, and challenges in future research paths for Healthcare 4.0 applications?

To address these questions, this article advances the theoretical understanding of Healthcare 4.0 solutions and addresses a gap in the existing literature on this topic. The structure of the paper is as follows: Section II presents a literature background, outlining the key concepts and themes explored in the study. Section III details the research methodology employed. Section IV focuses on the presentation of findings and discussion, offering answers to the research questions. Lastly, Section V provides final discussions, while Section VI presents the conclusions and suggests directions for future research.

II. HEALTHCARE 4.0 SOLUTIONS

The Industry 4.0's era has significantly changed the way we make decisions and manage productive systems (goods and services). In this case, different from the other industrial revolutions, which were based on milestones of scientific and innovative advancements, the fourth industrial revolution is not only characterized by technological innovations, but it represents a shift in how companies perceive and address technological challenges in the decision-making process [21]. This fact is illustrated by the fact that we cannot associate the Industry 4.0 with just one technological solution, but rather several pillars that make up this new era. Santos et al. [4] highlight that, in addition to Information Technology (IT), we can mention several other pillars of Industry 4.0, such as Cloud Computing, Internet of Things (IoT), Big Data, and Cyber-physical Systems. Moreover, other authors complement these pillars with significant solutions, such as Virtual and Augmented Reality, Computational Simulation, Collaborative robots, Blockchain and Artificial Intelligence techniques [2], [3], [22], [23], [24]. In this way, Figure 1 Illustrates the Industry 4.0 pillars.

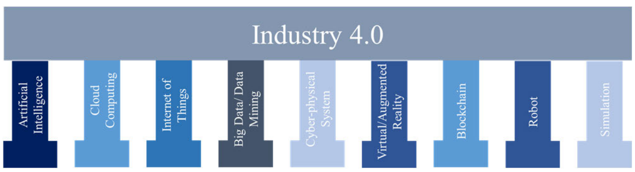


FIGURE 1. Industry 4.0 pillars (adapted from Santos et al. [4].

In the same way, the so-called Healthcare 4.0 is an extension of the 4.0 Era considering healthcare systems. For Khan et al. [25], Healthcare 4.0 represents the fourth revolution in the healthcare sector, driving innovation to new heights. This concept focuses on delivering highly personalized and efficient healthcare services to everyone. It marks a significant evolution from Healthcare 1.0, where patients relied on in-person visits for diagnosis and treatment. Healthcare 2.0 brought advancements like electronic medical records and online communication portals, enabling constant interaction between patients and healthcare providers. The transition to Healthcare 3.0 saw the adoption of telemedicine and remote monitoring, allowing patients to receive care conveniently at home. Now, Healthcare 4.0 takes digital integration to the next level, leveraging the Industry 4.0 technologies and pillars to create a more customized and efficient healthcare ecosystem. Tortorella et al. [20] reveal that the advances of Healthcare 4.0 have revolutionized decision-making support by introducing advanced technologies to enhance precision, efficiency, and patient-centered care.

Rodrigues et al. [26] highlight that the 4.0 era in health systems stood out driven by the technological advancements transforming hospital operations and medical practices. Today, there is an increasing demand for real-time data analysis. Accessing and utilizing real-time information might be a critical factor in life-and-death situations within healthcare environments and, therefore, the adoption of technologies in this environment is inevitable. The adoption of emerging solutions, such as AI, Big Data, and IoT, enable clinicians and healthcare administrators to make more informed decisions at the individual and systemic levels. These technologies facilitate the integration and analysis of vast, diverse data sources, ranging from electronic health records (EHRs) to real-time patient monitoring, providing actionable insights previously unattainable through traditional methods [27], [28]. Other applications are related to conserving and creating secure information flows based on Blockchain [29].

Furthermore, AI-powered systems support clinical decision-making by processing and interpreting complex datasets quickly and accurately. For instance, Machine Learning (ML) algorithms are utilized in diagnostic imaging to identify patterns and anomalies with high reliability, often assisting radiologists in detecting early-stage diseases such as cancer. Beyond imaging, AI-driven predictive analytics models forecast disease progression and patient risks, enabling preemptive interventions and personalized treatment plans [30]. However, deploying these systems raises challenges, including the need for transparent algorithms, mitigation of biases, and integration into existing healthcare workflows.

IoT devices, including wearable health monitors and connected medical equipment, are another cornerstone of Healthcare 4.0's ecosystem. These devices continuously capture critical health metrics such as heart rate, glucose levels, and oxygen saturation, which are then analyzed to inform real-time clinical decisions [28]. For example, IoT can alert healthcare providers to potential complications, such as arrhythmias or deteriorating vital signs, allowing immediate action. Despite their potential, barriers such as data interoperability, cybersecurity risks, and the standardization of device protocols hinder the seamless implementation of IoT solutions [16].

Healthcare 4.0 also harnesses Big Data analytics to support strategic decision-making for healthcare organizations. Trends in literature review explain how healthcare 4.0 is implemented by analyzing population health data, these tools enable administrators to identify trends, allocate resources effectively, and design targeted interventions [7]. For example, predictive models can forecast hospital admission rates, allowing for better resource planning and reducing strain on healthcare systems. However, successfully applying these tools requires addressing challenges related to data quality, privacy concerns, and the integration of disparate data sources. Several other technological solutions might be applied in healthcare environments, such as Robotic systems to support routine activities of health systems [15], Virtual and Augmented reality to allow the virtualization of the systems through Digital Twins [31], among other examples.

Despite the promising capabilities of Healthcare 4.0 technologies, gaps remain in their adoption and evaluation.

Current research often emphasizes technical capabilities rather than long-term clinical and operational impacts. Additionally, disparities in access to these technologies, particularly in resource-constrained settings, highlight the need for equitable deployment strategies. Closing these gaps is essential to fully realize the potential of Healthcare 4.0, ensuring that it delivers tangible benefits to patients and providers [32].

III. MATERIALS AND METHODS: A SYSTEMATIC LITERATURE REVIEW

Unlike traditional literature reviews, which permit exploratory research without stringent methodological guidelines, the Systematic Literature Review (SLR) investigates the literature in a structured manner, following specific steps to address certain scientific questions [33]. According to Tranfield et al. [34], SLR is anchored in two main areas: (i) A comprehensive examination of primary literature within a particular domain, and (ii) The application of statistical techniques to synthesize findings and enhance the reliability of the results. Consequently, we propose an SLR to explore the advances of Healthcare 4.0, adopting the methodology outlined by Oliveira et al. [35] and Santos et al. [36] through four phases: Planning, Searching/Screening, Analysis/Synthesis, and Presentation. In the Planning phase, the primary research objectives and questions are established. The Searching/Screening phase is dedicated to systematically reviewing the literature based on predefined criteria. The Analysis/Synthesis phase involves analyzing the findings, while the Presentation phase summarizes the results and draws key conclusions.

A. PLANNING

To define the objectives and Research Questions (RQs), the process began with an exploratory search on the topic of this paper. The Scopus® database, known as one of the most extensive and thorough multidisciplinary databases [37], was used for this purpose. The search strategy involved the keyword "Healthcare 4.0". Initially, we focused on peer-reviewed scientific journals and conference papers. Several meetings were held to delve into the use of Healthcare 4.0 solutions in health systems, gathering insights from existing literature. Professors from four universities from two countries, with substantial expertise in relevant areas, participated in these discussions. This collaborative effort helped researchers identify key unresolved issues within this field, guiding the development of the RQs.

Therefore, this research aims to conduct a comprehensive literature review on Healthcare 4.0, establishing a strong theoretical foundation in this field and identifying future trends. After defining the objectives, the Research Questions (RQs) were determined using the "CIMO" framework introduced by Denyer et al. [38]. This framework structures RQs into four core elements: the health sectors/areas and locations in which the work focused (Context), the decision objectives (Intervention), the Healthcare tools and solutions proposed by the authors (Mechanism), and the advantages, challenges, and open issues highlighted by the authors (Outcomes). As a result, this paper integrates a Systematic Literature Review (SLR) with the CIMO approach to investigate the state-of-the-art of Healthcare 4.0. The resulting RQs are as follows:

RQ1: In which health area/sector and in what region did the work focus (Context)?

RQ2: What were the objectives regarding decision-making? (Intervention)?

RQ3: What techniques and tools were adopted/proposed (Mechanism)?

RQ4: What are the advantages, open issues, and challenges in future research paths for Healthcare 4.0 applications (Outcomes)?

B. SEARCHING/SCREENING

The first step involves selecting the databases for the SLR. Three databases were selected: Scopus® , Web of Science® , and PubMed® . Based on the exploratory research, we opted to use the keyword "Healthcare 4.0" since most of the works in the area comprehensively adopts this term.

Afterwards, specific search terms were identified. In this way, searches were performed across the chosen databases and each search followed certain criteria for article inclusion in the SLR: (i) the search terms had to appear in the title, abstract, or keywords; (ii) only complete articles published in peer-reviewed scientific journals were considered, with a cutoff date of July 2024; (iii) articles had to be written in English; and (iv) only articles with practical applications were included, excluding review papers.

After removing duplicates, 173 articles that met the search criteria were identified. A screening process was then carried out, focusing on the abstracts to determine which papers aligned with the objectives of the SLR. At this stage, articles that did not fit the predefined research criteria were excluded. After the screening, 82 articles were selected for full-text review. Figure 2 outlines the steps taken during the Planning and Searching/Screening phases. It is important to note that while other papers discuss the topic of Healthcare 4.0, they were not included in this SLR as they did not meet the predefined selection criteria. Thus, the objective is not to provide an exhaustive review of all literature on the subject but to evaluate all studies that align with the SLR criteria.

C. ANALYSIS/SYNTHESIS AND PRESENTATION

The analysis and synthesis of the findings were carried out using a Microsoft Excel® spreadsheet, which enabled the organization of information from all 82 reviewed articles. Each article was systematically recorded in the spreadsheet based on predefined guidelines related to the research questions (RQs), and the extracted data was analyzed using descriptive statistics. The analyses were structured around each RQ, emphasizing the state of the art regarding Healthcare 4.0 solutions. Section IV will present the findings,

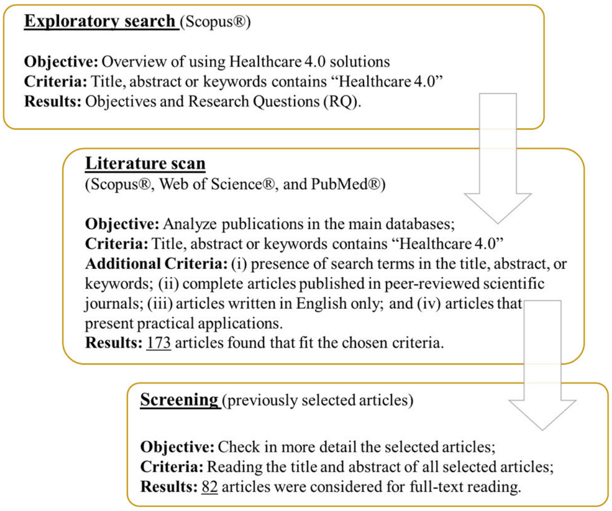


FIGURE 2. Procedures performed in the Planning and Searching/Screening stages.

with subsections dedicated to each RQ. Moreover, tables and graphs have been utilized to effectively summarize the results and enhance their understanding.

IV. FINDINGS

A. STATE OF THE ART

Among the 82 reviewed articles, it becomes clear that this research field is still emerging and underexplored, with the earliest publication dating back to 2018. However, the growing number of annual publications indicates its potential as a promising area of study. Figure 3 illustrates the yearly trends in publication, showing a notable rise in recent years. It is important to highlight that this review considered papers published up to July 2024 and, therefore, it is expected that the publications in this year will be more expressive. In this way, we can note that the analysis considering just half a year already shows that there is a tendency that in 2024 the number of publications will exceed the previous year. The analysis also revealed that the articles were published in 72 scientific journals, demonstrating that this is a multidisciplinary topic relevant across various research domains. In this case, Table 1 lists the top 10 journal sources that contribute approximately 31.7% of the total publications.

B. HEALTHCARE 4.0 SECTORS AND AREAS

In this section, we intend to discuss RQ1 "In which health area/sector and in what region did the work focus?".

Based on the selected articles, we categorized the application areas/sector into seven main categories: (i) Hospital General Facilities, covering different areas of a healthcare environment without highlighting a specific area/ sector; (ii) Operating Room; (iii) Patients Diagnosis and Evaluation area; (iv) Intensive Care Unit; (v) Exam/ medical procedures room; (vi) Home Care/ Remote Care, which consider applications focused on environments outside the hospital facilities; and (vii) Other, containing works whose area and sector

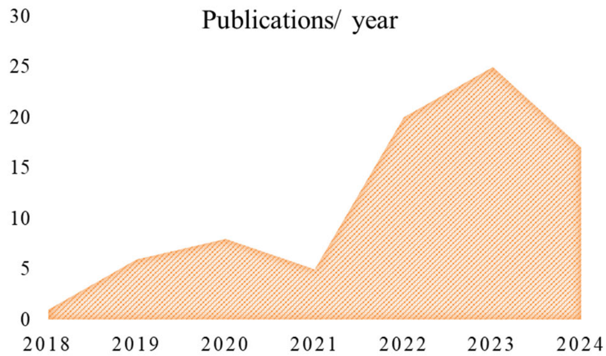


FIGURE 3. Annual publication considering the reviewed papers.

of application do not fit into the other categories. Figure 4 illustrates these categories according to their frequency in the analyzed works.

TABLE 1. Top 10 journal sources considering the reviewed papers.

Journals	Publications	[%]
IEEE Access	5	6,1%
IEEE Journal of Biomedical and Health Informatics	4	4,9%
IEEE Transactions on Industrial Informatics	3	3,7%
Cluster Computing	2	2,4%
Computers and Electrical Engineering	2	2,4%
IEEE Internet of Things Journal	2	2,4%
Journal of Industrial Information Integration	2	2,4%
Journal of Supercomputing	2	2,4%
Smart Health	2	2,4%
Wireless Personal Communications	2	2,4%
Others	56	68,3%

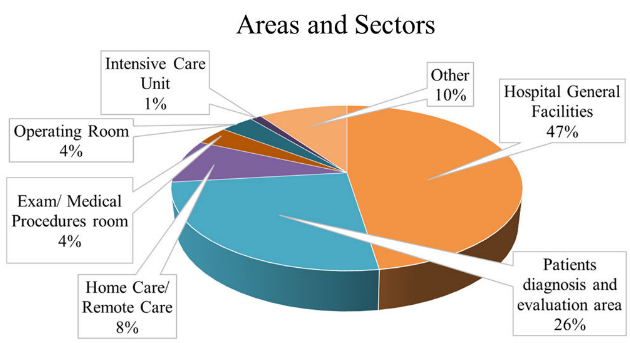


FIGURE 4. Pie chart of the main areas and sectors of the application.

The most present area/ sector was "Hospital General Facilities", present in around 47% of the works. In this case, it is noted that much of the work focused on generalist solutions that can be adopted in different hospital areas. The applications that stand out in this category refer to solutions, such as Blockchain, aimed at security and efficiency related to access and sharing of data, including data from patients, staff, and processes in the hospital environment [8], [17], [29], [39], [40], [41], [42], [43], [44], [45]. Other works presented different solutions that can be incorporated into several areas, such as robot skins [14], IoT devices [11], [46], cloud solutions [47], AI [48], among others. These and other tools and techniques will be explored in further sections.

The second most important area/ sector was the ''Patient diagnosis and evaluation area'', present in 26% of the works. In this case, we highlight that all papers that described applications involving disease diagnosis and patient monitoring and assessment were classified in this area. Several authors presented applications focused on patient monitoring in order to identify occurrences in advance [49], [50], [51]. Other works adopted advanced techniques, such as Machine Learning and Forecasting models to identify disease patterns and tendencies based on exams, historical data, etc. [52], [53].

The third most frequent area/ sector refers to ''Home care/ remote care'', which was present in 8% of the papers. In this case, these are applications focused on patient care outside hospital facilities. We highlight applications focused on patient monitoring through electronic devices such as smartphones [54] and other sensors and wearables [54], [55], as well as studies focused on telemedicine [56] and remote and secure patient access to healthcare systems [27].

The ''Exam/ medical procedure room'' and ''Operating room'' presented the same frequency in the analyzed works, about 4%. The first one refers to applications involving exams and related procedures and we highlight simulations focused on staff training [57], as well as exams [58] and specific medication [59]. The second one refers to surgery-related activities, covering in-loco procedures [26] and telesurgery [60], [61]. Finally, just 1% of the publications addressed intensive care units and, in this case, the focus was the use of technologies to allow monitoring of infants. Finally, the ''Other'' category refers to works that did not fit any other category and, in this case, we highlight general purposes involving the evaluation of Healthcare 4.0 solutions, where it was not possible to define the predominant areas/ sector. The authors explored technical and economic aspects [62], private health systems strategies [63], public systems [64], among other contexts [9], [12], [65], [66], [67].

On the other hand, considering the analysis of the regions where the works were developed, our objective was to explore the different approaches considering different cultures and development degrees. In this case, although most of the works (about 43.9%) did not mention the region where the work was placed, we note that there is an emphasis on applications in Asia (34.1%), with developments in India [30], [52], [53], [61], [68], [69], [70], [71], Saudi Arabia [8], [13], [49], [72], China [56], [73], [74], [75], Pakistan [10], South Korea [17], and Malaysia [58]. The second most frequent region was Europe (about 11% of the publications), with works developed in the United Kingdom [43], [76], Italy [57], Germany [77], Greece [28], Spain [54], among others [78], [79], [80]. Both Africa and South America come in third, with about 3.7% of the publications. On the first continent, work in Nigeria [50], [62] and Egypt [12] stands out. On the second continent, work developed only in Brazil [26], [81], [82]. About 2.4% of the publications were developed in North America, only in the U.S. Finally, Oceania was present in one work (1.2%), with an application in Australia. Table 2 summarizes the sector/ area and the regions of the analyzed works.

C. DECISIONS OBJECTIVES

This section presents some findings related to RQ2 ''What were the objectives regarding decision-making?''.

In analyzing the objectives of decision-making supported by Healthcare 4.0 solutions, we observed considerable diversity across the reviewed articles. From these, we categorized the decision objectives into seven main groups.

TABLE 2. Health areas/sector and LOCATION on which the work is centered.

Papers	Area/ Sector	Location
[8], [13], [17], [29], [30], [69], [71], [74], [75], [83], [84], [85]	Hospital General Facilities	Asia
[28], [43], [78], [79], [80]		Europe
[81]		South America
[42]		North America
[32]		Oceania
[14], [16], [25], [39], [44], [45], [46], [47], [48], [86], [87], [88], [89], [90], [91], [92]		Did not Inform
[10], [13], [49], [52], [53], [68], [70], [72], [73]	Patient diagnostics and evaluation area	Asia
[77]		Europe
[50]		Africa
[93]		North America
[51], [94], [95], [96], [97], [98], [99], [100], [101]		Did not Inform
[27], [56]	Home Care/ Remote Care	Asia
[54], [76]		Europe
[82]		South America
[15], [55]		Did not Inform
[58]	Exam/ Medical Procedures room	Asia
[57]		Europe
[59]		Did not Inform
[61]	Operating Room	Asia
[26]		South America
[60]		Did not Inform
[31]	Intensive Care Unit	
[9], [64], [65]	Other	Asia
[12], [62]		Africa
[63], [66], [67]		Did not Inform

The defined groups of decision objectives were: (i) Data Exchange, considering applications whose objective was to ensure the safe and effective sharing of data related to patients and the operation of healthcare systems; (ii) Diagnosis, based on applications aimed at improving the ability to diagnose diseases; (iii) Patient Monitoring, involving collecting patient data and monitoring them in real/near real-time; (iv) Care Activities Supporting, related to the adoption of solutions aimed at assisting in patient care activities such as medication, exams, procedures, etc.; (v) Operational Management, addressing operational decisions such as resource management and activities planning; (vi) Staff training, based on work whose objective was to train and qualify professionals and people involved in health-related activities; and (vii) Other, which include applications not falling into any of the previous categories. Figure 5 illustrates the distribution of articles across these categories, showing the proportion associated with each domain.

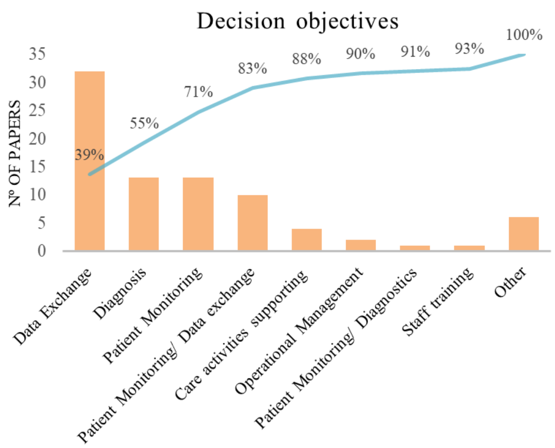


FIGURE 5. **Pareto chart of the main decision objectives.**

Data Exchange accounts for the majority of publications objectives, representing approximately 39% of the total. In this case, the main purpose is to guarantee that all data involved in the health activities might be recorded and shared safely. To this end, several authors suggest solutions that are based on access and registration protocols and paths aimed at greater security [8], [16], [41], [44] and performance [11], [60], [61] in sharing and exchanging sensitive data about patients, employees and operations of hospitals, clinics, etc.

Diagnosis and Patient Monitoring categories represent 15.9% of publications each. Considering Diagnosis, we found papers that adopted Healthcare 4.0 solutions to improve the disease diagnosis capacity, focusing on faster and more efficient treatment based on a more assertive diagnosis. In this way, most of the works aimed to evaluate patient data to predict the occurrence and evolution of muscular [68], cardiac [72], brain [53], [95], among other diseases [58], [70], [93], [97], [100]. On the other hand, Patient Monitoring contains several works focused on evaluating patients over time, aiming to better assist them. In this case, we observed few papers focused on patient monitoring in specific hospital areas, such as the intensive unit [31] and operating room [26], while the most of papers aimed at monitoring patients both in various hospital areas and in other locations (outside health facilities) [25], [49], [50], [82], [96], [98].

The fourth most frequent category (about 12.2%) combines two decision objectives: Patient Monitoring and Data Exchange. In this case, we did not identify a dominant objective, that is, the works focused on exchanging and sharing data with a specific focus on applications involving patient monitoring. Most of them are based on the use of the Internet of Medical Things (IoMT) and other support techniques for data analysis to support the collection of patients' data and their monitoring over time considering key health indicators [40], [46], [48], [92]. We also highlight that objective also collaborates to more efficient operational decisions regarding resource allocation, task planning, and collaboration between several hospital areas [79], [81].

Care activities supporting is a category that includes the use of Healthcare 4.0 solutions to support different care activities, such as medication administration, general treatment, home human-robot collaboration through remote health workers, etc. In this case, we observe applications in health facilities [14], [56], [77] and home care [15]. This category represents 4.9% of the reviewed papers. Operational Management was the sixth most frequent decision objective and it contains both specific fields, such as resource allocation and activities scheduling [12] and general fields, where the focus was to improve decisions in the health supply chain [13].

The seventh and eighth categories are present in around 1.2% of the papers each. One of them is a combination of two categories (Patient Monitoring and Diagnosis). In this case, it was also not possible to identify a predominant objective and the focus was to monitor patients to predict diseases and facilitate the early diagnosis [52]. On the other hand, the eighth category refers to Staff Training and, in this way, solutions and technologies were adopted to support health staff training through simulations and immersive experiences [57].

Finally, the "Other" category was considered since some works did not fit any other ones. In this context, we identified applications focused on describing several Healthcare 4.0 solutions and technologies, as well as their applicability, advantages, and limitations [62], [64], [66], [78]. We also highlight some works focused on improving technologies, solutions, and devices of Industry 4.0 to adapt them to a health context [13], [59].

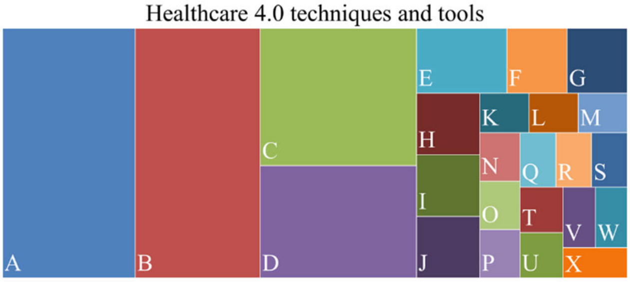
D. HEALTHCARE TECHNIQUES AND TOOLS

This section is dedicated to answering RQ3 "What techniques and tools were adopted/proposed?".

To guide the analysis of tools and techniques, we categorized the works according to the Industry 4.0 pillars. In this way, all the papers were evaluated and whenever possible, which of the pillars that have adopted or discussed by the authors were highlighted. The pillars observed were: (i) AI; (ii) IoT; (iii) CPS; (iv) Blockchain; (v) Cloud; (vi) Robot; (vii) Simulation; (viii) Virtual/ Augmented Reality; (ix) Big Data/ Data Mining; (x) and Others. Figure 6 presents the frequency at which each of the tools and techniques appears, where the area of each square represents its frequency. In other words, the larger the square area of a given tool/ technique, the more frequent it is in the works analyzed.

We can observe that most of the papers adopted or discussed AI, IoT, and Blockchain applications. In this way, AI applications (about 20.7%), we highlight some works that detailed the adopted techniques, such as Artificial Neural Networks [8], [13], [53], [58], Deep Learning techniques [91], [100], and classifiers such as K-NN, K-means and Decision Tree, and others [13], [52]. Other examples can be consulted in [9], [25], [49], [68], [72], and [95]. The objective of these works involved data analysis in identifying patterns and learning behaviors to support informed decisions.

Healthcare 4.0 techniques and tools



ID	Techniques and tools	[%]	ID	Techniques and tools	[%]
A	AI	20,7%	M	Cloud	1,2%
B	IoT	19,5%	N	Cloud, Blockchain, and AI	1,2%
C	Blockchain	13,4%	O	CPS	1,2%
D	AI and IoT	11,0%	P	CPS and Cloud	1,2%
E	Blockchain and AI	3,7%	Q	CPS and IoT	1,2%
F	AI and CPS	2,4%	R	CPS, IoT, and AI	1,2%
G	Cloud and IoT	2,4%	S	IoT, AI, and Cloud	1,2%
H	IoT and Blockchain	2,4%	T	IoT, AI, and Blockchain	1,2%
I	Robot	2,4%	U	IoT, AI, and VR/AR	1,2%
J	Big Data/ Data Mining	2,4%	V	Robot and CPS	1,2%
K	AI and Cloud	1,2%	W	Robot and IoT	1,2%
L	AI, CPS and Robot	1,2%	X	Simulation	1,2%

FIGURE 6. **Techniques and tools observed in the analyzed papers.**

Regarding IoT applications (about 29.5% of the works), objectives related to patient monitoring and data collection stood out, including the use of sensors and wearables to capture and share data from patients and hospital facilities. Some of these works are [12], [40], [50], [55], [57], [82], [84], [92], [94]. Finally, Blockchain applications come in third (13.4%) of the applications. In this case, we note several works that aim to guarantee security, privacy, and performance in data exchange, including protocols and encryptions for access to hospital management systems and, consequently, patient, staff and operational history data [17], [32], [41], [42], [43], [46], [63], [69].

Other Healthcare 4.0 were also present in the analyzed papers, such as Robot (2.4% of the papers), Cloud (1.2%), CPS (1.2%), simulation (1.2%), and Bid Data/ Data Mining (2.4%). Robot applications were related to collaborative [56] and skin [14] robots, which aim to propose solutions to support care activities through automated and autonomous robots. Cloud examples [47] focused on data storage and processing without physical structures, while CPS [77] and Simulation [59] involved the use of computational resources to virtualize the systems and mirror the behavior to evaluate scenarios and support more efficient decisions. It is important to highlight that CPS is usually associated with Digital Twins models, a virtual copy that can capture the physical behaviors in near/ real-time, as discussed by [77]. Finally, Big Data/ Data Mining [78], [80] was explored to support data analysis, including Business Intelligence (BI) and decision-support dashboard applications, as well as protocols to guarantee data quality.

The rest of the articles were organized into "hybrid" categories since it was not possible to identify a major tool/technique. AI and IoT were adopted together by 11% of the papers, focusing on exploring both techniques to allow data collection and further processing with advanced techniques [16], [48], [51], [73], [74], [79], [93], [99]. About 3.7% of the analyzed papers discussed the integration of Blockchain and AI to allow more efficient and safe systems [29], [45], [90]. Other three hybrid approaches were present in about 2.4% of the papers each. In this case, IoT and Blockchain [11], [71], and Cloud and IoT [54], [85] were adopted to optimize the security related to data exchange and improve health-related data collection, respectively, while AI and CPS were explored to enhance the virtualization of the health systems.

With 1.2% of the papers each, we highlight other hybrid approaches, such as AI and Cloud [39], AI, CPS and Robot [66], Cloud, Blockchain and AI [88], CPS and Cloud [75], CPS and IoT [76], CPS, IoT and AI [98], IoT, AI and Cloud [97], IoT, AI and Blockchain [60], IoT, AI and VR/AR [31], Robot and CPS [15], and Robot and IoT [61]. Finally, we highlight that the "Other" category was adopted since we did not identify any of the Healthcare pillars and, in this case, we have technical & economic analysis and evaluation of Healthcare 4.0 implementation [62], [64].

E. ADVANTAGES, CHALLENGES, AND OPEN ISSUES

The RQ4 "What are the advantages, open issues, and challenges in future research paths for Healthcare 4.0 applications?" will be explored in this section.

The use of advanced solutions such as IoT, AI, and Digital Twin in healthcare offers a range of unprecedented advantages for the sector, such as improved efficiency and quality in diagnostics. This enables faster and more accurate diagnostics and continuous monitoring, in addition to data security that ensures the integrity of patient information and confidentiality. However, challenges remain, such as higher data privacy and security, implementation complexity, and scalability. In the future, advances are expected in digital twins and personalized medicine, integration with AI and IoT, and algorithm optimization to reduce costs and latency in diagnostics. These and other aspects are presented in Table 3.

V. FINAL DISCUSSIONS

Unlike other literature reviews in this field, this work addresses different research questions and applies distinct search criteria. For example, Tlapa et al. [18] focused on Lean interventions in the Healthcare 4.0 context, while

TABLE 3. Main findings related to the use of emerging Healthcare Technologies.

Features	Findings
Advantages	• IoT, AI, and digital twins enable more accurate and faster diagnostics, as well as preventive interventions [13], [25], [70], [76], [87], [98]. • Blockchain and biometrics for electronic records ensure data integrity and confidentiality [30], [40], [63], [73], [83], [90]. • The use of digital twins and personalized medicine adapts treatment and supports decision-making [25], [77], [85]. • IoT technologies and non-intrusive sensors enable vital sign monitoring [76], [98]. • Adoption of IoT and blockchain for tracking and optimizing supply chains [13], [49]. • Predictive algorithms and automation improve resource usage and operational and energy efficiency [39], [58], [71], [72], [84], [96]. • Blockchain and data networks allow the secure sharing of health records across different systems [30], [90]. • Predictive technologies help anticipate health issues and reduce the impact of diseases [68], [101]. • Wireless body networks improve the reliability of captured data for health monitoring [91], [94]. • Advanced algorithms increase the accuracy of medical data and reduce measurement and calculation errors [44], [87].
Issues	• Privacy in IoT and blockchain environments due to the need to secure sensitive data [13], [39], [47], [63], [73], [90]. • Digital twins and blockchain require high investments, in addition to resistance to change and technical challenges [41], [49], [69], [78], [79]. • Large-scale IoT and WBANs face issues with latency, cost, and computational capacity [39], [63], [72], [89], [91]. • Devices with limitations in accuracy and durability complicate continuous and non-invasive monitoring [55], [98]. • Integrating multiple health data systems faces consistency and compatibility barriers [70], [89]. • Extensive training for healthcare professionals, which can be costly and time-consuming [57]. • Continuous data updating to ensure accuracy in diagnosis and monitoring is complex [8].
Opportunities	• Integrations between AI and IoT for faster diagnostics and more secure, interpretable systems [11], [13], [49]. • Digital twins can be developed for accurate diagnostics and customized treatments [25], [76], [77], [98]. • Encryption algorithms, deep learning, and process optimization will reduce response time [58], [87], [100]. • Blockchain for telesurgery and secure sharing of health records is a promising model [29], [60]. • Data collection and processing technologies can lead to more integrated healthcare systems [45], [64], [66]. • More precise sensors and advanced algorithms will enable continuous and non-intrusive monitoring [55], [76], [98]. • Automation in diagnostics and interventions is expected to evolve towards machine learning models [45]. • Technologies adapted for different geographic, cultural, and institutional contexts [62]. • IoT devices with greater energy efficiency, meeting the needs of energy-constrained networks [89]. • Wireless body area networks will be expanded to monitor patients' health outside hospitals [91], [94]. • Hospital wait time data analysis will allow for the creation of more efficient allocation models [82]. • Technologies to improve data resilience and redundancy aim to reduce failures in healthcare environments [11], [69].

Mwanza et al. [6] prioritized Healthcare 4.0 applications in low- and middle-income economies. Consequently, they employed different search mechanisms, leading to some differences in their results compared to the present work. However, it is possible to analyze their findings and identify both similarities and differences.

Mwanza et al. [6] stated that limited funding and inadequate infrastructure might hinder Healthcare 4.0 adoption in low- and middle-income economies. We argue that this challenge extends to all economies, including developed regions. In these cases, the resistance to adopting new technologies, due to uncertainty about outcomes and the high investment required, can limit resources for transforming healthcare facilities. On the other hand, both Mwanza et al. [6] and Tlapa et al. [18] highlighted that Healthcare 4.0 solutions can significantly enhance healthcare system performance, which aligns with our findings. Therefore, despite the challenges in adopting Healthcare 4.0, it is crucial to demonstrate its benefits through real case studies, and we suggest further research exploring the effort-versus-benefit analysis.

Ahsan and Siddique [19] and Tortorella et al. [20] conducted more comprehensive literature reviews, similar to this work. Ahsan and Siddique [19] analyzed 47 papers published up to 2021, examining applications, challenges, and potential future developments, while Tortorella et al. [20] reviewed 78 papers published until 2019, focusing on information technologies in healthcare systems, as well as related challenges, barriers, and contributions. A key difference between their studies lies in publication regions. Tortorella et al. [20] highlighted North America (mainly

Canada), while Ahsan and Siddique [19] emphasized Europe (particularly Italy and the U.K.). In contrast, our study reveals that Asia has gained prominence in recent years, with increasing publications from India, Saudi Arabia, and China, regions experiencing rapid development.

Regarding the benefits of Healthcare 4.0 implementation, our results align with those of Tortorella et al. [20], particularly in process transparency, online applications, and performance improvement. However, while Tortorella et al. [20] emphasized cost reduction, we highlight the need for studies that demonstrate this aspect. Based on the evaluated papers, it is unclear whether all investments in Healthcare 4.0 necessarily lead to cost reductions or financial viability. Tortorella et al. [20] also identified regulatory challenges, high investment costs, and a shortage of skilled professionals as key barriers. Although regulatory challenges were not explicitly mentioned in the analyzed papers, we emphasize that healthcare systems operate under strict regulations that must evolve alongside new technological solutions.

Finally, Ahsan and Siddique [19] discussed several tools and solutions, including AI for data analysis and disease diagnosis, blockchain for data exchange, and IoT for operational management. While our findings align with theirs, we note that in recent years, other technologies have gained prominence, particularly automated solutions such as robots and system virtualization through cyber-physical systems (CPS), simulation models, and VR/AR applications.

VI. CONCLUSION AND FUTURE DIRECTIONS

With the advent of Industry 4.0, technological solutions are becoming increasingly accessible and surpassing the limits of manufacturing systems, also impacting service and healthcare environments. In this case, we highlight Healthcare 4.0 as a revolution of health systems, allowing more efficient decisions considering the adoption of several Industry 4.0 pillars and technologies, such as IoT, Cloud, Big Data, Blockchain, Cyber-physical systems, among others. In this case, this paper focused on evaluating the adoption of Healthcare 4.0 solutions through a systematic literature review (SLR). The objective was to investigate the key characteristics highlighted in existing publications within this domain. A total of 82 peer-reviewed articles published in scientific journals and available in the main scientific databases were analyzed.

The articles reviewed highlight an underexplored and rapidly growing field. The works focused on several key areas, including "Hospital General Facilities", "Patient diagnosis and evaluation", "Home care/remote care", "Exam/medical procedure room", "Operating room", and "ICU applications". The Hospital General Facilities sector dominated, emphasizing generalist solutions like Blockchain for secure data sharing and IoT, AI, and cloud technologies. The other sectors adopted several Healthcare 4.0 tools to improve disease monitoring and diagnosis, as well as allow advancements in telemedicine, staff training, exams, and surgical procedures. Moreover, it is important to highlight that most studies lacked regional data, but Asia led, followed by Europe, Africa, South America, North America, and Oceania.

On the other hand, considering the objectives of the decisions, "Data Exchange" dominates, focusing on secure sharing of sensitive data using protocols for improved security and performance. "Diagnosis" and "Patient Monitoring" targets disease prediction, patient evaluation, and monitoring inside and outside hospitals. The combination of "Patient Monitoring" and "Data Exchange" emphasize IoT and data analysis for better patient care and operational decisions. "Care Activities Supporting" involves solutions for treatments and home care, while "Operational Management" focuses on resource allocation and scheduling. Categories combining "Patient Monitoring" with "Diagnosis" and "Staff Training" explore early diagnosis and immersive training.

Considering the techniques and tools adopted by the authors, AI, IoT, and Blockchain were the most discussed technologies, focusing on data analysis, patient monitoring, and secure data exchange. AI works use techniques like Neural Networks and Deep Learning, while IoT emphasizes sensors and wearables. Blockchain ensures security and privacy in data management. Robots, Cloud, CPS, Simulation, and Big Data are less frequent but contribute to automation, data processing, and system virtualization. Finally, hybrid approaches integrate multiple technologies, such as AI and IoT, or Blockchain and AI, enhancing data collection, security, and system efficiency.

The analysis of the results, guided by the identification of advantages, challenges, and open issues in the future research paths for Healthcare 4.0 applications, highlights a comprehensive overview of the implications of emerging technologies in the healthcare sector. The identified advantages include significant improvements in diagnostic efficiency and quality, enabled by IoT technologies, artificial intelligence, and digital twins, which facilitate faster and more accurate diagnostics, promote preventive interventions, and provide personalized decision-making support. Additionally, solutions such as blockchain and biometrics reinforce the confidentiality and integrity of patient data, while non-intrusive sensors and IoT device networks expand continuous health monitoring capabilities.

However, critical challenges remain to be addressed. Among them are data privacy and security, high implementation costs, and the difficulties of integrating diverse health data systems. Technical barriers are also evident, such as the limited computational capacity of IoT networks and the continuous need to update data to ensure diagnostic reliability. Another relevant point is the resistance to adopting new technologies by healthcare institutions and professionals.

Regarding future perspectives, this review identifies several promising opportunities. These include the development of deep learning algorithms and process optimization aimed at reducing latency and costs. Furthermore, there is an expectation of increased integration between artificial intelligence and IoT, as well as advances in the use of digital twins for personalized diagnostics. Another promising outlook is the development of technologies that are more adaptable to different cultural and institutional contexts, with the goal of democratizing access to healthcare innovations.

Finally, it is worth highlighting that, despite the transformative potential of Healthcare 4.0, the identified challenges underscore the need for a multidisciplinary and comprehensive research agenda. This agenda should emphasize overcoming practical and ethical barriers while seeking to maximize the social and economic benefits of these technologies.

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