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Facilitating Decision-Making for the Adoption of IoT Technologies in the Healthcare Sector

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Sciences de la gestion
(Spécialisation Global Supply Chain Management)

Mémoire présenté en vue de l'obtention
du grade de maîtrise ès sciences en gestion
(M. Sc.)

Octobre 2024

HEC MONTRĒAL

Comité d'éthique de la recherche

CERTIFICATE OF ETHICS APPROVAL

This is to confirm that the research project described below has been evaluated in accordance with ethical conduct for research involving human subjects, and that it meets the requirements of our policy on that subject.

Project No.: 2025-5737

Title of research project: Facilitating Decision-Making for the Adoption of IoT Technologies in Healthcare Sector: A Sustainable Approach

Principal investigator: Arzhang Khoshghalb

Date of project approval: July 02, 2024
Effective date of certificate: July 02, 2024
Expiry date of certificate: July 01, 2025

Maurice Lemelin
Président
CER de HEC Montréal

Signé le 2024-07-03 à 08:53

Résumé

Le secteur de la santé a été confronté à de nombreux défis, notamment des pressions sociales et économiques, aggravées par une demande croissante et un vieillissement de la population. Les hôpitaux intelligents adoptent des technologies de pointe qui ont le potentiel de révolutionner les services de santé. L'Internet des objets de la santé (IoHT) est l'une de ces innovations, jouant un rôle clé dans la refonte du système médical pour offrir des services plus efficaces, pratiques et personnalisés.

Pour adopter avec succès de nouvelles applications IoHT, les hôpitaux doivent élaborer une stratégie de transition précise, dont la première étape consiste à identifier quelles technologies sont les plus appropriées. Par conséquent, deux aspects principaux doivent être pris en compte : (1) l'impact potentiel de ces technologies sur les critères d'amélioration de la performance et (2) le degré de préparation nécessaire à l'adoption de l'IoHT.

Cette recherche vise d'abord à offrir une revue complète des différentes applications IoT adaptables dans les hôpitaux. Ensuite, nous concevons un outil d'aide à la décision pour prioriser ces applications en fonction de deux ensembles de critères : attractivité et la préparation requise. À cet égard, un cadre de prise de décision multicritères à deux niveaux a été adopté. Dans la première étape, nous avons déterminé les différents poids des critères et sous-critères à l'aide de la méthode AHP et des avis d'experts. Ensuite, différentes applications IoHT ont été classées en fonction de ces critères à l'aide de la méthode TOPSIS et des avis d'experts.

Ce cadre est adaptable aux hôpitaux de divers pays, en tenant compte des besoins spécifiques, des préférences, des capacités technologiques et des structures organisationnelles propres à chaque système de santé. Dans cette étude, cependant, le cadre a été appliqué spécifiquement aux hôpitaux iraniens. Les résultats mettent en lumière les domaines prioritaires pour les applications IoHT dans ce contexte, offrant des informations précieuses sur les préférences locales. Cette recherche fournit aux décideurs une meilleure compréhension des investissements à réaliser dans les nouvelles technologies, dans le but d'améliorer la durabilité et de répondre aux critères de préparation nécessaires.

Mots clés: Internet des Objets de la Santé, Internet des Objets Médicaux, Hôpital Intelligent, Attractivité, Préparation, Processus Hiérarchique Analytique (AHP), Technique pour l'Ordre de Préférence par Similarité à la Solution Idéale (TOPSIS).

Méthodes de recherche: Prise de Décision Multicritère (MCDM), AHP, TOPSIS, Enquête, Questionnaire, Revue de la littérature.

Abstract

The healthcare sector has faced numerous challenges, including social and economic pressures, further exacerbated by rising demand and an aging population. Smart hospitals embrace cutting-edge technologies that have the potential to revolutionize healthcare services. The Internet of Health Things (IoHT) is one of these innovations, playing a pivotal role in reshaping the medical system to deliver more efficient, convenient, and personalized services.

To successfully adopt new IoHT applications, hospitals must develop a precise transition strategy, and the first step is to identify which technologies are the most appropriate. Consequently, two main aspects must be addressed: (1) the potential impact of these technologies on performance improvement and (2) the degree of readiness required for IoHT adoption.

This research aims first to offer a comprehensive review of different IoT applications suitable for hospitals. Then, we design a decision support tool to prioritize these applications based on two sets of criteria: attractiveness and required readiness. In this regard, a two-level Multi-Criteria Decision-Making framework has been adopted. In the first step, we determined different weights of criteria and sub-criteria using the AHP method and experts' opinions. Then, different IoHT applications were ranked based on those criteria using the TOPSIS method and experts' opinions.

This framework is adaptable to hospitals across various countries regardless of location, irrespective of their private or public sector status. In this study, however, we have focused on applying the framework specifically within the context of Iran as a case study. The findings highlight the priority areas for IoHT applications in this context, offering valuable insights into local preferences. This research equips decision-makers with a clearer understanding of where to invest in new technologies, with the dual goal of enhancing performance and meeting required readiness criteria.

Keywords: Internet of Health Things, Medical Internet of Things, Smart Hospital, Attractiveness, Readiness, Analytical Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

Research methods: Multi-criteria Decision-Making (MCDM), AHP, TOPSIS, Survey, Questionnaire, Literature review.

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List of Abbreviations and Acronyms

ADR: Adverse Drug Reaction

AHP: Analytic Hierarchy Process

AI: Artificial Intelligence

BDA: Big Data Analytics

C.I: Consistency Index

CPS: Cyber-Physical System

C.R.: Consistency Ratio

DT: Digital Twin

ECG: Electrocardiogram

EHR: Electronic Health Record

EWS: Early Warning System

I4.0: Industry 4.0

IoT: Internet of Things

IoHT: Internet of Health Things

IoMT: Internet of Medical Things

MCDM: Multi-Criteria Decision-Making

MIoT: Medical Internet of Things

NFC: Near Field Communication

R.I.: Random Index

SCOT: Smart Cyber Operating Theater

TOPSIS: Technique for Order of Preference by Similarity to the Ideal Solution

VMS: Visitor Management System

VSMS: Vital Signs Monitoring System

WSN: Wireless Sensor Network

Acknowledgments

This thesis would not have been possible without the help and support of many amazing people.

First and foremost, I would like to express my sincere gratitude to my co-supervisors, Martin Cousineau and Valérie Bélanger. Your unwavering support and guidance throughout this journey have been invaluable. I am incredibly thankful for your patience, availability, and insightful advice at every stage of this research.

I am also grateful to HEC Montréal and the International Observatory on the Societal Impacts of AI and Digital Technologies (OBVIA) for their generous support, which made this research possible.

A massive thank you goes out to my family and friends, who have played a huge role in helping me finish this work, whether directly or indirectly. To my wife, parents, and brothers, your constant love, encouragement, support, and belief in me have kept me going. To my amazing friends -Rohollah, Hamoon, Haimd, Pedram, Mohammad, Shahab, Kaveh, Jai, and Trung- I could not have done this without you!

General Introduction

The Internet of Things (IoT) has significantly affected many sectors, including energy, manufacturing, finance, supply chain and logistics, agriculture, and health (Abbasi et al., 2022; Hossein Motlagh et al., 2020; Kalsoom et al., 2021; Kashani et al., 2021; Nižetić et al., 2020; Rebelo et al., 2022). IoT is a network of connected devices that autonomously or with limited human intervention can send, receive, and monitor data using Internet protocols (Manavalan & Jayakrishna, 2019; Rejeb et al., 2023). At its simplest level, IoT connects physical devices like mobile phones, wearables, vehicles, and homes with technologies such as Radio Frequency Identification (RFID), wireless sensors, detectors, and mobile apps. At a more advanced level, these devices are integrated with other disruptive technologies, such as Artificial Intelligence (AI), digital twins, cyber-physical systems, Big Data Analytics (BDA), cloud computing, etc. (Farahani et al., 2020; Hsu & Lin, 2018).

This combination can generate a considerable amount of precise and real-time data, helps businesses improve their performance, visibility, traceability, and transparency, and makes decision-making faster, easier, and more precise (Ben-Daya et al., 2019; C. Chauhan et al., 2021; Li et al., 2023; Nižetić et al., 2020). Adopting IoT can offer different benefits depending on situations and sectors, with its most important one being the potential to gain a competitive advantage (Klisenko & Serral Asensio, 2022; Pino et al., 2024b).

While many industries are trying to implement these new technologies, healthcare ranks as the third largest sector in the global IoT market after automotive and consumer IoT. The number of IoT devices in healthcare is predicted to double, reaching a remarkable 2.8 billion (*Internet of Things: market data & analysis*, 2023). Hospitals are one of the most critical service points in the healthcare sector, and they are supposed to provide timely treatment with limited resources. Some medical services in hospitals are vital, such as timely and precise diagnosis and treatment, and any mistakes or delays can directly harm patients and result in serious, sometimes detrimental, and irrecoverable consequences (Fischer et al., 2020; Han et al., 2023; Rodrigues et al., 2022). In addition, many hospitals are struggling with budget deficits, compelling them to enhance their cost efficiency without compromising the quality of their services (Pereno & Eriksson, 2020).

As a solution, they primarily focus on adopting new technologies to enhance their competitiveness and create a sustainable healthcare system (Sony et al., 2023). These technologies could offer favorable opportunities, including operational cost saving, process time reduction, and improving privacy and security for all stakeholders in the hospitals (Li et al., 2023; Tortorella, Fogliatto, Espôsto, et al., 2022). Rajaei et al. (2024) explored numerous emerging technologies applicable to a smart hospital, such as BDA, AI, blockchain, and IoT. They highlighted that the IoT ranked as the most frequent technology from both academic and industrial perspectives (Kanokphanvanich et al., 2023; Rajaei et al., 2023).

However, many IoT applications are still in their early stages, and firms are still unaware of their advantages and risks. Additionally, there is uncertainty about how to implement them effectively (Benotmane et al., 2023; Nižetić et al., 2020). Considering these challenges, firms should carefully assess their IoT adoption strategy from different points of view. It is crucial for firms to evaluate their current situation, carefully examine the various IoT alternatives, identify each's benefits requirements, and accordingly assess the gap (Lee & Lee, 2015; Pino et al., 2024a).

The IoHT devices, applications, and technologies apply to medical processes such as health condition monitoring, smart rooms, etc., and also to non-medical operational processes such as environmental condition monitoring, waste management, inventory management, etc. (Han et al., 2023; Mohamad Jawad et al., 2022; Rodrigues et al., 2022; Tortorella, Fogliatto, Sunder M, et al., 2022). Also, they could be categorized based on the location of the application, including in-home healthcare, outdoor, on-body, in-hospital, and clinical (Huang et al., 2023). In addition, IoHT applications could be categorized considering healthcare stakeholders: applications for medical service providers, nurses, practitioners, laboratory service providers, regular in/out patients, ambient assisted living, people with disabilities, maternity care, children monitoring, personalized medical applications, and applications for emergencies (Aghdam et al., 2021; Almotairi, 2023; Krishnamoorthy et al., 2023). However, given the vastness of the healthcare sector, this research will focus on the application layer of the IoT architecture within the hospital domain, which can be utilized for both medical and non-medical operational processes, such as patient tracking and monitoring, smart building, and inventory management.

The criteria selection plays a vital role in the analysis of technology adoption and will help organizations make precise decisions about which technologies to adopt, considering their capabilities and the expected results (Hsu & Yeh, 2017; Kamal et al., 2020). It also helps them wisely optimize their investments and take advantage of maximizing the benefits of the selected technology while minimizing risks (Kazemargi & Spagnoletti, 2020; Parra & Guerrero, 2020; Parra et al., 2021). To address this concern, we identify the most appropriate medical and non-medical IoT applications adaptable to hospitals. Next, we propose a framework to assess and prioritize the IoHT alternatives based on two sets of criteria: attractiveness and readiness. The attractiveness criteria consider aspects that help improve an organization's performance, such as cost savings and quality of services; on the other hand, readiness attributes consider the organizations' current capabilities, strengths, and weaknesses to adopt applications, such as required investments, technological infrastructures, expertise, and skill sets.

This research will use different methodologies, mainly Multi-Criteria Decision-Making (MCDM) techniques, for each step. We conduct a comprehensive and detailed literature review to identify the most important and relevant criteria for the healthcare sector. To collect the necessary data, we design a questionnaire and conduct a survey with a panel of experts from Tehran University of Medical Sciences (TUMS). TUMS, which comprises 11 faculties, 16 teaching hospitals, and over 100 research centers, offers an extensive network of professionals ideal for our study. After collecting experts' opinions, the Analytic Hierarchy Process (AHP) is adopted to assign different weights to decision criteria because (sub)criteria might have different importance compared to each other. Also, to identify the appropriate IoT applications, we conduct a literature review. Then, we adopt the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) method to rank the alternatives.

The remainder of this research is organized as follows: The next chapter will present our study in the format of a scientific article. This includes an introduction that provides an overview of IoT in healthcare and highlights the significance of this research. The research methodology section details the literature review process, discusses the background of the AHP and TOPSIS methods, and outlines the steps of our survey. The third section presents the results of the literature review on two key concepts. It outlines various IoT applications in the healthcare sector and details the associated attractiveness and readiness criteria and sub-criteria. Following this, we present the experimental results and discuss their implications for our case study. The research concludes with a comprehensive summary of the findings.

Chapter 1: Facilitating Decision-Making for the Adoption of IoT Technologies in the Healthcare Sector

Abstract

The healthcare sector has faced numerous challenges, including social and economic factors, further exacerbated by rising demand and an aging population. Smart hospitals, which utilize advanced technologies, could be a game-changer in improving healthcare services. The Internet of Health Things (IoHT) is at the core of these innovations, playing a crucial role in reshaping the medical system to deliver more efficient, convenient, and personalized health services.

To successfully adopt new Internet of Things (IoT) applications, hospitals must develop a precise transition strategy, and the first step is to identify which technologies are the most appropriate. Consequently, two main aspects must be addressed: (1) whether hospitals are ready to adopt these applications and (2) whether these applications are beneficial enough for the hospitals. While the literature contains models for new technology adoption, there is a gap in a comprehensive IoT adoption framework for hospitals considering medical and non-medical alternatives.

This research aims first to offer a thorough review of different IoT applications suitable for hospitals. We propose a decision support tool to prioritize these applications based on two sets of criteria: performance improvement and required readiness. In this regard, a two-level Multi-Criteria Decision-Making framework has been adopted. In the first step, we determined different weights of criteria and sub-criteria using the Analytical Hierarchy Process (AHP) method and experts' opinions. Then, different IoT alternatives were ranked based on those criteria using the (Technique for Order of Preference by Similarity to the Ideal Solution) TOPSIS method and experts' opinions.

This framework is suitable for implementation in hospitals globally, regardless of their location or whether they are in the private or public sector. However, in this study, we have specifically applied the framework within the context of Iran, using it as a case study. The results could clarify the preference and high-priority areas for IoHT applications in

Iranian hospitals. This research provides insights for decision-makers to make the best choices when investing in new technologies, enabling them to improve their performance while meeting the required readiness criteria.

Keywords: *Internet of Health Things, Medical Internet of Things, Attractiveness, Readiness, Technology Adoption, AHP, TOPSIS*

1.1 Introduction

The Internet of Things (IoT) has helped many fields, such as energy, finance, manufacturing, supply chain and logistics, agriculture, health, etc., achieve considerable progress in both academia and industry (Abbasi et al., 2022; Hossein Motlagh et al., 2020; Kalsoom et al., 2021; Kashani et al., 2021; Nižetić et al., 2020; Rebelo et al., 2022). This technology could be defined as an interconnected and interlinked network of devices capable of sending and receiving data and monitoring their environment autonomously without the help of humans, using just the internet protocol (Manavalan & Jayakrishna, 2019; Rejeb et al., 2023). In its basic forms, IoT integrates physical devices such as mobiles, wearable devices, vehicles, homes, etc., with technologies such as RFIDs, wireless/remote sensors, detectors, mobile apps, etc. In a more advanced level of IoT adoption, these hardware and software devices are merged with artificial intelligence (AI), cloud computing, Big Data analytics (BDA), Digital Twin (DT), Cyber-Physical Systems (CPSs), etc., to facilitate connecting, exchanging, analyzing, and monitoring data independently (Farahani et al., 2020; Hsu & Lin, 2018).

The advancements of these technologies have led to new opportunities, enhancing the efficiency and quality of services and production processes. They can generate a significant amount of precise and real-time data for businesses, help to improve their performance, visibility, traceability, and transparency, and make the decision-making process faster, easier, and more precise (Ben-Daya et al., 2019; C. Chauhan et al., 2021; Li et al., 2023; Nižetić et al., 2020). These advantages obtained from the IoT adoption may differ according to the situation and industry; however, it is widely agreed IoT will provide competitive advantages (Klisenko & Serral Asensio, 2022; Pino et al., 2024b).

Although several industries are investing in these intelligent technologies, healthcare stands out as the third largest market within the global IoT market after automotive and consumer IoT. It is projected that the quantity of IoT connections in healthcare will experience a twofold increase, from 1.4 billion to an impressive 2.8 billion (*Internet of Things: market data & analysis*, 2023). Habibzadeh et al. (2019) believe a strong relationship exists between technological advancements and IoT adoption in healthcare systems (Habibzadeh et al., 2019). In addition, the recent pandemic has accelerated the adoption of those technologies, helping healthcare systems to provide services remotely in a cost-effective, personalized, and proactive manner (Bhatia & Diaz-Elsayed, 2023).

Hospitals are one of the most important service points in the healthcare sector, responsible for providing appropriate and prompt treatment within limited resources; however, facing many serious challenges (Fischer et al., 2020; Han et al., 2023). Some medical processes in hospitals are vital, and any faults or delays in managing such processes may directly affect patients' situations and result in detrimental and irretrievable consequences (Rodrigues et al., 2022). On the other hand, many hospitals are struggling with budget deficits, compelling them to enhance their cost efficiency without compromising the quality of their services (Pereno & Eriksson, 2020). In the 2023 fiscal year, hospitals in Ottawa, Canada, faced $65 million in deficits (Payne, 2024), and a similar situation happened for the Québec government with a new healthcare providers' wage settlement (Battaglia, 2024). Moreover, with the ever-increasing pressure of stakeholders, environmental regulatory limitations, and the challenges previously mentioned, hospitals need to implement sustainable approaches in their services to optimize the interests of all stakeholders (Rahat et al., 2024; Tushar et al., 2023; Zhu et al., 2018).

As a solution, they primarily focus on adopting new technologies to enhance their competitiveness and create a sustainable healthcare system (Sony et al., 2023). These technologies could offer favorable opportunities, including operational cost saving, process time reduction, and improving privacy and security for all stakeholders in the hospitals (Li et al., 2023; Tortorella, Fogliatto, Espôsto, et al., 2022). Rajaei et al. (2024) explored numerous emerging technologies applicable to a smart hospital, such as BDA, AI, blockchain, and the IoT. They highlighted that the Internet of Things ranked as the most frequent technology from both academic and industrial perspectives. (Kanokphanvanich et al., 2023; Rajaei et al., 2023).

The IoHT devices, applications, and technologies can be utilized for medical/clinical processes such as health condition monitoring, smart rooms, as well as for non-medical operational processes such as environmental condition monitoring, waste management, and inventory management (Han et al., 2023; Mohamad Jawad et al., 2022; Rodrigues et al., 2022; Tortorella, Fogliatto, Sunder M, et al., 2022). Also, they could be categorized based on the location of the application, including in-home healthcare, outdoor, on-body, in-hospital, and clinical (Huang et al., 2023). In another study, Tortorella et al. (2021) divided these digital applications into four categories based on hospitals' value chains: applications for hospitals' supply chains, diagnosis, treatment, and follow-up. (Tortorella, Fogliatto, Sunder M, et al., 2022). In addition, IoHT applications could be categorized considering healthcare stakeholders: applications for medical service providers, nurses, practitioners, laboratory service providers, regular in/out patients, ambient assisted living, people with disabilities, maternity care, children monitoring, personalized medical applications, and applications for emergencies (Aghdam et al., 2021; Almotairi, 2023; Krishnamoorthy et al., 2023).

Some studies, such as Li et al. (2023), have divided IoT applications in healthcare according to their IoT architecture layers. The first layer consists of sensors/detectors that detect and capture any changes in the monitored environment and act as a cornerstone in the IoT network, including patients' condition monitoring sensors, environmental condition sensors, and tracking sensors. The next layer is the communication or gateway layer, such as Wi-Fi, Bluetooth, Zigbee, 4G, 5G, RFID, etc., with the main functions of gathering, converting to the standard format, pre-processing, and transferring data from the sensors layer to the upper layer. The third layer is the cloud or processing layer, which includes centralized technologies, such as cloud computing, and distributed technologies, such as edge and fog computing, with more reliability and security. The cloud generally consists of web servers, databases, and interfaces for storing, managing, processing, and analyzing data. The highest layer of the IoHT architecture is known as the application layer, also known as the function, action, or business layer. The final outputs of this layer are charts, graphs, business models, and application-specific services that could facilitate the decision-making for the final users. This layer can integrate with other emerging technologies, such as AI, Ml, and BDA, to provide real-time, high-quality, more precise, and cost-efficient services and applications to address different needs within healthcare systems (Aghdam et al., 2021; Ahmed et al., 2024; Aman et al., 2021; Huang et al., 2023; Kashani et al., 2021; Li et al., 2023; Munir et al., 2022; Sadeghi & Mahmoudi, 2024).

Verma et al. (2023) analyze various aspects of IoHT, such as its network terminology and communication layer. They also discuss IoHT's services, applications, adoption issues, and security concerns and believe it can often be difficult to distinguish between a service, an application, or a solution. Additionally, they classify IoHT applications into two main categories: solo-condition and multi-condition applications depending on the number of parameters they could monitor. Using a comparative study, they outline the most significant services applicable to healthcare systems, including ambient assisted living, wearable healthcare solutions, adverse drug reactions, emergencies, etc. (Verma et al., 2023).

Calvillo-Arbizu et al. (2021) clarify the recent trends of IoHT through a comprehensive literature review. Their research investigates various services, applications, technologies, and challenges within the health domain and describes major requirements. They point out that Healthcare systems have unique needs that are distinct from other domains, such as industry, SMEs, and smart cities, and should be taken into account when implementing IoHT (Calvillo-Arbizu et al., 2021).

Ahmadi et al. (2019) conducted a comprehensive study on the use of IoT applications in healthcare, covering different domains, technologies, and architectural components. They examined various applications based on the type of disease and classified them into four categories: in-home, mobile health, electronic health, and in-hospital. The study emphasizes that implementing IoT applications in hospitals can decrease both the cost and duration of hospitalization (Ahmadi et al., 2019).

Sadoughi et al. (2020) focused on IoT advancements, specifically within the field of medicine. They underlined that about 80% of IoT applications in this field are for three sub-fields of medicine: neurology, cardiology, and mental disorders. In addition, their survey revealed that the in-home and in-hospital domains are the two most frequent places for IoT applications (Sadoughi et al., 2020).

In 2024, Ahmed et al. categorized IoMT (Internet of Medical Things) into two types: implantable and wearable medical devices. They highlighted the significance of applying data fusion techniques to the collected data by IoMT. Integrating and analyzing a vast amount of data from multiple sources could be beneficial in various fields, such as early seizure and Alzheimer's detection, telesurgery, teledentistry, digital biomarkers, and more (Ahmed et al., 2024).

To better understand IoHT's uses, Pradhan et al. (2021) distinguished between IoHT services and applications. The term 'services' refers to the concepts utilized in creating IoT devices, while 'applications' refers to the specific uses of these devices for diagnosing health issues or measuring certain parameters. They identified eight different services and eleven applications designed for the healthcare industry (Pradhan et al., 2021). In addition, many studies focus on just one area of IoHT, such as Babu and Bhoomadevi's (2022) research on hospital equipment tracking and monitoring (Babu & Bhoomadevi, 2022). Baqer et al. (2022) investigated IoT technologies to measure, analyze, and improve hospital air quality (Baqer et al., 2022). Fischer et al. (2020) designed an IoT-based framework for hospitals to allocate human resources while meeting patients' needs efficiently (Fischer et al., 2020).

On the other hand, Many organizations have understood the value of integrating disruptive technologies into their strategies. However, their level of engagement varies; some merely intend to do so, while others actively explore their options. Some are still in the early stages, and a few have reached more advanced implementation levels. Organizations need different requirements before and after adopting IoT and may face various challenges, including stakeholders' different expectations, data complexity, security, privacy, etc. (Benotmane et al., 2023; Ganzarain Epelde & Errasti, 2016; Yang et al., 2022). In addition, many IoT applications are still in their early stages of development. Their benefits still are not entirely known to the firms, and there is a lack of clarity on how to approach them (Benotmane et al., 2023; Nižetić et al., 2020). Given these challenges, potential benefits, and the significant investment required for IoT adoption, firms should carefully evaluate their IoT adoption strategy from different points of view (Lee & Lee, 2015; Pino et al., 2024a). It is crucial for firms to evaluate their current situation, carefully examine the various IoT alternatives, and identify each's benefits, requirements, and accordingly, the gap (Benotmane et al., 2023; Pino et al., 2024a). To enhance the effectiveness of IoT adoption and fully take advantage of IoT technologies, firms need to consider two factors: whether these technologies are beneficial for their organization and how capable they are of implementing them.

There have been studies on IoT applications that are useful in the healthcare sector. However, most have only focused on medical IoT and have not included operational or non-medical IoT applications for hospitals. This study aims to identify not only medical applications but also non-medical IoT alternatives suitable for hospitals, such as inventory management, smart buildings, and hospital waste management. Additionally, there is a lack of a systematic approach to adopting IoT technologies tailored for hospitals.

The primary objectives of this research are to determine the most appropriate IoT applications for hospitals and to identify suitable criteria for ranking and prioritizing the alternatives with a focus on two sets of criteria: attractiveness and readiness. After identifying different IoHT applications and various criteria, the next objective is to compare, prioritize, and rank IoHT alternatives based on the identified criteria. However, this process can be complex since we need to consider the different preferences of multiple decision-makers. In addition, the criteria may sometimes conflict with each other, include different measurement units, and vary in qualitative and quantitative aspects, all simultaneously (Hwang & Yoon, 2012). In this regard, the MCDM techniques could significantly assist decision-makers with appropriate technology selection (Boonsothonsatit et al., 2024).

Many studies in both the healthcare domain and technology selection field have adopted MCDM approaches. Sharma and Sehrawat (2020) identified seven criteria and 21 sub-criteria affecting cloud computing technologies in the healthcare sector and developed an integrated hybrid approach using AHP and TOPSIS to identify the most suitable cloud service provider (Sharma & Sehrawat, 2020). Boonsothonsatit et al. (2024), outlined seven crucial criteria for technology adoption for hospitals and utilized a hybrid decision-making framework to first assign weights to these criteria and next rank different alternatives for medication dispensing systems (Boonsothonsatit et al., 2024). In another research, Wang et al. (2020) adopt a hybrid MCDM method to assess different security criteria for adopting IoHT systems in the healthcare environment (Wang et al., 2020).

Mohammadzadeh et al. (2018) employed an integrated fuzzy Analytical Network Process method to select and rank the most significant challenges regarding IoT technology implementations (Mohammadzadeh et al., 2018). In another study, the most recent disruptive technologies in Industry 4.0 have been identified, and the most suitable ones have been ranked based on a fuzzy TOPSIS model tailored for SMEs (Bhatia & Diaz-Elsayed, 2023).

In this study, we adopt an integrated MCDM method to select the most appropriate alternatives for adopting IoHT technologies. As the criteria may have different weights, at first, we use a pairwise comparison method -AHP- to determine and assign appropriate weights to each criterion. Next, we utilize a distance-based method -TOPSIS- for comparing and ranking alternatives using weights calculated in the AHP phase. In a comprehensive study, Zayat et al. (2023) determined 328 studies using different MCDM techniques in the I4.0 scope and identified AHP and TOPSIS as the most frequently used methods among all MCDM techniques, 26% and 21%, respectively (Zayat et al., 2023). In the following, we briefly explain the background of AHP and TOPSIS and the steps.

This decision-making framework can be implemented in hospitals across different countries, regardless of whether they operate in the private or public sector. However, for this study, we applied the framework specifically within the context of Iran. To gather the required data, we surveyed a panel of experts from the Tehran University of Medical Sciences (TUMS), the largest medical university in Iran. TUMS oversees numerous educational hospitals and research centers, making it an ideal setting to assess the integration of IoT applications in healthcare.

As far as we know, there has not been any previous research explicitly focusing on IoT solutions designed for hospitals. This work can be seen as a fundamental exploration of the concept of IoHT applications and the identification of relevant criteria for the context of the hospital. Moreover, the framework presented here offers health policymakers and hospital managers a practical tool for evaluating, prioritizing, and improving hospital performance by adopting IoHT technologies.

In this regard, the remainder of this research is organized as follows: The next section presents the research methodology, explains the literature review process, provides background information on the AHP and TOPSIS methods, and describes the survey steps. The third section presents the findings of the literature review on two key concepts, highlighting various IoT applications within the healthcare sector and detailing the related attractiveness and readiness criteria and sub-criteria. Subsequently, we present the experimental results and analyze their implications for our case study. The research concludes with a detailed summary of the findings.

1.2 Research Methodology

This research employs a variety of methodologies for each step, as outlined in Figure 1, which illustrates the overall structure. We conduct a comprehensive and detailed literature review to identify the relevant and most important IoT applications and criteria for hospitals. The findings of the literature review will help develop the hierarchy of the study's framework. Following this, we apply the framework to design a questionnaire to survey to gather necessary data. The Analytic Hierarchy Process (AHP) is adopted to assign different weights to decision criteria because they might have different importance compared to each other. Then, we adopt the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) method to rank the alternatives. The following sections will discuss each of these steps in detail.

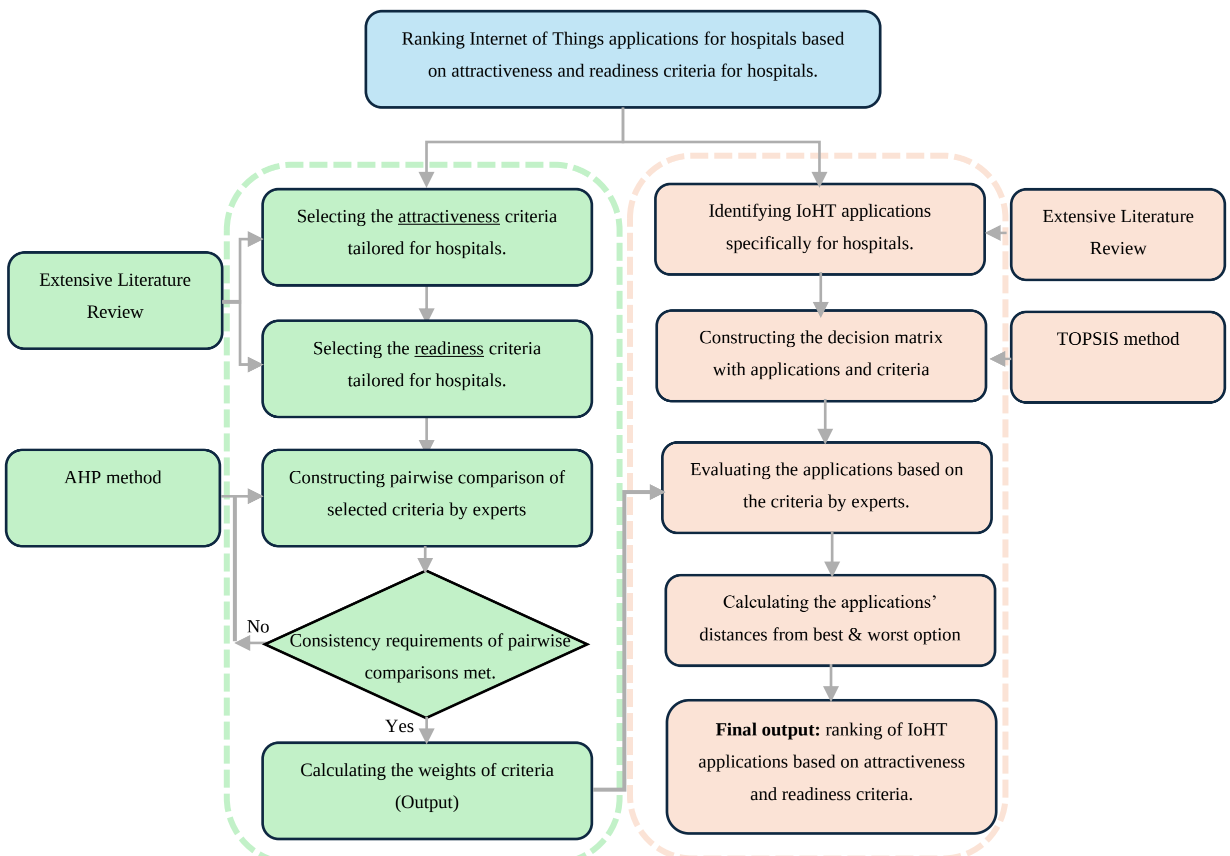

Figure 1: The Proposed Framework of the Study

1.2.1 Phase 1: Literature Review

The literature review served two primary purposes for this research: identifying various applications of IoHT within hospitals and establishing suitable criteria for evaluating these applications. To achieve this, we conducted a systematic literature review using a series of specific search strings to identify relevant applications and appropriate criteria.

In recent years, the adoption of IoT technologies has significantly increased, particularly within the healthcare sector. However, given the vastness of the healthcare sector, this research will focus solely on the application layer of the IoT architecture within the hospital domain, which can be utilized for both medical and non-medical operational processes. The key terms for the application part included "Internet of Healthcare Things" (IoHT), "Internet of Medical Things" (MIoT), and combinations of "Internet of Things" (IoT) with "Healthcare."

To prioritize IoHT applications, we must identify criteria that are appropriate for the healthcare sector. These criteria are regarded as independent attributes that help in comparing, scoring, and ranking various alternatives (Pereno & Eriksson, 2020). The criteria selection plays a vital role in the analysis of technology adoption and will help organizations make precise decisions about which technologies to adopt, considering their capabilities and the expected results (Hsu & Yeh, 2017; Kamal et al., 2020). It also helps them wisely optimize their investments and maximize the benefits of the selected technology while minimizing risks (Kazemargi & Spagnoletti, 2020; Parra & Guerrero, 2020; Parra et al., 2021). The key searching words for the criteria section included "healthcare performance," "healthcare readiness," "technology adoption," "hospital sustainability," "healthcare sustainability," "hospital performance," and combinations of them. These search strings were carefully selected to capture the breadth of current advancements in IoT technologies applied explicitly to the healthcare sector.

After compiling an initial list of IoHT alternatives and related criteria, we conducted a second round of searches. This involved pairing each identified application and criterion with terms such as "hospital" and "healthcare" to ensure a deeper contextual understanding and to cover all pertinent literature comprehensively.

We established strict inclusion criteria to ensure the quality and relevance of the selected literature. To capture the latest innovations, trends, and research findings, we mainly focused on articles published after 2019. However, in some cases, we considered articles published before 2019 if they were highly relevant, insightful, and provided significant value to the research or there was limited research in a topic after 2019. Additionally, we prioritized high-impact factor journal articles, reputed conference papers, and book chapters from top academic publishers such as ScienceDirect, IEEE, and Springer, ensuring that the sources we reviewed were both credible and highly regarded in the academic community.

From this search, 42 papers were identified, of which 31 were directly related to the enabling technologies, services, and applications of IoHT. Additionally, 36 book chapters were found, with 19 being more closely related to the focus of this research. This comprehensive literature review provides a solid foundation for understanding the various IoT applications in hospitals, along with insights into the challenges and opportunities presented by these technologies. Based on the findings of the literature review, we could develop the hierarchy of the applications, criteria, and sub-criteria for this research.

1.2.2 Survey and Questionnaire Design

In the next step, we need to design a survey to gather experts' opinions on the significance of the identified criteria and the prioritization of applications. The survey details, including its design and implementation, are outlined below.

Expert Panel: MCDM techniques, such as AHP and TOPSIS, can be successfully applied with a small group of knowledgeable decision-makers (Darko et al., 2019; Doloi, 2008). In contrast to statistical surveys, which require a large number of participants, MCDM can effectively be adopted with smaller, expert-driven data gathered from experts. These techniques use rational judgments of expert panels, which means the responses are collected from individuals with significant experience, education, and knowledge of the subject, resulting in precise comparisons. (Rehman & Ali, 2022; Shrestha et al., 2004).

Although no exact formula or sample size exists for MCDM methods, many studies have used sample sizes of less than ten experts. Table 1 presents studies where MCDM models were applied with fewer than ten experts. These references demonstrate that small expert panels, ranging from 3 to 10 participants, have been successfully used in various decision-making models across different research contexts.

Table 1: Sample Size in MCDM Studies

No.	Research	Journal	Year	Technique(s)	Number of Experts
1	Development of a Hybrid AHP-TOPSIS Decision-Making Framework for Technology Selection in Hospital Medication Dispensing Processes (Boonsothonsatit et al., 2024)	IEEE Access	2024	AHP / TOPSIS	5
2	Facilitating decision-making for the adoption of smart manufacturing technologies by SMEs via fuzzy TOPSIS (Bhatia & Diaz-Elsayed, 2023)	International Journal of Production Economics	2023	AHP / TOPSIS	3
3	Barriers and strategies for sustainable manufacturing implementation in SMEs A hybrid fuzzy AHP-TOPSIS framework (Abdullah et al., 2023)	Sustainable Manufacturing and Service Economics	2023	AHP / TOPSIS	5
4	A hybrid fuzzy-AHP-TOPSIS model for evaluation of manufacturing relocation decisions (Sequeira et al., 2023)	Operations Management Research	2023	AHP / TOPSIS	5
5	Evaluating readiness degree for Industrial Internet of Things adoption in manufacturing enterprises under interval-valued Pythagorean fuzzy approach (Sumrit, 2022)	Production & Manufacturing Research	2022	AHP	5
6	Datasets of skills-rating questionnaires for advanced service design through expert knowledge elicitation (Nguyen et al., 2022)	Scientific Data	2022	AHP	5
7	Using AHP-TOPSIS methodologies in the selection of sustainable suppliers in an electronics supply chain (Menon & Ravi, 2022)	Cleaner Materials	2022	AHP / TOPSIS	4
8	A combined AHP and TOPSIS approach for prioritizing the attributes for successful implementation of agile manufacturing (Kumar et al., 2020)	International Journal of Productivity and Performance Management	2020	AHP / TOPSIS	8
9	Evaluation of hospital disaster preparedness by a multi-criteria decision making approach The case of Turkish hospitals (Ortiz-Barrios et al., 2020)	International Journal of Disaster Risk Reduction	2020	AHP / TOPSIS	7
10	Application of fuzzy fault tree analysis based on modified fuzzy AHP and fuzzy TOPSIS for fire and explosion in the process industry (Yazdi et al., 2020)	International Journal of Occupational Safety and Ergonomics	2020	AHP / TOPSIS	4
11	Evaluation of the Challenges in the Internet of Medical Things with Multicriteria Decision Making (AHP and TOPSIS) to Overcome Its Obstruction under Fuzzy Environment (Tariq et al., 2020)	Mobile Information Systems	2020	AHP / TOPSIS	4
12	Evaluation and selection of mobile health (mHealth) applications using AHP and fuzzy TOPSIS (Rajak & Shaw, 2019)	Technology in Society	2019	AHP / TOPSIS	3
13	A Group Decision Making Framework Based on Neutrosophic TOPSIS Approach for Smart Medical Device Selection (Abdel-Basset et al., 2019)	Journal of Medical Systems	2019	AHP / TOPSIS	4
14	Building an Improved Internet of Things Smart Sensor Network Based on a Three-Phase Methodology (Wang et al., 2019)	IEEE Access	2019	AHP / TOPSIS	5
15	Application of HFACS, fuzzy TOPSIS, and AHP for identifying important human error factors in emergency departments in Taiwan (Hsieh et al., 2018)	International Journal of Industrial Ergonomics	2018	AHP / TOPSIS	7

Criteria for Inclusion: To ensure the survey results are reliable and relevant, we have specific criteria for including experts in the study:

- Professionals with extensive experience in their respective fields.
- Individuals involved in projects or research on new healthcare technology.
- Experts with academic publications related to the adoption and implementation of new technologies in healthcare settings.

Questionnaire: The questionnaire of this research consists of four distinct sections. Firstly, we introduce the research and outline its objectives. The following section gathers some demographic and background information about the experts. The third section assesses the weights of selected criteria and sub-criteria. In the final section, experts are asked to score selected alternatives based on the established criteria.

Scales: To assess the weights of criteria and sub-criteria (3^{rd} section of the questionnaire), we use the 9-point Likert scale for pairwise comparisons. Experts are asked to score the importance of each pair of criteria on a scale from 1 to 9, where 1 means equal importance (i and j have the same importance), and 9 indicates extreme importance (i is absolutely more important than j). For the fourth section, a 7-point Likert scale is adopted, where 1 indicates strong disagreement or very low relevance, and 7 indicates strong agreement or very high relevance. This approach allows for a precise understanding of the relative importance of criteria and helps capture the experts' assessment of IoT alternatives.

1.2.3 Phase 2: AHP

Developed by Thomas L. Saaty in 1970, AHP is recognized as one of the most well-known and widely used MCDM techniques across various domains in both academia and industry. This method is based on relative importance comparison for each pair of elements in a decision. Due to its simplicity and flexibility in addressing conflicting, both qualitative and quantitative items, it could be combined with other techniques such as integer programming, metaheuristics, data envelopment analysis, and other MCDM methods (Mendes & Mendes, 2011; Saaty, 2016; Thakkar, 2021). It adopts a hierarchical structure to simplify a complicated decision to simpler sub-systems and requires decision-makers to provide pair-wise comparisons. The decision matrix will be fulfilled using a 9-point scale for experts' opinions, explained in Table 2 (Saaty, 1980). The following briefly explains the required steps for calculating decision criteria weights using AHP (Boonsothonsatit et al., 2024; Islam et al., 2022; Kumar et al., 2020; Menon & Ravi, 2022; Saaty, 1990):

Table 2: Saaty Rating Scale

Value of a_{ij}: Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	***i*** and ***j*** have the same importance
3	Moderate importance	Item ***i*** is slightly more important than item ***j***
5	Strong importance	Experience and judgment strongly favor ***i*** over ***j***
7	Very strong importance	***i*** is favored very strongly over ***j***
9	Extreme importance	***i*** is absolutely more important than ***j***
2 – 4 – 6 – 8	Intermediate values	Applicable when compromise is needed among items
1/2 – 1/3 - … - 1/9	Reciprocal values	If a_{ij} = x when comparing ***i*** over ***j***, then a_{ji} = 1 / x when comparing ***j*** over ***i***

Step 1: Develop a hierarchical framework with the goal at the top, followed by criteria at the subsequent level, and sub-criteria at the bottom level.

Step 2: Create comparison decision matrices (Equation 1) using the Saaty scale for pairwise comparison between all criteria where d_{ij} is the relative importance of ***i***th criteria over ***j***th criteria, and $d_{ij} = 1 / d_{ji}$, $i, j \in (1, 2, \ldots, n)$ and ***n*** is the number of criteria:

$$D = (d_{ij}) = \begin{bmatrix} d_{11} & \cdots & d_{1n} \\ \vdots & \ddots & \vdots \\ d_{n1} & \cdots & d_{nn} \end{bmatrix} \qquad (1)$$

Step 3: Calculate normalized weights of criteria in 3 sub-steps: Sum all elements in each column (Equation 2), then normalize the decision matrix (Equation 3), and next calculate weights of criteria by taking the average of each row (Equation 4 and 5):

$$\sum_{i=1}^{n} d_{ij} \text{ for j = 1, 2, …, n} \qquad (2)$$

$$a_{ij} = d_{ij} / \sum_{i=1}^{n} d_{ij} \text{ for j = 1, 2, …, n} \qquad (3)$$

$$w_i = \sum_{j=1}^{n} a_{ij}/n \text{ for } i = 1, 2, \ldots, n \qquad (4)$$

$$W = [wi]_{n\times 1} \qquad (5)$$

Step 4: To check the consistency of experts' comparisons, we need first to calculate the maximum eigenvalue (Equation 6), Consistency Index (Equation 7), and Consistency Ratio (C.R.), where R.I. is a random index obtained from Table 3 (Equation 8):

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{(Dw)_i}{w_i}\right) \qquad (6)$$

$$C.I. = \frac{\lambda_{max} - n}{n-1} \qquad (7)$$

$$C.R. = \frac{C.I.}{R.I.} \qquad (8)$$

Table 3: Random Index (R.I.) Values (Saaty, 1980)

N (Number of criteria)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
R.I. (Random Index)	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.52	1.54	1.56	1.58	1.59

The acceptable value for the C.R. should be equal to or less than 10% or 0.1. Otherwise, the inconsistency cannot be neglected, and experts must be required to revise their comparisons. The criteria weights obtained in this phase serve as the input for the next step.

1.2.4 Phase 3: TOPSIS

This method employs a straightforward concept to rank alternatives based on a set of criteria. The optimal alternative is determined by its proximity to the Positive Ideal Solution (PIS) and its distance from the Negative Ideal Solution (NIS). It consists of the following steps (Hwang & Yoon, 2012; Thakkar, 2021; Tzeng & Huang, 2011):

Step 1: Construct an $m \times n$ decision matrix for m alternatives in rows and n criteria in columns where x_{ij} denotes the performance of alternative i based on criteria j.

Step 2: As each criterion may have different units, matrix D is normalized using Equation 9:

$$r_{ij} = x_{ij} \Big/ \sqrt{\sum (x_{ij})^2} \qquad i = 1, 2, \ldots, m \text{ and } j = 1, 2, \ldots, n \tag{9}$$

Step 3: The weighted normalized matrix is obtained using AHP phase output by Equation 10:

$$v_{ij} = w_j \, r_{ij} \qquad i = 1, 2, \ldots, m \text{ and } j = 1, 2, \ldots, n \tag{10}$$

w_j is the weight of jth criteria and $\sum_{j=1}^{n} w_j = 1$

Step 4: PIS and NIS are calculated in this step by equations 11 and 12, where J_1 and J_2 are the beneficial and non-beneficial criteria, respectively:

$$PIS = A^* = (v_1^*, v_2^*, \ldots, v_n^*) = ((\max v_{ij} \mid j \in J_1), (\min v_{ij} \mid j \in J_2)) \tag{11}$$

$$NIS = A^{-} = (v_1^-, v_2^-, \ldots, v_n^-) = ((\max v_{ij} \mid j \in J_2), (\min v_{ij} \mid j \in J_1)) \tag{12}$$

Step 5: The separation values for each alternative are determined from both PIS and NIS using the Euclidean distance (Equations 13 and 14):

$$S_i^* = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^*)^2} \quad \text{for } i = 1, 2, \ldots, m \tag{13}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \quad \text{for } i = 1, 2, \ldots, m \tag{14}$$

Step 6: The relative closeness to the ideal positive solution is calculated by Equation 15. At this step, the most favorable alternatives can be ranked in a descending order regarding closeness to the PIS (C_i^*):

$$C_i^* = (Si^-)/(Si^* + Si^-), \qquad 0 \le C_i^* \le 1 \qquad \text{for } i = 1, 2, \ldots, m \tag{15}$$

1.3 Results and Case Study Discussion

This section first presents the findings from the literature review, introducing the hierarchical structure of the research based on the identified IoHT applications and evaluation criteria. Following that, the results of the AHP and TOPSIS analyses for the case study will be outlined. Finally, the section will conclude with a discussion of the findings.

1.3.1 Development of Alternatives: IoHT Applications in Hospitals

To identify the alternatives, we conducted a literature review focusing on the application of the IoT within the hospital domain, which can be used for both medical and non-medical operational processes. After conducting a thorough literature review, we identified ten alternatives (refer to Figure 2 for an overview). The results of the literature review for alternatives are presented in detail in the following:

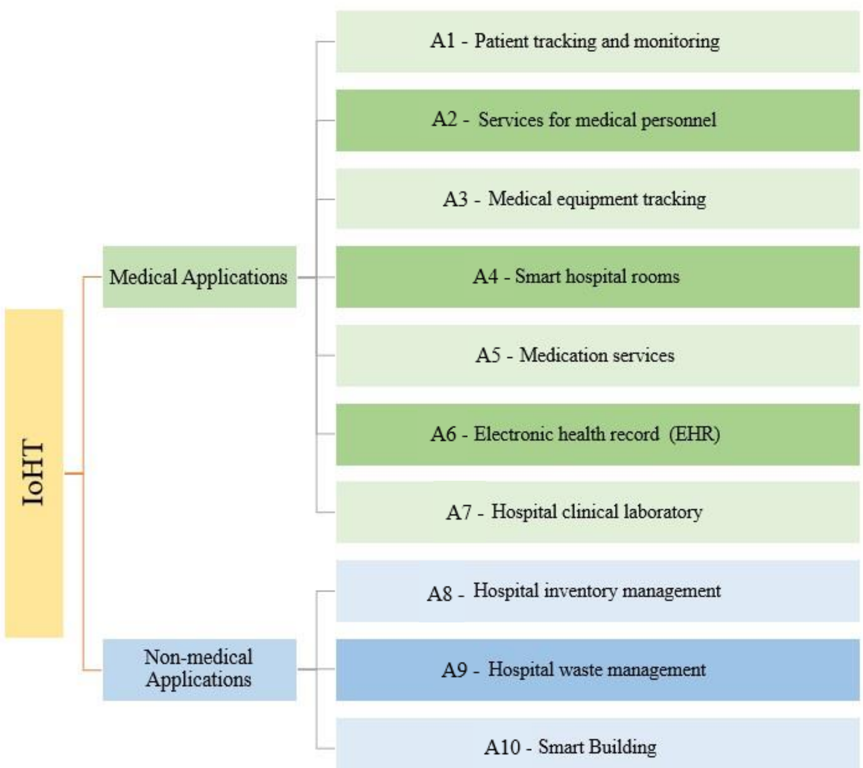

Figure 2: IoHT Applications in Hospitals

A1 - Patient monitoring and tracking: IoT applications can be adopted in hospitals to track patients' locations and monitor their vital signs, including fall detection systems, body temperature, blood pressure, electrocardiogram (ECG), etc. This will help healthcare providers gain valuable insights into early diagnosis, prompt decision-making, and treatment. In addition, by using IoT systems such as Vital Signs Monitoring Systems (VSMS) and Early Warning Systems (EWS), hospital resources, nurses, and medical practitioners can be optimally utilized (Sahu et al., 2022). Sangeethalakshmi et al. (2023) presented an IoT system customized for in-hospital settings in which, by using a computer or smartphone, medical professionals can instantly monitor a patient's vital signs regardless of their location (Sangeethalakshmi et al., 2023). Wang et al. (2024) suggested integrating an IoT-enabled system with CCTV cameras in ICU rooms to improve monitoring and measuring patient vital signs (Wang et al., 2023). In another study, Trigo et al. (2020) proposed an IoT-enabled patient-tracking system tailored for hospital complexes with multiple buildings interconnected by tunnels (Trigo et al., 2020). Precise and fast fall detection systems are crucial for various patients, including the elderly, newborns, and maternity patients; hence, Nooruddin et al. (2020) developed a real-time IoT-based fall detection system (Nooruddin et al., 2020).

A2 - Services for medical personnel: Integrating IoT technologies in hospitals can increase healthcare providers' efficiency and improve human resources management, including nurses and doctors. IoT has enabled medical professionals to deliver many healthcare services remotely through digital technologies like telesurgery. It also will help decrease the response time when nurses and doctors are needed and minimize human resource bottlenecks by tracking their in-door location and analyzing their schedules, peak time, and overload (Fischer et al., 2020; Yamashita et al., 2021). Álvarez-Díaz and Caballero-Gil (2021) suggest an IoT-based decision support system for employee tracking for the hospital environment while considering their privacy concerns (Álvarez-Díaz & Caballero-Gil, 2021). Furthermore, an IoT network can help medical personnel by automating routine tasks and freeing their time to focus on more demanding work (Lederman et al., 2021). Dubey et al. (2017) proposed an innovative IoT service to control a syringe pump for infusion-based medicine in ICUs. Nurses can access this service through a web link or mobile application. The application also works as a monitoring device, showing the remaining amount of medicine and time for completion (Dubey et al., 2017).

A3 - Medical instruments/equipment/asset tracking: One primary use of IoT in hospitals is tracking and monitoring the location of medical equipment and non-medical assets and inventory (e.g., blood products, pharmaceutical products, ventilators, nebulizers, wheelchairs, etc.) (Javaid et al., 2022; Sahoo et al., 2023). Man et al. (2015) developed an IoT-based asset management system for hospitals (IoT-HAMS) and tested it successfully at a hospital in Singapore (Man et al., 2015). Ushimaru et al. (2019) focused on visualizing instrument/equipment consumption in surgery operating rooms using IoT (Ushimaru et al., 2019).

A4 - Smart hospital rooms: Hospitals could leverage IoT services, such as interconnected devices, in-room sensors, wearable devices, smart beds, etc., to provide more efficient and patient-centric services. These technologies could be adopted not only for patient rooms but also for other hospital areas, such as medication rooms or operating theaters, where controlling temperature and humidity is crucial (Islam et al., 2020; Kumar et al., 2023). Leng et al. (2022) developed a 5-layer IoT framework tailored for hospitals to manage the environmental conditions of various rooms. This platform allows users to monitor and control the real-time status of all areas, view alarm thresholds, and even make automatic adjustments as necessary (Leng et al., 2022). Al-Salihi et al. (2022) introduce a novel decision support system called Smart Cyber Operating Theater (SCOT) using IoT. The primary advantage of SCOT is that it enables surgeons to connect multiple devices within the operating room and integrate various types of surgical information. All this information is displayed in real time on a central strategy desk in the operating room (Al-Salihi et al., 2022).

A5 – Medication services: Adverse Drug Reaction (ADR) is listed among the top ten causes of death in North America. It is estimated that each year in Canada, ADRs account for 200,000 hospital admissions, resulting in tens of thousands of deaths and costing more than $13 billion annually (*The Canadian Pharmacogenomics Network for Drug Safety*, 2024). IoT-based technologies could be a promising solution to transform hospital medication management practices by ensuring medicines' correct time and dosage and minimizing medication errors while monitoring their side effects and adverse reactions (Javaid et al., 2022; Lederman et al., 2021). Dayananda and Upadhya (2024) designed a multi-user smart pill expert system integrated with IoT appropriate for both in-hospital and in-home use (Dayananda & Upadhya, 2024).

A6 – Electronic Health Record (EHR): The application of IoT in managing EHRs in hospitals provides numerous opportunities to assist in more personalized decision-making for optimal healthcare delivery and to enhance security and privacy. Leveraging the data gathered by IoT networks and applying other embedded new technologies, such as BDA, could result in earlier and more precise disease detection (Al-Rawashdeh et al., 2022; Jagadeeswari et al., 2018; Koren & Prasad, 2022). However, given the highly sensitive nature of data collected within this network, security and privacy have always been a considerable challenge (Reegu et al., 2023; Sharma et al., 2023; Zaman et al., 2022). Ray et al. (2021) promptly address these issues in their research and propose an innovative Blockchain-IoT EHR (BIoTHR), enabling consistent, safe, and protected data transmission (Ray et al., 2021). In another study, Ganiga et al. (2020) developed a Near Field Communication (NFC) technology along with IoT to enhance HER management in hospitals and improve patient flow, particularly during emergencies or when patients cannot communicate (Ganiga et al., 2020).

A7 – Hospital clinical laboratory: The laboratory department plays a crucial role in the hospital's daily activities, providing diagnostic services. IoT applications could be integrated into all pre-analytic, analytic, and post-analytic phases in laboratories, leading to increased accuracy, improved security, and decreased time (Munir et al., 2022). In the literature, many studies propose useful platforms applicable to laboratories. Parks et al. (2022) suggest an open-source IoT-based architecture supporting the analysis of different biological experiments. This network could monitor laboratory instruments and the status of experiments and send an alarm in case of any abnormality through an online web tool (Parks et al., 2022). Le et al. (2022) developed a smart sample transport box based on Narrow Band-IoT (NB-IoT) technology and RFID capable of real-time location tracking, temperature, and humidity of the box, and all patient records, required experiments, sender and receiver departments (Le et al., 2023).

A8 – Hospital inventory management: Hospital supplies rank second in terms of expenses for Canadian hospitals, following healthcare providers' compensation (*Canadian Institute for Health Information,* 2022). This finding aligns with a similar study conducted for more than 3500 US hospitals, where supplies account for approximately 15% of total expenditures (Abdulsalam & Schneller, 2019). In addition to their financial importance, hospital supplies and inventory are vital for providing timely and high-quality services such as pharmaceutical inventory, blood products inventory, ventilators, etc. IoT applications could significantly improve hospitals' supply chain traceability, transparency, and performance (Sathiya et al., 2023). Jebbor et al. (2023) designed an innovative IoT-based automated network for hospital inventory replenishment management. They adopt different technologies, including RFID-equipped tow-bin systems, smart box-pickers, etc., and their simulation results show a considerable reduction in the stockout decrease of 99.98% for the medical inventory and 90.47% regarding ward supplies (Jebbor et al., 2023). Shamayleh et al. (2020) combine IoT applications with machine learning tools to develop a predictive maintenance approach, resulting in about 25% cost savings (Shamayleh et al., 2020). In another study, Chen et al. (2022) explore the pharmaceutical supply chain from a hospital point of view and develop an IoT-BC solution to enhance the visibility and flexibility of hospital supply chains (Chen et al., 2023).

A9 – Hospital waste management: Although hospital waste comprises various types, including sharp, infectious, chemical, radioactive, and biomedical waste (such as human/animal anatomical and blood-contaminated), all require precise and sustainable disposal management. There are lots of innovative IoT-based applications applicable to hospital waste management, including smart waste monitoring, sorting, and smart bin management systems (Ishaq et al., 2023; Kumari et al., 2013; Mohamed et al., 2023; Qureshi et al., 2023).

A10 – Smart Building: Smart buildings could leverage IoT in different lifecycle phases (construction, operation, maintenance, management) addressing different issues. These technologies could monitor and manage various systems in a building, including HVAC (Heating, Ventilation, Air Conditioning), lighting, elevators, gates, etc. The result is a more accurate predictive maintenance plan, enhanced facility reliability, improved performance, optimized energy consumption, and an environmentally sustainable output (Alwan et al., 2019; Broday & Gameiro da Silva, 2023; Jia et al., 2019; Kumar et al., 2021; Malagnino et al., 2021). In addition, by considering IoT requirements in building infrastructure, subsequent adoption of IoT for other purposes, specifically in a hospital domain, becomes significantly easier. A unified standard allows all sensors, devices, protocols, and technologies to communicate seamlessly and smoothly in a network. Yu et al. (2020) designed a smart building architecture implementing IoT to support the decision-making process for building operation and maintenance management (Yu et al., 2020). In another study, Tahir et al. (2020) suggested an IoT-based wireless sensor network (WSN) system capable of detecting environmental changes such as temperature, light, and humidity and, consequently, sending off an alarm if the changes pass the set threshold (Tahir et al., 2020).

Another area for improvement in hospital buildings is access control and physical security. Certain sensitive areas - such as medication storage, pediatric wards, and patients’ data storage sections - require unique authentication for access approval in hospitals. An IoT-based central access control system can not only address the concerns mentioned above but also enhance the monitoring, controlling, and managing cyber security systems, visitor management systems (VMS), fire/emergency detection, and alarm systems (Mohammadiounotikandi et al., 2023; Yu et al., 2020; Zhang et al., 2018). Considering the various clients of a hospital (including inpatients, their escorts and visitors, outpatients, emergency patients, and hospital staff), it is evident that their needs, priorities, and travel behavior differ significantly from those of regular workplaces, schools, or other contexts (Kara & Bilgiç, 2021). Therefore, implementing appropriate hospital transportation and parking systems could improve the smooth flow of crowds entering or leaving the hospital, decrease search time, and mitigate environmental effects such as CO_2 emissions (Ji et al., 2023). Sedrati et al. (2023) suggest an IoT governance framework incorporating blockchain technology customized for hospital parking platforms. In their research, they define different criteria and constraints for the system, and based on them, the system lets parking lot doors open or remain closed for each driver using sensors, cameras, etc. This system can also differentiate between various entities and adjust its governance mode based on its decision-making processes (Sedrati et al., 2023). Tekouabou et al. (2022) developed an IoT system equipped with a predictive model to optimize the accessibility of parking lots in smart parking (Tekouabou et al., 2022).

In reviewing the literature on IoHT applications in hospitals, it becomes evident that many technologies have been proposed and implemented to enhance various aspects of healthcare. The diversity of IoHT applications spans from patient monitoring and tracking systems to inventory and waste management solutions, each addressing unique challenges within the healthcare environment. To provide a comprehensive understanding of these applications, we have categorized the key IoHT applications commonly discussed in the literature, along with some examples of their specific use cases. Table 4 summarizes these applications, highlighting their functions and the references supporting their use. This overview serves as a foundation for the next steps of our research.

Table 4: Literature on IoHT Applications in Hospitals

No.	Applications	Other names / Specific applications	References
A1	Patient tracking and monitoring	• Elderly / newborn / children / maternity wards • Patient tracking • Monitoring of vital signs • Fall detection systems	Wang et al. (2024) ; Sangeethalakshmi et al. (2023) ; Sahu et al. (2020) ; Trigo et al. (2020) ; Nooruddin et al. (2020)
A2	Services for medical personnel	• Medical personnel tracking • Smart badges • Staff performance tracking	Álvarez-Díaz & Pino Caballero-Gil (2021) ; Yamashita et al. (2021) ; Lederman et al. (2021) ; Fischer et al. (2020) ; Dubey et al. (2017)
A3	Medical instruments/ equipment tracking	• Location recognition and tracking for equipment (wheelchairs, ventilators, nebulizers, etc.) • Monitoring of hospitals' assets • Equipment management	Sahoo et al. (2023) ; Javaid et al. (2022) ; Ushimaru et al. (2019) ; Man et al. (2015)
A4	Smart hospital rooms	• Smart ICU room • Smart newborn room • Smart bed	Kumar et al. (2023) ; Leng et al. (2022) ; Al-Salihi et al. (2022) ; Islam et al. (2020)
A5	Medication services	• Drug management • Adverse drug reaction	Dayananda & Upadhya (2024) ; Javaid et al. (2022) ; Lederman et al. (2021)
A6	Electronic health record (EHR)	• Patient charting	Sherma et al. (2023) ; Reegu et al. (2023); Zaman et al. (2022); Koren & Prasad (2022); Al-rawashdeh et al. (2022); Ray et al. (2021); Ganiga et al. (2020); agadeeswari et al. (2018)
A7	Hospital clinical laboratory	• Pre-analytical laboratory phase • Analytic Laboratory Phase • Post-analytical Laboratory Phase	Le et al. (2022) ; Munir et al. (2022) ; Parks et al. (2022)
A8	Hospital inventory management	• Pharmaceutical and drugs inventory management • Blood inventory management	Sathiya et al. (2023) ; Jebbor et al. (2023) ; Chen et al. (2022) ; Shamayleh et al. (2020) ; Abdulsalam & Schneller (2019)
A9	Hospital waste management	• Smart bins	Ishaq et al. (2023); Mohamed et al. (2023) ; Qureshi et al. (2023) ; Kumari et al. (2013)
A10	Smart Building	• Temperature / Humidity / Air quality / light/ noise monitoring • Fire and smoke detection and alarm system • Smart parking • Visitor management system	Broday & Silva (2023) ; Kumar et al. (2021) ; Malagnino et al. (2021) ; Tahir et al. (2020) ; Yu et al. (2020) ; Jia et al. (2019) ; Alwan et al. (2018) ; Mohammadiounotikandi et al. (2023) ; Yu et al. (2020) ; Zhang et al. (2018) ; Sedrati et al (2023) ; Ji et al. (2023) ; Tekouabou et al. (2022) ; Kara & Bilgiç (2021)

1.3.2 Development of Criteria: Attractiveness and Readiness

We conduct a literature review to identify the appropriate criteria and sub-criteria for prioritizing the IoHT applications within the hospital domain. We can categorize these criteria into two main groups: attractiveness and readiness. The attractiveness criteria are factors that could help improve an organization's performance, such as cost savings and quality of services; in addition, capabilities attributes consider the organizations' current capabilities, strengths, and weaknesses to adopt applications, such as the required amount of investments, technological infrastructures, expertise and skills sets. These criteria are helpful for organizations when selecting technology. They help to assess not only the attractiveness of different applications available in the market but also the level of readiness and capabilities required to implement those applications within an organization (Brozzi et al., 2018; Chandler & Hanks, 1994; Dahooie et al., 2023; Garousi Mokhtarzadeh et al., 2020). In the following two subsections, we will provide a more detailed description of the literature review findings on the criteria identification and importance of both attractiveness and readiness criteria.

Attractiveness Criteria

C1 - Health Effectiveness: The ultimate goal of each healthcare system is to provide precise high-quality care for all who need services while avoiding unnecessary services for those unlikely to benefit (America, 2001; Sciences et al., 2018). IoT, with its interconnected network of smart devices, can potentially evolve the healthcare system into a more effective one by improving health outcomes and quality of care (Kanokphanvanich et al., 2023; Papa et al., 2020; Uslu et al., 2020). Accordingly, one of the most important criteria regarding adopting IoHT applications for hospitals is health effectiveness, which indicates how beneficial an application could be for a hospital in achieving its main goal.

C2 – Patient Waiting Time: Undoubtedly, hospitals offer some lifesaving services, and failing to meet certain quality measures, such as patient waiting times, could result in irreparable consequences, such as the deterioration of the patient's condition (Amos et al., 2020; Souza et al., 2020). The waiting time criterion not only directly impacts the selection of an IoHT application but also indirectly affects other measures such as quality of care, patient satisfaction, and patient turnaround time (Demeulemeester et al., 2013; Lot et al., 2018; Meng et al., 2015; Santos-Jaén et al., 2022).

C3 – 24/7 Availability: A socially significant factor regarding healthcare is service availability (24/7) at any time, anywhere, and by any device (Mehra & Sharma, 2021; Zadtootaghaj et al., 2019). IoT applications will enable healthcare systems to offer services with a higher degree of availability and keep systems operational without any interruption. It needs to be mentioned that better performance in this measure could decrease the performance on other criteria, such as increasing the risk of security issues and system jamming (Alam et al., 2022; Farhin et al., 2020; Pang et al., 2015; Yaacoub et al., 2020).

C4 – Privacy and Security: These are two intertwined concepts, and lots of researchers have mentioned them as one single criterion (Mohammadzadeh et al., 2018). Privacy is regarded as one of the most basic needs of individuals, and in the context of IoT, it concerns the individuals' rights to gain control of gathering, using, and sharing their personal medical information. On the other hand, security involves protecting data, systems, and organizations against unauthorized access. In simple terms, privacy is more entity-centric, but security is about systems. IoT embedded with other I4.0 technologies, such as Blockchain and AI, could greatly improve both the security and privacy of all stakeholders in the healthcare systems (Hathaliya & Tanwar, 2020; Hsu & Yeh, 2017; Miao et al., 2024; Osama et al., 2023; Rahman et al., 2024; Raj & Prakash, 2023; Razdan & Sharma, 2022; Zadtootaghaj et al., 2019).

C5 – Energy Management (consumption/saving): Based on a Natural Resources Canada survey, hospitals utilize a considerable amount of energy (2.54 GJ/m^2) in terms of energy intensity, almost ahead of most commercial and institutional sectors (*Natural Resources Canada*, 2020). This huge energy demand is mainly because of the utilization of highly energy-intensive equipment, including HVAC systems and medical devices, coupled with 24/7 operating time. IoT networks could be very beneficial in hospitals' energy management by supporting saving power and energy consumption and efficiency (Bhatia

& Diaz-Elsayed, 2023; Kanokphanvanich et al., 2023; Li et al., 2021; Mirghafoori et al., 2018; Nagariya et al., 2022; Nasrollahi et al., 2022).

C6 – Waste Management: Hospital biomedical waste could be generated everywhere during patients' diagnosis, treatment, or immunization process, and due to their 24/7 operational time, hospitals are among the largest waste generators. They could be hazardous, such as infectious wastes, sharp wastes, pharmaceutical or chemical wastes, radioactive wastes, or non-hazardous, such as food and fruit scraps (Bamakan et al., 2022; Belsare & Singh, 2022; Mehra & Sharma, 2021; Singh et al., 2023). New technologies such as IoT could enhance hospital waste management and improve its performance both in environmental and financial factors. They could help smart waste management from the beginning of waste monitoring (smart garbage bin) to tracking, collecting, and processing (A. Chauhan et al., 2021; Gaur, 2022; Kanokphanvanich et al., 2023; McGain & Naylor, 2014; Nagariya et al., 2022; Ramson et al., 2020; Sosunova & Porras, 2022; Yang et al., 2022).

C7 – Resource Conservation: In addition to natural resources like water, air, and gas, hospitals rely on invaluable medical resources such as organs, blood products, plasma, oxygen, pharmaceutical products, etc. Efficient monitoring, preservation, and inventory management of these resources are critical for ensuring optimal healthcare service delivery. IoT technologies can be leveraged in different areas in hospitals: supply chain management, condition monitoring, inventory management, and shelf-life optimization, helping them to improve resource management performance (Kumar & Chaudhary, 2021; McGain & Naylor, 2014; Sharma et al., 2020; Yan, 2017; Zahoor & Mir, 2021).

C8 – Saving in Operational Costs: IoT adoption in hospitals can lead to substantial operational cost savings not only directly by improving resource management efficiency, more effective monitoring and treatment solutions, remote surgery, telemedicine, etc., but also indirectly by some social and environmental efforts such as reducing energy consumption costs and waste management costs (Alansari et al., 2017; Bhatt & Bhatt, 2017; Elabed et al., 2021; Mehra & Sharma, 2021; Nagariya et al., 2022; Tun et al., 2021; Yildiz Çankaya & Sezen, 2019; Zadtootaghaj et al., 2019).

Readiness Criteria

To take full advantage of IoT potential, it is necessary to not only consider the attractiveness of applications but also think about the organization's capabilities and the degree of readiness to implement those applications. Different technologies demand varying amounts of organizational readiness regarding cultural alignment, expertise, investment requirements, legal compliance, and more. This assessment ensures precise decision-making, successful implementation, effective risk mitigation, and the optimal utilization of technology investments. In other words, readiness criteria will provide invaluable insights into organizations' current abilities, conditions, and specific requirements to adopt IoT technologies while also indicating areas for improvement, strengths, and weaknesses (Çınar et al., 2021; Pino et al., 2024a, 2024b; Ustundag et al., 2018).

C9 - Cost of Application: Economic feasibility is an important factor in adopting any new technology. No matter how beneficial a technology may be, it needs to be examined in terms of the capital investment required for its implementation (Bhatia & Diaz-Elsayed, 2023). The cost of IoT applications is likely to vary from the traditional technologies depending on their level of complexity, as well as if they will be integrated into the organization's existing technologies to improve them or if they are completely new solutions. This criterion has been mentioned in lots of research and is considered as one of the significant barriers to IoHT adoption (Hsu & Yeh, 2017; Nasrollahi et al., 2022; Noletto et al., 2017; Yang et al., 2022).

C10 – Technological readiness: Technological readiness refers to the infrastructures, systems, and components an organization needs to implement new technology and is the first concrete step toward Industry 4.0. (Amaral & Peças, 2021; Klisenko & Serral Asensio, 2022). Benotmane et al. (2023) defined three subdimensions for this criterion, including architecture, device management, and platform management (Benotmane et al., 2023). In the context of IoT, it covers components such as hardware, software, network capabilities, data storage systems, backup power, and hardware compatibility and has been mentioned in lots of studies (Balasubramanian et al., 2021; Hsu & Yeh, 2017; Lokuge et al., 2019; Nasrollahi et al., 2022; Ronaghi, 2024).

C11 – Required expertise training: Emerging technologies demand different levels of IT expertise, digital skills, training, and coaching. Implementing complex technologies, such as some IoT applications, might require advanced technical skill sets and higher human resource readiness. According to Ronaghi's (2022) research, human resource readiness stands out as the most critical dimension for the adoption of new technology in a smart hospital (Amaral & Peças, 2021; Benotmane et al., 2023; Hsu & Yeh, 2017; Kanokphanvanich et al., 2023; Ronaghi, 2024).

C12 – Cultural Readiness: This factor refers to how an organization's core values could facilitate integrating, accepting, and utilizing IoT technologies. In the context of hospitals, cultural readiness needs to be considered among all stakeholders, including different factors such as top management commitment, effective communication, and collaboration, and change management strategies (Lokuge et al., 2019; Pino et al., 2024b; Ronaghi, 2024; Sumrit, 2022).

In the context of implementing IoT applications in hospitals, the assessment of both readiness and attractiveness is critical for successful adoption. Table 5 summarizes the most relevant sub-criteria found in the literature, categorized under the two primary criteria: attractiveness and readiness.

To summarize the findings of our literature review, it is evident that most of the studies in the literature have concentrated solely on medical applications, such as patient monitoring and diagnostic tools, while largely missing the critical role of operational and non-medical IoT applications in hospitals. This creates a significant gap, as hospitals require comprehensive solutions beyond medical devices to optimize overall efficiency. Moreover, there is a noticeable gap in the literature regarding what criteria should be considered when adopting IoT applications in hospitals. The selection of criteria is a crucial step in technology adoption, as it enables organizations to make well-informed decisions about which technologies to implement based on their capabilities and anticipated outcomes. A well-defined set of criteria not only guides the decision-making process but also helps organizations optimize their investments, ensuring they extract the maximum benefits from the chosen technology while minimizing associated risks.

Table 5: Literature on Readiness and Attractiveness Criteria

No.	Criteria	Sub-criteria	References
1	Attractiveness	Health Effectiveness	Kanokphanvanich et al. (2023); Papa et al. (2020); Uslu et al. (2020); Dhalla & Tepper (2018)
2		Patient Waiting Time	Rattan et al. (2022); Santos-Jaén et al (2022); Souza et al (2020); Amos et al (2020); Lot et al. (2018) …
3		24/7 Availability	Alam et al. (2022); Mehra & Sharma (2021); Farhin et al (2020); Yaacoub et al. (2020); Pang et al (2012)
4		Privacy and Security	Rahman et al (2024); Miao et al. (2024); Raj & Prakash (2023); Osama et al (2023); Neves et al. (2022); Klisenko & Asensio (2022) …
5		Energy Management	Bhatia & Diaz-Elsayed (2023); Nasrollahi et al. (2022); Kanokphanvanich et al. (2023); Li et al. (2021); Nagariya et al (2021); Kumar & Chaudhary (2021); Wang et al. (2021); ….
6		Waste Management	Singh et al. (20223); Bhatia & Diaz-Elsayed (2023); Sosunova et al (2022); Bamakan et al. (2022); Chauhan et al. (2021); Nagariya et al (2021); Mehra & Sharma (2021); Yang et al. (2021); …
7		Resource Conservation	Kumar et al. (2021); Zahoor & Mir (2021); Sharma et al (2020); Yan (2017); McGain & Chris Naylor (2014)
8		Saving in Operational Costs	Mehra & Sharma (2021); Elabed et al (2021); Nagariya et al (2021); Tun et al (2020); Cankaya & Sezen (2018); Alansari et al (2017)
9	Readiness	Cost of Application	Bhatia & Diaz-Elsayed (2023); Nasrollahi et al. (2022); Yang et al. (2021); Parra & Guerrero (2020); Hsu & Yeh (2016) …
10		Technological readiness	Benotmane et al (2023); Ronaghi (2022); Balasubramanian et al (2021); Klisenko & Asensio (2021); Amaral & Peças (2021); Lokugea et al (2019); Hsu & Yeh (2016)
11		Required expertise & training	Kanokphanvanich et al. (2023); Benotmane et al (2023); Ronaghi (2022); Amaral & Peças (2021); Hsu & Yeh (2016); Palacios-Marqués et al (2015)
12		Cultural Readiness	Pino et al. (2024); Sumrit (2022); Ronaghi (2022); Lokugea et al. (2019)

To address these gaps, we developed the hierarchical structure of our study based on the criteria and alternatives mentioned in previous sub-sections, as shown in Figure 3.

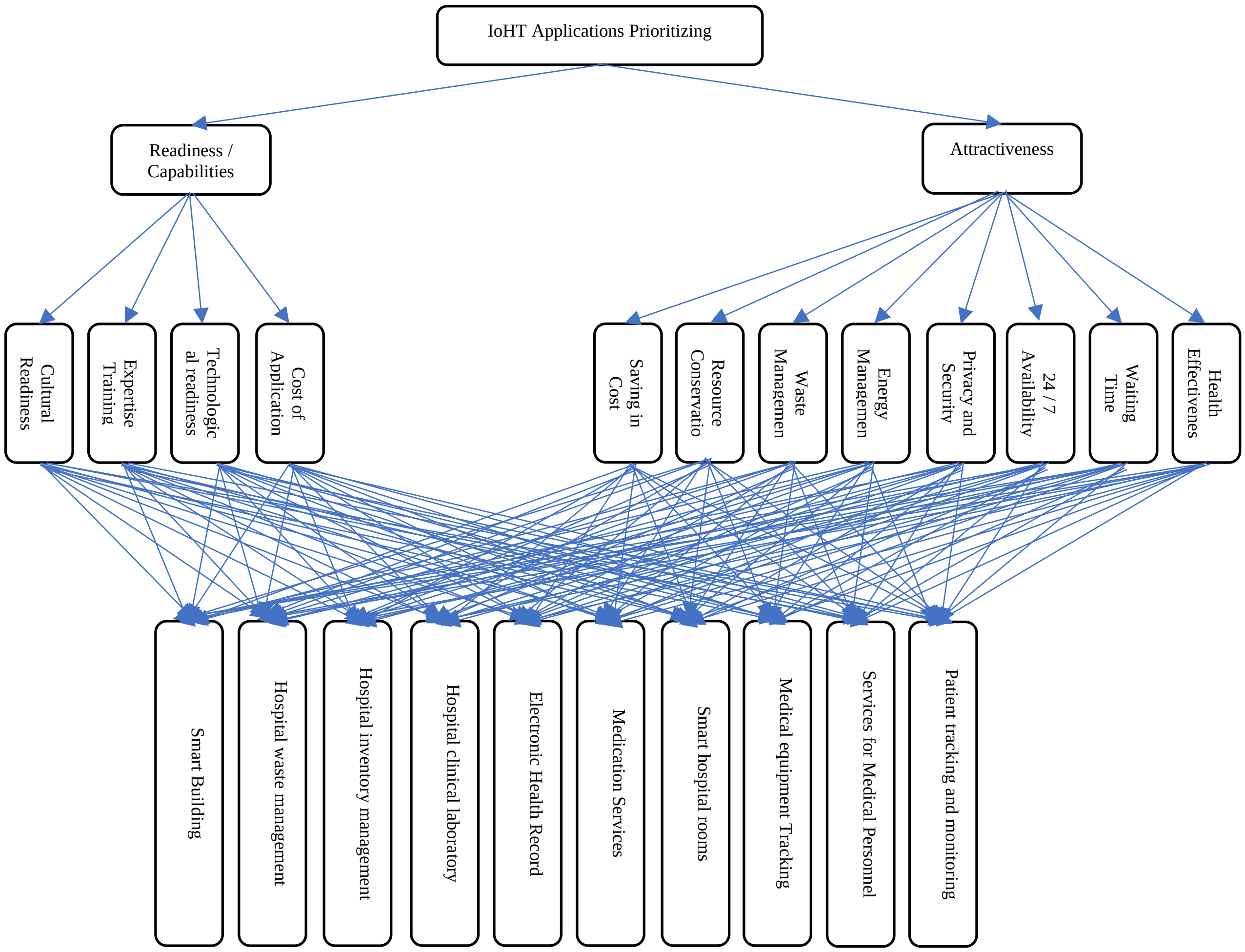

Figure 3: Hierarchy Structure of the Study

1.3.3 Questionnaire Distribution and Data Collection

We applied the proposed framework in Iranian hospitals as a case study. In this context, the details and results of our survey, along with the distribution of the questionnaire, are presented as follows (the questionnaire is available in Appendix 1):

Survey location: This research was conducted at the Tehran University of Medical Science (TUMS) in Tehran, Iran, in 2024. TUMS is a leading university in medical research, education, and healthcare innovation in Iran. As one of Iran's oldest and most highly-ranked medical universities, TUMS has a strong reputation for high academic services and standards and ensures access to knowledgeable and experienced experts. TUMS has 11 faculties, including the School of Advanced Technologies in Medicine, and runs 16 educational hospitals. It also manages several pharmacies and laboratories with the latest medical technologies, offering a wide range of specialized services. In addition, the university hosts more than 100 research centers focused on various medical fields, promoting and supporting innovation and technology advancements. This network and its experts are ideal for our study and will provide valuable insight into the preferences, potentials, and challenges of integrating IoT in healthcare.

Questionnaire distribution and expert panel responses: In this case study, to ensure a comprehensive survey, a skilled team of experts has been selected from various departments within TUMS. The team comprises professionals from different faculties, research centers, or who have published extensively on IoT technologies all related to healthcare. The invitation emails were sent to the selected experts, who were asked to participate in the survey. Participants were allowed to complete the questionnaire using the Qualtrics platform, allowing for online or offline submissions. They could either fill out the questionnaire directly on the platform or download it, complete it offline, and then upload the completed file to the platform.

Seven experts accepted the invitations and completed the questionnaire. Based on explanations provided in the previous section and Table. 1, this response number provides an adequate foundation for the study's findings. Most participants (six out of seven) are physicians, four are physicians and faculty members, while three also serve as heads of their respective departments. Regarding education, the field of study for six experts is medical, with one expert specializing in management science. Regarding the level of study, three participants have completed a fellowship, two are currently at the resident level, and one expert has a Ph.D. All experts have extensive experience in their respective fields, with over ten years of professional practice.

1.3.4 Results of AHP Phase: Criteria Weighting

After collecting data from experts, the comparison decision matrices are constructed to calculate the criteria weights for each level. Each pair of criteria has a single question in the designed questionnaire (d_{ij}), and the other value is reciprocal to that pair's value (d_{ij} = 1 / d_{ji}). In addition, all the values on the main diagonal of matrixes are equal to 1 (d_{ii} = 1). Three decision matrices were developed based on the questionnaire responses provided by the experts. Each cell represents the geometric mean of all experts' opinions for each comparison, as shown in Tables 6 to 8, corresponding to the attractiveness sub-criteria, readiness sub-criteria, and main criteria, respectively. The relative weights column in each table shows the importance of each (sub)criterion compared to the others in that table.

Table 6: Decision Matrix for Attractiveness Criteria

Attractiveness	Health Effectiveness	Waiting Time	24/7 Availability	Privacy & Security	Energy Management	Waste Management	Resource Conservation	Saving in Costs	Relative Weights
Health Effectiveness	1	3.33	5.52	2.19	7.37	7.81	5.85	2.74	0.33
Patient Waiting Time	0.30	1	2.43	0.50	4.59	5.35	3.41	0.58	0.13
24/7 Availability	0.18	0.41	1	0.32	3.65	4.38	2.63	0.34	0.08
Privacy and Security	0.46	2.00	3.17	1	5.41	6.48	5.38	1.06	0.19
Energy Management	0.14	0.22	0.27	0.18	1	1.64	0.40	0.18	0.03
Waste Management	0.13	0.19	0.23	0.15	0.61	1	0.37	0.15	0.02
Resource Conservation	0.17	0.29	0.38	0.19	2.48	2.67	1	0.29	0.05
Saving in Costs	0.37	1.74	2.95	0.94	5.61	6.68	3.39	1	0.17

Table 7: Decision Matrix for Readiness Criteria

Readiness	Cost of Application	Technological readiness	Required expertise	Cultural Readiness	Relative Weights
Cost of Application	1	2.89	3.34	4.46	0.52
Technological readiness	0.35	1	1.81	2.83	0.24
Required expertise	0.30	0.55	1	0.70	0.121
Cultural Readiness	0.22	0.35	1.43	1	0.123

Table 8: Decision Matrix for Main Criteria

	Attractiveness	Readiness	Relative Weights
Attractiveness	1	0.57	0.36
Readiness	1.77	1	0.64

The model was executed using the Superdecision software (free version: V2_10). Table 9 and Figures 4 and 5 present the local and global weights for the criteria and sub-criteria.

Table 9: Weights of Criteria and Sub-criteria

Level	Index	Crietria / Sub-criteria	Weight		Rank
			Local (w_L)	Global (w_G)	
1		**Attractiveness**	**0.36**		
1-1	C1	Health Effectiveness	0.33	0.12	3
1-2	C2	Patient Waiting Time	0.13	0.05	8
1-3	C3	24/7 Availability	0.08	0.03	9
1-4	C4	Privacy and Security	0.19	0.07	6
1-5	C5	Energy Management	0.03	0.01	11
1-6	C6	Waste Management	0.02	0.01	12
1-7	C7	Resource Conservation	0.05	0.02	10
1-8	C8	Saving in Costs	0.17	0.06	7
2		**Readiness**	**0.64**		
2-1	C9	Cost of Application	0.52	0.33	1
2-2	C10	Technological readiness	0.24	0.15	2
2-3	C11	Required expertise	0.121	0.08	5
2-4	C12	Cultural Readiness	0.123	0.08	4

The local weights column represents the relative weight of each sub-criterion within its respective criterion. The sum of the local weights of the sub-criteria over each criterion equals 1:

$$\sum_{1}^{8} W_{C_n}^{local} = 1 \quad , \quad For\ Attractiveness\ Crierion$$

$$\sum_{9}^{12} W_{C_n}^{local} = 1 \quad , \quad For\ Readiness\ Criterion$$

In contrast, the global weights column shows the final weight of each sub-criterion, irrespective of its parent criterion. The sum of the global weights for all sub-criteria equals 1, reflecting their overall importance in the model.

$$\sum_{1}^{12} W_{C_n}^{Global} = 1$$

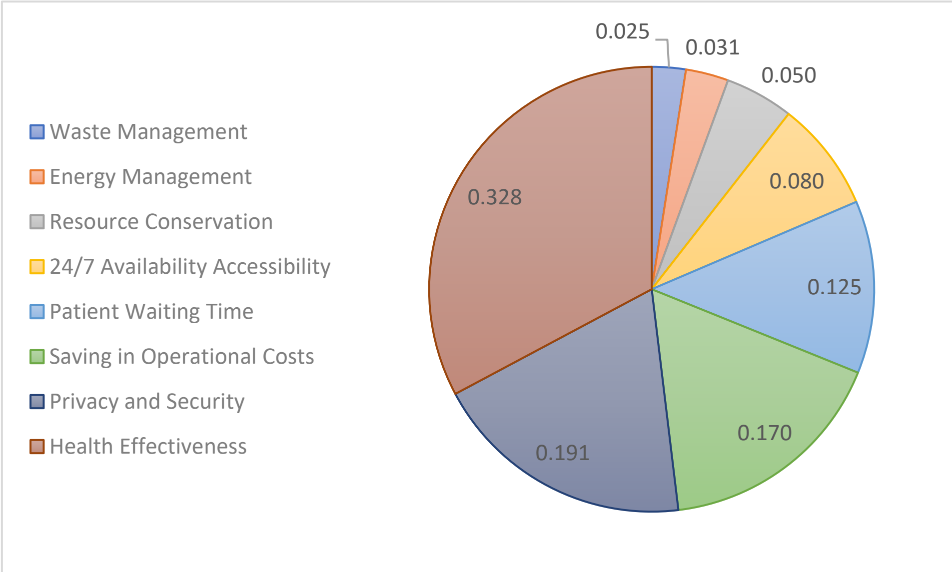

Figure 4: Attractiveness Sub-criteria Weights

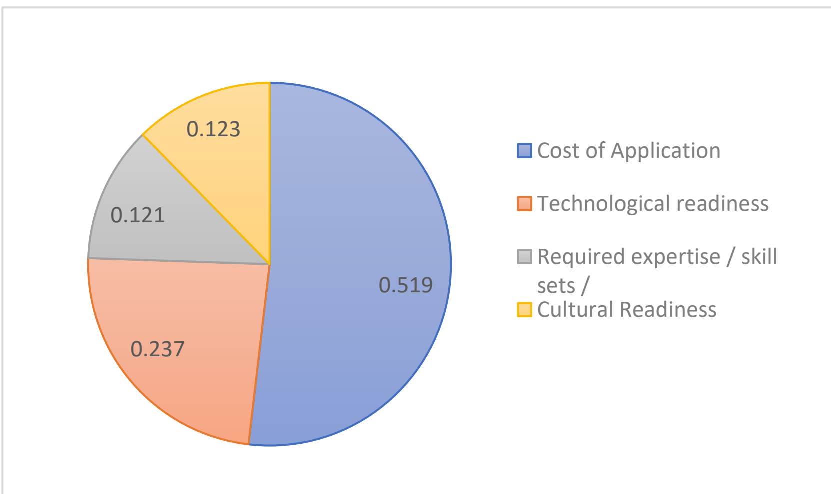

Figure 5: Readiness sub-Criteria Weights

In step 4, the consistency ratio (C.R.) is calculated to ensure the consistency of the comparisons and the reliability of the results. The CRs for the attractiveness and readiness decision matrices are 0.031 and 0.038, respectively, which are both less than the threshold of 0.1, indicating that the comparisons and results are consistent.

1.3.5 Result of TOPSIS Phase: Applications Prioritization

To obtain the IoHT applications ranking based on the identified sub-criteria, the decision matrix is developed and normalized using Equation (9), shown in Table 10. In this matrix, we transformed the decision matrix values into dimensionless values to ensure comparability across different criteria.

Next, the weights obtained by AHP in the previous phase are applied to the sub-criteria and weighted-normalized decision matrix using Equation (10), shown in Table 11. Each element in the matrix is obtained by multiplying the normalized value and the weight assigned to its respective criterion. This matrix displays the normalized values adjusted by their corresponding criterion weights, ensuring that criteria with higher weights have a greater impact on the final ranking of the alternatives.

Then, the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) are calculated based on Equations (11) and (12), shown in Table 12. The PIS represents the best possible solution, which maximizes the benefit criteria and minimizes the negative criteria. On the other hand, the NIS shows the worst possible solution, minimizing the benefit criteria and maximizing the negative criteria. These solutions serve as benchmarks to assess the alternatives by comparing their proximity to these ideal and negative ideal solutions.

The alternatives' distances from the PIS and NIS are calculated using Equations (13) and (14). In this step, the Euclidean distance between each alternative and both the PIS and the NIS is computed. The distance from the PIS represents how far an alternative is from the best possible outcome, while the distance from the negative ideal solution shows how far it is from the worst possible outcome.

Table 10: TOPSIS Decision Matrix - Normalized

Sub-criteria / Alternatives (Applications)	Attractiveness								Readiness			
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
A1 - Patient tracking and monitoring	0.3863	0.348	0.406	0.3963	0.1149	0.0946	0.38	0.4535	0.2965	0.3225	0.347	0.3669
A2 - Services for medical personnel	0.4036	0.4059	0.4151	0.3197	0.1639	0.1222	0.4003	0.4228	0.3836	0.3418	0.4024	0.3589
A3 - Medical equipment tracking	0.2505	0.3053	0.3017	0.1699	0.1149	0.0946	0.2683	0.3031	0.2845	0.2983	0.3044	0.2949
A4 - Smart hospital rooms	0.3949	0.348	0.3331	0.33	0.6315	0.3505	0.3536	0.326	0.3836	0.3621	0.3484	0.3589
A5 - Medication services	0.3566	0.3019	0.3317	0.3197	0.1041	0.377	0.299	0.2298	0.3061	0.2872	0.3767	0.3669
A6 - Electronic health record	0.2595	0.3687	0.3264	0.4522	0.1041	0.1222	0.2267	0.2205	0.2731	0.3061	0.3576	0.3669
A7 - Hospital clinical laboratory	0.3616	0.3687	0.2907	0.3762	0.1149	0.1153	0.2733	0.2298	0.3061	0.3161	0.3484	0.3346
A8 - Hospital inventory management	0.2838	0.3099	0.3529	0.1161	0.3218	0.41	0.3831	0.3942	0.2798	0.2799	0.2258	0.2388
A9 - Hospital waste management	0.0651	0.081	0.0684	0.0836	0.1041	0.5612	0.1052	0.0825	0.2685	0.2711	0.1649	0.1323
A10 - Smart Building	0.2434	0.185	0.1751	0.3665	0.6315	0.437	0.3536	0.3176	0.3527	0.3621	0.1852	0.2554

Table 11: TOPSIS Decision Matrix - Weighted

Sub-criteria / Alternatives (Applications)	Attractiveness								Readiness			
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
A1 - Patient tracking and monitoring	0.0458	0.0158	0.0118	0.0274	0.0013	0.0008	0.0068	0.0278	0.0982	0.0488	0.0269	0.0289
A2 - Services for medical personnel	0.0478	0.0184	0.0120	0.0221	0.0018	0.0011	0.0072	0.0259	0.1271	0.0517	0.0312	0.0283
A3 - Medical equipment tracking	0.0297	0.0138	0.0087	0.0117	0.0013	0.0008	0.0048	0.0186	0.0942	0.0451	0.0236	0.0232
A4 - Smart hospital rooms	0.0468	0.0158	0.0097	0.0228	0.0071	0.0031	0.0064	0.0200	0.1271	0.0548	0.0270	0.0283
A5 - Medication services	0.0422	0.0137	0.0096	0.0221	0.0012	0.0034	0.0054	0.0141	0.1014	0.0434	0.0292	0.0289
A6 - Electronic health record	0.0307	0.0167	0.0095	0.0312	0.0012	0.0011	0.0041	0.0135	0.0905	0.0463	0.0277	0.0289
A7 - Hospital clinical laboratory	0.0428	0.0167	0.0084	0.0260	0.0013	0.0010	0.0049	0.0141	0.1014	0.0478	0.0270	0.0263
A8 - Hospital inventory management	0.0336	0.0140	0.0102	0.0080	0.0036	0.0037	0.0069	0.0242	0.0927	0.0423	0.0175	0.0188
A9 - Hospital waste management	0.0077	0.0037	0.0020	0.0058	0.0012	0.0050	0.0019	0.0051	0.0889	0.0410	0.0128	0.0104
A10 - Smart Building	0.0288	0.0084	0.0051	0.0253	0.0071	0.0039	0.0064	0.0195	0.1168	0.0548	0.0144	0.0201

Table 12: TOPSIS Positive & Negative Ideal Solutions

	SU1	SU2	SU3	SU4	SU5	SU6	SU7	SU8	SU11	RE1	RE2	RE3	RE4
Positive Ideal Solution – A^*	0.0478	0.0184	0.0120	0.0312	0.0071	0.0050	0.0072	0.0278	0.0889	0.0410	0.0128	0.0104	0.0478
Negative Ideal Solution – A^{-}	0.0077	0.0037	0.0020	0.0058	0.0012	0.0008	0.0019	0.0051	0.1271	0.0548	0.0312	0.0289	0.0077

Finally, the relative closeness to the ideal positive solution is calculated by Equation (15), which is shown in Table 13. This measure indicates how close each alternative is to the PIS compared to the NIS. The resulting value ranges between 0 and 1, where a higher value indicates that the alternative is closer to the PIS and, therefore, more desirable. The results show the ranks of the most favorable alternatives in descending order (Figure 6). In this regard, "patient monitoring and tracking," with a score of 0.684251, simultaneously has the minimum distance from the positive ideal solution and maximum distance from the negative ideal solution, ranking it as the most favorable application. Additionally, "Hospital waste management" is the least favorable application.

Table 13: Relative Closeness to the Ideal Solution and Final Rankings

	S^*	S^{-}	C*	Rank
A1 - Patient tracking and monitoring	0.027634	0.059885	0.684251	1
A2 - Services for medical personnel	0.048534	0.051637	0.515492	7
A3 - Medical equipment tracking	0.034766	0.046032	0.569717	6
A4 - Smart hospital rooms	0.048107	0.048191	0.500439	8
A5 - Medication services	0.033813	0.050095	0.597022	5
A6 - Electronic health record (EHR)	0.034056	0.053908	0.612839	4
A7 - Hospital clinical laboratory	0.031111	0.051741	0.6245	3
A8 - Hospital inventory management	0.029972	0.053697	0.641778	2
A9 - Hospital waste management	0.056175	0.048382	0.462737	10
A10 - Smart building	0.040983	0.039967	0.493724	9

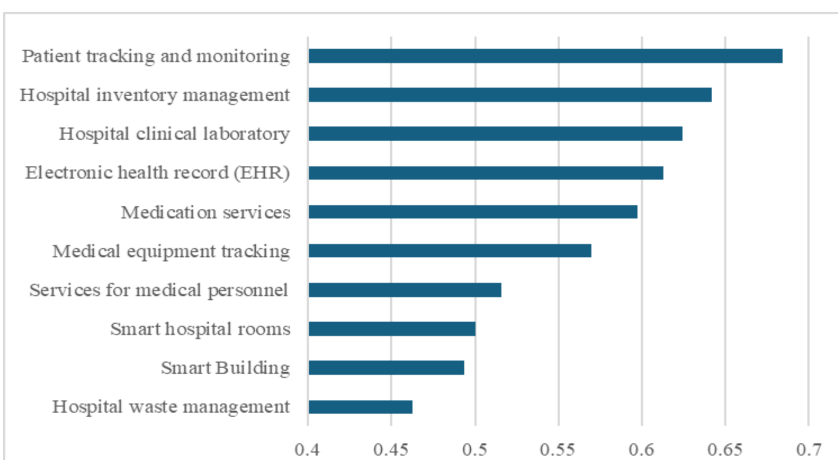

Figure 6: Final Rankings of Alternatives

1.3.6 Discussion

The first objective of this research was to identify different options for IoT applications and the related criteria for assessing those applications within a hospital domain. The study identified two main criteria, twelve sub-criteria, and ten IoT applications as alternatives.

The main objective of this research was to rank and prioritize the most appropriate alternatives based on the identified sub-criteria. This decision-making framework, along with all identified alternatives and (sub)criteria, is perfectly adaptable for implementation in hospitals worldwide. It is important to note that the results of this case study are well-suited to the context of Iran, as the expert panel was deliberately diversified, representing various departments and backgrounds. However, the outcomes may differ in other countries, depending on their unique preferences and priorities.

As these criteria/sub-criteria have different weights, we used a combined AHP-TOPSIS method. By adopting AHP, experts assigned different weights to each (sub)criterion, and the following are the insights we can draw from the AHP results:

- According to experts' opinions (Table 13), "health effectiveness" stands out as the most critical sub-criterion from a attractiveness perspective. However, this significance is understandable. By providing high-quality and precise treatments, health effectiveness could, directly and indirectly, address healthcare systems' core objective.
- The next two most crucial sub-criteria under the attractiveness criterion are "privacy and security" and "saving in costs". The latter targets the financial stability of the healthcare systems, enabling them to serve more patients and improve health outcomes without compromising quality. The former aims to improve the patients' trust by protecting health data from breach and unauthorized access.
- In the context of environmental attractiveness, experts have assigned less weight to "energy management" and "waste management." While these are crucial for the efficient and environmentally responsible operation of hospitals, the findings

indicate that they are considered less critical compared to sub-criteria that directly impact patient care and safety.

- On the other hand, in terms of readiness, experts consider the "cost of applications" as the most crucial factor in adopting new technologies in hospitals, indicating whether they can financially afford the new technology. The following two are "technological" and "cultural" readiness. Technological readiness is essential as the effective implementation of IoT in hospitals relies on having the necessary infrastructure, network, and systems in place; without a robust technological foundation, the full potential of IoT cannot be fully realized.
- Cultural readiness ranks third, indicating that the successful adoption of IoT in hospitals also depends on the willingness and ability of all stakeholders to embrace new technologies. Healthcare professionals need to be open to integrating IoT into their daily practices. This sub-criteria is key to overcoming resistance to change and ensuring that the human aspect of IoT implementation is handled smoothly.
- Our survey findings reveal another notable insight: Readiness is far more important than attractiveness when it comes to adopting new technologies like IoT in hospitals. This highlights the importance of preparation before integrating IoT. According to experts, hospitals must first assess and ensure that their existing capabilities, infrastructure, and conditions are well-aligned with the demands of IoT technologies. Only by confirming this readiness can hospitals effectively incorporate these innovations and enhance their performance in different .

Finally, in the last part of our research, the TOPSIS method shows the most appropriate IoHT applications based on the above-mentioned (sub)criteria. For each alternative, the score of C_i^* was calculated, indicating the rank of the alternative. Based on the experts' opinions, the final ranking of alternatives is as follows:

$$A_1 > A_8 > A_7 > A_6 > A_5 > A_3 > A_2 > A_4 > A_{10} > A_9$$

- As we can see, IoT applications for "patient monitoring and tracking" gained the highest value and ranked first among all alternatives as the most favorable regarding attractiveness and required readiness. These applications cover a wide range of in-body, on-body, wearable, digestible, implantable, etc. IoHT devices are capable of different tasks, such as vital signs monitoring, illness and symptoms prediction and detection, fall detection, depression and mood monitoring, etc. The "Patient monitoring and tracking" ranking as the top IoT application is logical due to its critical role in enhancing health effectiveness sub-criteria. These applications ensure continuous monitoring and quick response to patient needs leading to better resource management and significantly reducing waiting times.

- "Hospital inventory management" ranked second due to better scores from the readiness sub-criteria, including less technological and cultural readiness required. These applications could be adopted within different hospital departments, such as pharmacy storage rooms, blood banks, or regular daily supplies. IoT has access to a large amount of real-time data, ensures that the necessary medical supplies are always available, and the more efficient monitoring, planning, and management of hospital inventory.
- Surprisingly, "services for medical personnel" like telemedicine and telesurgery scored the same as "patient tracking and monitoring" for attractiveness criteria but ranked lower overall. This is mainly due to the higher level of investment, technological, and cultural readiness required, and the relatively high weights of these sub-criteria.

However, considering the high impact of readiness criteria such as technological readiness, cost of applications, and cultural readiness, it is important to mention:

- Although the AHP results show that the readiness sub-criteria are weighted significantly more heavily than the attractiveness sub-criteria, the TOPSIS results indicate that experts assign relatively similar scores to the alternatives across the readiness sub-criteria.
- Before the COVID-19 pandemic, doctor televisits were uncommon, but after that, people got culturally ready for such a visit. In the same way, IoT will become an inseparable part of our daily lives in the next few years, and the technological, cultural, and investment required to adopt it will become less and less significant. Therefore, we run a sensitivity analysis with different weights for two main

criteria, attractiveness and readiness, to find out how the rankings will change when weights vary in the future. As illustrated in Table 14, the alternatives' rankings fluctuate as the weight assigned to attractiveness increases from 0 to 1, indicating potential future changes in priorities as IoT adoption progresses.

Table 14: Sensitivity Analysis for Attractiveness and Readiness Criteria

Attractiveness Weights[1] →	**0**	**0.25**	***0.36[2]***	**0.5**	**0.75**	**1**
Applications ↓			**Ranks**			
A1 - Patient tracking and monitoring	5	2	***1***	1	1	1
A2 - Services for medical personnel	10	9	***7***	4	2	2
A3 - Medical equipment tracking	3	3	***6***	9	9	9
A4 - Smart hospital rooms	9	10	***8***	5	3	3
A5 - Medication services	7	7	***5***	3	5	5
A6 - Electronic health record (EHR)	4	4	***4***	6	6	6
A7 - Hospital clinical laboratory	6	6	***3***	2	4	4
A8 - Hospital inventory management	2	1	***2***	7	8	8
A9 - Hospital waste management	1	5	***10***	10	10	10
A10 - Smart building	8	8	***9***	8	7	7

1: $W_{attractiveness} = 1 - W_{readiness}$

2: Current weights based on the experts' opinions

- When attractiveness is given no weight (i.e., 0), readiness becomes the sole determining factor, with "Hospital waste management" ranked first, followed by "Hospital inventory management" and " Medical equipment tracking". This ranking highlights that these applications are the most feasible for immediate adoption, with the current hospital readiness.
- As the importance of attractiveness increases to 0.25, "Patient tracking and monitoring" rises to second place, reflecting its potential, while "Hospital inventory management" retains the top spot.
- At higher attractiveness weights (0.5 and above), "Patient tracking and monitoring" consistently holds the top rank, while applications like "Smart hospital rooms" and "Services for medical personnel" also move up the ranks. This shift reflects the expected rankings of applications when the weight of attractiveness in decision-making outweighs the readiness criteria.
- The sensitivity analysis clearly demonstrates that as attractiveness becomes a more critical factor in the future, IoT applications that provide greater environmental and resource efficiency, such as "Patient tracking and monitoring," will likely be prioritized. Meanwhile, applications requiring high

readiness but lower performance improvement potential, like "Hospital inventory management," may lose their rankings.

1.4 Conclusion

The Internet of Things (IoT) is a rapidly expanding emerging technology that has revolutionized many areas and developed new concepts, such as smart cities, smart energy grids, smart buildings, connected vehicles, and many others. One area that has gained much interest from policymakers and business owners is the Internet of Things. IoHT's role in healthcare is vital in advancing the quality of care, increasing operational efficiency, and improving the performance of the healthcare system. Hospitals, as the most critical service points in the healthcare sector, could greatly benefit from the IoHT. However, for this to happen, they must be aware of their different options and how to select the most suitable ones. Although several studies have discussed various IoHT applications within the healthcare sector, there is a lack of a decision-making framework tailored for hospitals to help them gain the most from their investment.

This study provides a comprehensive review of IoHT applications in hospitals and identifies the critical criteria for selecting IoHT. Firstly, through an extensive literature review, we categorized in-hospital IoHT applications into ten different applications within two main categories: medical and non-medical. Additionally, we outlined two primary criteria and 12 sub-criteria to rank these applications.

The decision-making framework, as well as the identified options and criteria, can be effectively applied in hospitals worldwide. However, it is important to highlight that the weights and final rankings in this case study are particularly relevant to the Iranian context, as the expert panel was intentionally selected to represent a wide range of departments and backgrounds. That said, the results may vary in other countries depending on their specific preferences and priorities.

The identified sub-criteria vary in importance compared to one another; therefore, AHP and experts' comparisons were used to assign appropriate weight to each sub-criterion. In the next step, experts were asked to score ten IoHT alternatives regarding twelve sub-criteria, and TOPSIS was used to prioritize the alternatives. This decision-making framework, with all identified alternatives and (sub)criteria, is adaptable for implementation in all kinds of hospitals worldwide, whether in the private or public sector, although the weights and final priorities may vary based on the country or hospital type. However, in this study, the framework was applied within the specific context of Iran as a case study. Data was collected through a survey of experts from TUMS, Iran's largest medical university. Experimental results show that readiness criteria are much more important than attractiveness criteria, indicating that hospitals must first assess and ensure that their existing capabilities align with the demands of IoT technologies before integrating them. The results outline the "Cost of applications" and "Technological readiness" as the most important ones. Also, "Health effectiveness" and "privacy and security" stand out as the essential criteria from the performance improvement viewpoint. On the other hand, criteria related to environmental performance improvement gained the least weight. The results of this research suggest that "patient monitoring and tracking," "hospital inventory management," "EHR," and "Hospital clinical laboratory" are the high-priority areas for IoHT adoption in hospitals.

This study provides valuable theoretical and managerial contributions. As far as we know, no research has focused on IoT explicitly tailored for hospitals. This research could serve as a starting point for the concept of IoHT applications and identifying appropriate criteria for hospital settings. Moreover, health policymakers and hospital managers could utilize this framework to evaluate, prioritize, and improve hospital performance using IoHT applications.

It is important to note that while this study provides valuable insights into IoHT applications, it does have limitations, and there are suggestions for future studies. The AHP and TOPSIS techniques use experts' opinions to compare and evaluate the alternatives. As the number of criteria or alternatives increases, the number of questions in the questionnaire and the time required to fill it out also increases. Therefore, we had to limit the sub-criteria to twelve and the alternatives to ten. For the future, we recommend conducting similar research focusing on either attractiveness or readiness criteria.

Hospitals consist of many stakeholders, including health providers, patients, technology providers, investors and financial stakeholders, regulatory bodies and government agencies, and insurance companies. The results of this research are structured based on the opinions of just healthcare providers and hospital administration. For future studies, we suggest conducting research from different stakeholders' points of view.

Future research could extend this study by conducting similar methodologies in other areas of the healthcare sector. Finally, other emerging technologies, such as artificial intelligence, cyber-physical systems, and big data analytics, when integrated with IoT, present promising avenues for further investigation. These technologies could be examined for their potential to enhance healthcare delivery, optimize hospital operations, and contribute to the broader transformation of the healthcare industry.

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General Conclusion

The Internet of Things (IoT) has rapidly turned into a key emerging technology, bringing innovative concepts like smart cities, smart energy grids, smart manufacturing, and connected vehicles. The IoHT has become increasingly important in the healthcare sector, offering the potential to enhance care quality, facilitate operations, and support sustainable healthcare practices. As a central point in the healthcare system, hospitals could greatly benefit from IoHT adoption. However, to unlock these benefits, it is crucial for hospitals to not only understand the various IoHT options available but also to have a clear strategy for selecting and implementing the most effective solutions. While there has been considerable discussion in the literature about IoHT applications in healthcare, a significant gap remains in providing hospitals with a tailored decision-making framework to guide their IoHT investments and ensure they achieve maximum impact. In this context, to adopt the most appropriate alternatives, hospitals must consider two sets of criteria: performance improvement (as attractiveness) and readiness (as capability). Readiness is defined by a hospital's technological infrastructure, the capabilities of its staff, the alignment of its organizational culture with innovation, and financial readiness. It means that if the hospitals are ready to adopt new technologies, considering their current situations and capabilities. On the other hand, attractiveness criteria focus on the long-term viability and ongoing effectiveness of the technology or system and performance improvement.

This study provides a comprehensive review of IoHT applications in hospitals and identifies the critical criteria for selecting IoHT. Firstly, through an extensive literature review, we categorized in-hospital IoHT applications into ten different applications within two main categories: medical and non-medical. Additionally, we provided an in-depth analysis of the criteria critical to the successful adoption and prioritization of IoT applications in hospitals. We outlined two main criteria, readiness and attractiveness, and twelve sub-criteria to rank these applications.

The identified sub-criteria vary in importance compared to one another; therefore, AHP and experts' comparisons were used to assign appropriate weight to each sub-criterion. In the next step, experts were asked to score ten IoHT alternatives regarding twelve sub-criteria, and TOPSIS was used to prioritize the alternatives.

The findings outline the importance of readiness as the cornerstone for the effective implementation of IoT technologies, indicating that hospitals must first assess and ensure that their existing capabilities align with the demands of IoT technologies before integrating them. Without readiness elements, the full potential of IoT technologies, regardless of their impacts on performance improvement, cannot be realized. While improving performance is crucial for technology adoption, it becomes a priority only after the hospital is fully prepared to implement and manage the change. Experimental results show that the "Cost of applications" and "Technological readiness" are the most important ones. Also, "Health effectiveness" and "Privacy and security" stand out as the essential attractiveness sub-criteria. On the other hand, criteria related to environmental performance improvement gained the least weight. The results of this research suggest that "Patient tracking and monitoring," "Hospital inventory management," "Hospital clinical laboratory," and "EHR" are the high-priority areas for IoHT applications in hospitals.

The study offers important contributions to theory and management. To our knowledge, there has been no prior research focused on IoT tailored specifically for hospitals. This research could help identify suitable criteria for hospital settings and serve as a foundation for IoHT adoption. The findings of this study, particularly the prioritization of high-priority areas for IoHT applications in hospitals, provide valuable insights that can inform and enlighten healthcare policymakers, hospital managers, and researchers in the field of IoT and healthcare technology. Additionally, policymakers and hospital managers could use this framework to assess, prioritize, and enhance hospital performance through IoHT applications.

However, it is worth noting that despite providing valuable insights into IoHT applications, this study does have some limitations, and there are suggestions for future research. AHP and TOPSIS techniques rely on expert opinions to compare and evaluate alternatives. As the number of criteria or alternatives increases, the number of questions in the questionnaire and the time required to complete it increases. Due to this, we had to limit the number of sub-criteria and alternatives to twelve and ten, respectively. For future studies, it is suggested that similar research be conducted specifically for each attractiveness or readiness criterion.

Hospitals involve various stakeholders, including health providers, patients, technology providers, investors, regulatory bodies, government agencies, and insurance companies. The results of this research are based on the opinions of only healthcare providers and hospital administration. For future studies, it is recommended that research be conducted from the perspectives of different stakeholders. Additionally, integrating other emerging technologies such as AI, cyber-physical systems, and BDA with IoT offers exciting opportunities for further exploration.

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Appendix 1: Questionnaire

Demographic Information

Type of position (you could choose more than 1 option for this question):

☐Medical doctor (Fellow/Resident/…)

☐ Allied health staff (Pharmacist/ Laboratory technologist/…)

☐ Nurse (Clinical/Emergency room/...)

☐ Directing Board

☐ Medical Director

☐ Head of Department

☐ Academic Faculty

☐ Others (please indicate): …………

Academic education background (you could choose more than 1 option for this question):

☐Medicine

☐ Nursing

☐Public Health

☐Science

☐Management - Health information

☐Others (please indicate): …………

Level of education (you could choose more than 1 option for this question):

☐ Bachelor's

☐ Master's

☐ Medical Doctor (MD)

☐ Doctor of Philosophy (Ph.D.)

☐Others (please indicate): ……………

Years of experience:

☐less than 2 years

☐2 to 5 years

☐6 to 10 years

☐more than 10 years

Instruction for the 1st part:

In this part, we provide the instructions for scoring and comparing different criteria:

- If you consider the item in the left column of the table more important than the factor on the right side in the same row, then indicate the most appropriate number on the left side of the "equa"column, indicating the relative importance of those two items.

- If you consider the item in the right column of the table more important than the factor on the left side in the same row, then indicate the most appropriate number on the right side of the "equal" column, indicating the relative importance of those two items.

- If you consider the two items in the same row equally important, indicate the "equal" column or 1.

Intensity of Importance	Definition	Explanation
1	Equal importance	***i*** and ***j*** have the same importance
3	Moderate importance	Item ***i*** is slightly more important than item ***j***
5	Strong importance	Experience and judgment strongly favor ***i*** over ***j***
7	Very strong importance	***i*** is favored very strongly over ***j***
9	Extreme importance	***i*** is absolutely more important than ***j***
2 – 4 – 6 – 8	Intermediate values	Applicable when compromise is needed among items

- If you need more information about the comparing factors please read the explanation part at the end of this questionnaire.

- Please pay attention to the consistency of your comparison. For example, if you consider item A more important than item B, and item B more important than item C, then you would consider item A more important than item C.

Criteria i		9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Criteria j	
		i is more important								Equal	j is more important									
1	Attractiveness	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Readiness	1

Attractiveness Criteria

Sub-criteria i		9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Sub-criteria j	
		i is more important								Equal	j is more important									
1	Health Effectiveness	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Patient Waiting Time	1
2	Health Effectiveness	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	24/7 Availability	2
3	Health Effectiveness	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Privacy and Security	3
4	Health Effectiveness	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Energy Management	4
5	Health Effectiveness	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Waste Management	5
6	Health Effectiveness	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Resource Conservation	6
7	Health Effectiveness	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Saving in Operational Costs	7
8	Patient Waiting Time	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	24/7 Availability	8
9	Patient Waiting Time	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Privacy and Security	9
10	Patient Waiting Time	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Energy Management	10
11	Patient Waiting Time	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Waste Management	11
12	Patient Waiting Time	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Resource Conservation	12
13	Patient Waiting Time	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Saving in Operational Costs	13
14	24/7 Availability	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Privacy and Security	14
15	24/7 Availability	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Energy Management	15
16	24/7 Availability	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Waste Management	16
17	24/7 Availability	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Resource Conservation	17
18	24/7 Availability	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Saving in Operational Costs	18
19	Privacy and Security	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Energy Management	19
20	Privacy and Security	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Waste Management	20
21	Privacy and Security	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Resource Conservation	21
22	Privacy and Security	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Saving in Operational Costs	22

Attractiveness Criteria																				
Sub-criteria i		i is more important								Equal	j is more important								Sub-criteria j	
		9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9		
23	Energy Management	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Waste Management	23
24	Energy Management	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Resource Conservation	24
25	Energy Management	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Saving in Operational Costs	25
26	Waste Management	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Resource Conservation	26
27	Waste Management	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Saving in Operational Costs	27
28	Resource Conservation	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Saving in Operational Costs	28

Readiness Criteria																				
Sub-criteria i		i is more important								Equal	j is more important								Sub-criteria j	
		9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9		
1	Cost of Application	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Technological readiness	1
2	Cost of Application	☐	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Required expertise and skill sets	2
3	Cost of Application	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Cultural Readiness	3
4	Technological readiness	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Required expertise and skill sets	4
5	Technological readiness	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Cultural Readiness	5
6	Required expertise and skill sets	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Cultural Readiness	6

Instruction for the 2nd part:

- Please indicate how much you agree or disagree that "application X (in the row) could improve attractiveness criterion Y (in the column)" using a 7-point Likert scale:

Intensity of Importance	Explanation
1	Strongly disagree
2	Disagree
3	Somewhat disagree
4	Neither agree nor disagree
5	Somewhat agree
6	Agree
7	Strongly Agree

No.	Applications	Health Effectiveness	Waiting Time	24/7 Availability	Privacy and Security	Energy Management	Waste Management	Resource Conservation	Saving in Operational Costs
1	Patient tracking and monitoring								
2	Services for medical personnel								
3	Medical equipment tracking								
4	Smart hospital rooms								
5	Medication services								
6	Electronic health record (EHR)								
7	Hospital clinical laboratory								
8	Hospital inventory management								
9	Hospital waste management								
10	Smart Building								

- Please indicate the level of criterion Y (in the column) needed to adopt application X (in the row) using a 7-point Likert scale:

Intensity of Importance	Explanation
1	Very low
2	Low
3	Somewhat low
4	Neither low nor high
5	Somewhat high
6	High
7	Very high

No.	Applications	Cost of Application	Technological readiness	Required expertise and skill sets	Cultural Readiness
1	Patient tracking and monitoring				
2	Services for medical personnel				
3	Medical equipment tracking				
4	Smart hospital rooms				
5	Medication services				
6	Electronic health record (EHR)				
7	Hospital clinical laboratory				
8	Hospital inventory management				
9	Hospital waste management				
10	Smart Building				