Towards a new era of IoT applications to overcome Pandemic situations: Intelligent systems and recovery strategies to overcome Covid-19

Dr. Manpreet Kaur Maan, Dr. Inderjit Kaur
1SGGS College, sec-26, Chd., 2Akal Group of Technical and Management Institution

Abstract—Since its emergence, the Internet of Things (IoT) applications have proved their effectiveness in several areas or social activities. The economic, scientific, and social interests of these applications are to establish an enhanced environment based on sustainable development, by ensuring the growing convergence between the reinforcement of traceability and development mechanisms of activities and people, mobility advances and security, and also among intelligent systems. However, economic and technological advances can be disrupted by various situations, including pandemic situations, disrupting normal life, and forcing a consistent change in priorities as well as the policies of nations. These variations are considered catalysts for technological improvement and innovation. In this paper, we discuss the case of Covid-19 as a pandemic that impacted the adoption of IoT in countless sectors namely smart homes, healthcare, transportation, smart buildings, smart cities, and industrial fields. Analyzing the impact of Covid-19 on IoT adoption allowed us to highlight the main challenges that need to be addressed as well as the important research directions to increase IoT adoption in these sectors.

Keywords—Internet of Things (IoT), COVID-19, Smart Homes, Healthcare, Smart Buildings, Smart Cities, Transportation, Industrial IoT.

I. INTRODUCTION

In the history of humanity, pandemics occur as a result of some imbalances or disparities due to either social or environmental changes e.g.: wars, agricultural revolution, great discoveries, and colonial empires, the industrial revolution, and globalization, etc. The consequences of a pandemic have proved to be quite significant, millions of people can die, which impacts the demography, and the economy can be disrupted, which influences the stability of countries as well as individuals. The year 2019 will be remembered in history as the year of the global coronavirus spread. This disease has impacted globally not only healthcare systems, but also educational systems, the economy, social life, as well as public governance. The rise of coronavirus disease has pointed out the vital need to predict the potential threats to conceptualize pandemic situations.

To overcome the COVID-19 crisis, each country plans and adopts its anti-contagion strategies based on some current, historical, and context-specific path, which contains several stages e.g.: studying, learning, developing, negotiating with others, and sharing ideas across governments, etc. These stages are subject to numerous conditions such as cultural or social orientations, economic conditions, institutional landscape, and political styles.

During Covid-19, governments have been dealing with a high degree of sensitivity to the political situation, uncertainty, and disagreements over stringent policy measures, as well as worries regarding the duration and the end of the adopted measures. That has created a remarkable precision to use advanced technologies and improve decision-making to overcome pandemic situations. Among the disciplines, which have contributed to the control of the situation, the Internet of Things (IoT), which can be simply defined as interconnected devices able to sense, and transfer data which to be analyzed and use a capital of intelligence for decision making to overcome pandemic situations.

IoT technologies have proved promising benefits for different domains such as manufacturing, healthcare, agriculture, transportation, and telecommunication. Regardless of the huge benefits of the IoT, its adoption has been significantly slower than estimated [2, 3] due to various reasons including privacy, security, and trust issues, the structural inertia, the lack of considerable use cases with a strong return on investment, the long capital cycles, as well as the lack of specialist workforce to implement IoT [2, 3, 4, 5].

Since its sudden emergence, the coronavirus pandemic has impacted human life and has made it difficult to return to a normal lifestyle. For that, COVID-19 has promoted the digital transformation [6, 7], and forced individuals, organizations, and governments to review and adapt their priorities as well as their operational process. This has triggered a strong need to overcome the reasons already mentioned and adopt IoT faster in many sectors. For example, many governments have invested interesting resources in IoT and intelligent technologies to fight COVID-19. Also, the new lifestyle, especially studying or working from home, has proved the huge importance of IoT technologies for remote asset control, employee tracking, and remote decision making [8]. Thus, many governments have amplified their investments in IoT [9, 10]. Moreover, the global war against COVID19 has resulted in a less strict stance on privacy issues, higher trust in technology, and fast-tracked approval procedures. Moreover, the global war against COVID19 is characterized by a less stringent interest in privacy concerns, as a high reliance on smart technologies and procedures allows the safety of human life first and the limitation of accelerated contamination. This also highlights the importance of faster adoption of IoT in various sectors.

In this paper, we study and discuss the impact of the COVID-19 pandemic on the adoption of IoT in different sectors. Since the appearance of the first cases of COVID-19, various papers have been published addressing IoT and COVID19 situations [11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. Yet, our work meaningfully gives different aspects. Firstly, the majority of the existing works focus on
IoT in healthcare in an exclusive way, which is normal because COVID-19 is a health crisis. Though, this pandemic has impacted practically every aspect of the human race. For this reason, we studied its impact on IoT uses in several important sectors, of course, including healthcare. Secondly, the existing works frequently focus on the use of IoT and intelligent technologies to overcome COVID-19. Instead, despite some similarities, our focus is mainly directed to discuss the impact of COVID-19 on adopting IoT. Otherwise, although these existing works focus on the way IoT impacts COVID-19, we focus on the way COVID-19 is impacting the use of IoT in various sectors. Finally, several existing works only discussed the potential applications of IoT for COVID-19 and, yet, we discuss the impact of COVID-19 on the adoption and implementation of IoT as well as its new leads, which have been accepted and approved by researchers.

The rest of this paper is organized as follows. Section II presents a general overview of the existing works that discuss COVID-19 and digital technologies, especially IoT. Section III explains the impact of COVID-19 on different IoT uses. In Section IV, we discussed the challenges as well as the important research directions. The conclusion is presented in Section V.

II. RELATED WORKS

Coronavirus disease has appeared in 2019, as a new virus never seen before, the entire human population is hypothetically vulnerable to COVID-19 infection [21]. Rocking and disrupting the world, COVID-19 impacted the normal living way, which people adopted before in cities and society. For example, as a result of the pandemic consequences and the need for distance and hygiene, people are increasingly favoring the use of private cars, contrary to all the debates that have previously supported urban mobility [22, 23, 24, 25]. To this end, many studies have shown that better transportation decision-making requires consideration of sustainability as well as the quality of life in cities, which are subject to high motorization and increasing mobility loads [26, 27].

A review of the underlying literature reveals a limited number of studies on the interference between human mobility and viral epidemics. Some of these works have assessed the impact of the earlier outbreak on travel behavior and economic consequences e.g.: SARS and H1N1 [28, 29, 30]. These studies have shown a rather remarkable decrease in mobility during pandemic periods. However, they are limited to the short term, studying just the pandemic period without exploring the post-pandemic world. This encumbrance that has traumatized the mobility of human beings has disrupted the world economy, so governments have been forced to find quick and efficient solutions. This has amplified the need for the adoption of technologies that can remedy the problem of mobility of people, in a sanitary setting, to carry out different daily tasks.

In the last two years, many researchers have discussed the vital importance of using IoT and intelligent technologies to deal with COVID-19 or even with possible future pandemics. Kadi studied the adoption of digital technologies and highlighted the impact of COVID-19 for the adoption of various concepts e.g. e-Commerce, e-Health, e-work, and e-Education [6]. Ndiaye et al. have presented a detailed review on IoT contributions in healthcare during COVID-19 [11]. They enlisted recent advances in Healthcare IoT (HIoT) and outlined a comparison of different IoT application strategies before and during COVID-19. Bai et al. presented an agreement of various Chinese experts on IoT-aided diagnosis of COVID19 [12]. Singh et al. have enlisted the different impacts of IoT implementation in healthcare considering time, cost, and efficiency [13].

Ting et al. have explored various applications of IoT, AI, Big Data, and Blockchain to mitigate the impact of COVID-19 [14]. In that context, some IoT applications that can be useful to fight COVID-19 were presented by Rahman et al. [15]. Javaid et al. have discussed how different Industry 4.0 technologies are contributing to pandemic mitigation, especially IoT, AI, and Virtual Reality [16]. Vaishya et al. presented some applications of artificial intelligence for COVID-19 [17]. Chamola et al. presented a comprehensive analysis of the COVID-19 pandemic as well as the role of IoT and intelligent technologies i.e.: AI, drones, 5G, and blockchain, in handling its influences [18].

Mokbel et al. have proposed fully automated contact search architecture [19]. Nasaijpour et al. discussed various IoT applications in healthcare through three main stages: early diagnosis, quarantine, and post-recovery [20]. Recently, Nayak discussed the importance of using Artificial Intelligence AI, Machine Learning ML, and additional intelligent technologies for the prediction of COVID-19 [31]. In the same sense, Dong and Yao used IoT solutions to combat COVID-19. They presented a detailed study on the capabilities of existing IoT systems. Thus, they discussed the benefits of IoT applications for COVID-19 diagnosis [32].

Alam proposed a four-layered architecture using Blockchain and IoT technologies to fight COVID-19 [33]. The Blockchain warranties the privacy and security of the shared information among IoT nodes. Kelly et al. discussed the role of IoT in existing healthcare infrastructure [34]. They also highlighted the implications of IoT data to enhance healthcare infrastructure and simplify the decisions making. Besides, they enlisted the existing enablers and difficulties in implementing IoT-based healthcare.

Golinielli et al. presented a survey denoting the initial efforts in adopting digital healthcare technologies to fight against COVID-19 [35]. Chang studied the limitation of the existing AI techniques to master the pandemic situations, and highlighted the need of using AI-based approaches to predict and overcome future pandemics [36]. Abir et al. explained the importance of the use of both AI and IoT to potentially fight against COVID-19 [37].

III. IMPACT OF COVID-19 ON IOT AND NEW LEADS

The pandemic coronavirus disease appeared in 2019, shortened to COVID-19, due to a new virus acknowledged as Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2). This virus is defined by impulsive respiratory infections, which can cause fatal and severe life-threatening symptoms [21]. COVID-19 has caused systematic changes, including macroeconomic changes, in global societies and organizations [38, 39].
A. IoT importance in life

Understanding the Internet of Things concerning its various applications is of paramount importance to ensure a radical change in people's habits and lifestyles. By the way, the IoT can be defined by the exchange of information and digital data between the objects present in the real world and the Internet network. It allows the collection of user data to interact between different connected objects either via Wi-Fi or Bluetooth. The Internet of Things uses a variety of information and communication technologies, both old and new, to provide systems capable of:

- Collect, store and process data;
- Communicate and interconnect;
- Ensure the ubiquity of information;
- Improve self-control and learning abilities.

For the complete networking of devices, it is essential, first of all, to ensure an extremely mobile Internet to be able to overcome the obstacles of the speed of data transfer, evaluation, and security of processing, while benefiting from networks with a wide variety of devices and technical architectures such as:

- Measuring sensors that record physical or chemical states (such as temperature, pressure, brightness, humidity, pH, or motion) to make the measurement results usable digitally, and then translate them into electrical signals;
- RFID (Radio Frequency Identification) is a technology allowing the identification without contact of an object using electromagnetic waves. To allow the reader to recognize and locate it, the object is equipped with a radio tag and a unique code;
- Location technologies such as GPS, WLAN, and Bluetooth, which can overcome even greater distances and transmit more information;
- Wireless networks are based on 3G (UMTS) and 4G (LTE) mobile communications, but they are not instantaneous. A newer generation is needed for high data volumes and real-time transmission. In the future, the following standards are expected to advance networking:
  - 5G: the fifth generation of mobile communications standards represents a major step forward in development: 5G can handle 10,000 megabits per second;
  - NarrowBand-IoT (NB-IoT): This radio technology is also an innovation. Although it only transmits small amounts of data, it has other advantages: thanks to its high signal strength, it also reaches hard-to-reach places, such as underground receivers or devices in thick-walled systems.
- Cloud technologies that offer powerful virtual storage and data processing networks;
- Embedded computing: microprocessors and thin computing systems that work only in conjunction with other devices;
- Intelligent systems that are based on artificial intelligence technologies.

The uses of the Internet of Things result in numerous applications that have a significant impact on the daily lives of individuals, businesses, and communities. The potential benefits expected to facilitate its adoption by this diversity of users. IoT applications have been questioned either for security or safety reasons. However, since 2019 and the emergence of Covid-19, the scope of IoT application is accentuated by requiring a strong speed of adoption of new IoT solutions in different sectors. Monitoring and controlling this pandemic required new strategies as well as cross-border policies by different governments [40]. This required rapidly sharing of global facts and study of information behavior [41]. This has promoted the adoption of IoT as well as smart technologies in different fields, especially in healthcare, and education. Financially, in the short term, the global recession has damaged all economic sectors. Yet, in the medium and long term, this pandemic has triggered a real need to accelerate IoT adoption in extra sectors.

B. General Impact

The sudden appearance of this pandemic is affecting the whole of society by hindering daily activities in a more and more direct way. Practically, COVID-19 has a significant impact on everything while the features and final consequences remain unclear. This leads to unsuccessful pandemic planning and management. Essentially, understanding the role of advanced technologies in supporting individuals and governments provides new perspectives to manage the pandemic successfully. These technologies aim to afford rapid communication, seamless connectivity, technological influence in healthcare, mobility, surveillance and security, digitalization, etc.

The lockdown, as well as health strategies, has opened up a range of opportunities to adopt IoT by offering innovative solutions that remedy user needs while meeting priorities and requirements for a new normal. In this sense, the technical and research teams are driven to provide new products and services, which are aligned with the new user requirements. Figure 1 describes a view of the impact of COVID-19. To achieve this, organizations are forced to devote considerable budgets to research and development to align with new research issues. Around the world, governments are facing a severe crisis, which needs good decision-making regarding the rapid changes on the ground conditions, as well as the possible profound future uncertainties. Given the significant costs of the COVID-19, on humans or economic systems, the actions of governments are under increased inspection. And as this pandemic progresses, a glaring reality is coming into strong and clear relief: the challenges and the impacts of COVID-19 are not fairly or regularly dispersed across societies.
For the first time in history, overnight people all over the world have been disrupted by closing schools, borders, common spaces, and the need to work remotely. The only option is to use technology platforms, IoT tools to ensure some sort of inter-connectivity between different users and carry out the necessary functionality. Common technologies could offer people new alternatives to learn, work, communicate with family or friends, and live with the help of smart technologies and especially with the help of Internet access. The general outcomes and impacts of coronavirus pandemic have proved the need to adapt research agendas for the upcoming decades.

Since the appearance of this pandemic, many research teams are focusing on examining and detecting COVID-19. For that, our study is focused on the way COVID-19 is impacting the use of IoT. Over the past decade, researchers have examined and proved the importance of intelligence. More recently, they have tracked and studied the uses of IoT as new dynamics to manage several processes taking into account the strong pandemic pressure. Connected tools have provided citizens with the ability to access essential services via various technologies. This has served to sharpen the focus on the challenges that can plague governments to provide effective and timely key solutions. In particular, COVID-19 upset one racial and equity group, highlighting the need for rapid and widespread adoption of IoT technologies to implement smart solutions that facilitate the work of governments by addressing these impacts in a robust manner.

**C. IoT on Healthcare**

The healthcare industry is in a state of great despair. Healthcare services are more expensive than ever, the world's population is aging and the number of chronic diseases is increasing. As a healthcare crisis initially, the direct impact of COVID-19 on healthcare industries is more obvious. Juniper Research has denoted that IoT incomes are expected to increase by nearly 20% due to its enhanced adoption in the healthcare sector [42].

**Fig. 1. The impact of COVID-19 on IoT adoption**

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**Fig. 2. Advanced IoT architectures for Healthcare sector**

**Fig. 3.**
The acceleration of IoT adoption in this sector requires taking into account changes in regulations and procedures, requirements and innovations of wearable devices, as well as testing and traceability needs, as illustrated in Fig.2.

1) Changes in regulations and procedures

The Internet of Things (IoT) paradigm has broad applicability in many fields, including healthcare. Certainly, IoT cannot prevent the population from aging or eradicate chronic diseases at the same time, but it can at least facilitate the work processes in the healthcare sector, especially in terms of accessibility. In these past years, the full adoption of this paradigm in the health field was a mutual hope, as it allows medical centers to operate with more competence and patients to get better treatment. So its applications have been quite slow because of regulatory policies regarding privacy, approval procedures, and data security.

With the sudden arrival of Covid-19, health systems have been forced to quickly adopt regulations regarding emergency procedures, including validating the adoption of new technologies as soon as possible. This acceleration of IoT adoption can be explained by different examples such as:

- The U.S. Food and Drug Administration (FDA) have granted an emergency certificate of approval for the use of a low, digital ejection fraction electrocardiogram tool. Also, the FDA certified the possibility of using AI-CT algorithms from the technology company Aidoc for the detection of COVID-19 [43].
- The Eko’s electrocardiogram low ejection fraction tool, which can help clinicians to spot cardiac complications related to the coronavirus disease [44].
- Lumify, a wearable ultrasound device from Philips, has received FDA clearance. Lumify features a sensor connected to users' smartphones to improve patient care while connecting professionals, locations, and patients [45].

The World Health Organization (WHO) has warned that the rate of infections is quite high in overpopulated hospitals and emergency rooms [46]. Accordingly, adjusting healthcare systems to minimize hospital visits has triggered a huge need for new procedures, in particular the acceleration of adopting telehealth and home care. Numerous countries have been encouraging the use of telehealth services on their public health programs, which can be accessed via the internet. The severe and urgent rise in the use of telehealth has boosted the adoption of IoT technologies in the healthcare sector.

The use of these healthcare methods based on IoT and smart technologies guarantees unparalleled benefits that could improve the quality and effectiveness of treatments, protect patients from infections, and consequently improve the performance of the healthcare system. For this purpose, different analyses have highlighted the relationship between telemedical diagnostic systems, smart systems, the Internet of Medical Things (IoMT), IoT technologies, as well as the machine learning and Big Data techniques for the prevention of COVID-19 [47, 48]. Therefore, new IoMT platforms have been proposed for virtual, remote monitoring and follow-up [49, 50, 51, 52].

2) Requirements and Innovations of Wearable Devices

For many years, wearable devices, such as smart watches or wristbands, have been serving humans. However, since December 2019, their uses had known an undeniable increase to fight COVID-19, and of course, had gained more interest in managing other future pandemics [53]. The collected data from these devices may have alerted users to the case of changes associated with COVID-19 [54]. Wearable devices have also contributed to ensuring social distancing or disseminating health information [55], facilitating tracking and contact tracing [56], as well as providing mental consultation and care [57, 58]. To overcome the pandemic, different applications are boosting the use of wearable tools. This denotes the revolution in healthcare through IoT technology [59], with an increase in investments, which would exceed $64 billion in 2024 [60].

In this sense, different collaborations have been created. The WHOOP bracelet, which is one of these examples, allows the measurement of the respiratory rate according to the resting heart rate (RHR) as well as the heart rate variation (HRV). The collected data from WHOOP are transferred to the corresponding mobile application and then sent to the WHOOP system in the cloud [61]. Philips has also industrialized disposable patches for the COVID-19 early detection [43] as well as disposable biosensors to detect early COVID19 patient deterioration [62].

In recent years, the study of data from IoT systems has enabled the diagnosis of various diseases such as asthma and pneumonia via the analysis of cough records [63]. Researchers at Harvard University and MIT used AI to study whether COVID-19 subjects could be accurately distinguished from just a forced cough on a cell phone [64]. The system was based on more than 5000 cough recordings. The results show that this model detects COVID-19 subjects with an accuracy of 97.1%. This highlights the potential of incorporating smart solutions into wearable devices to provide real-time, non-invasive solutions for disease outbreak prediction and surveillance [65, 66, 67, 68, 69].

3) Testing and traceability needs.

In recent years, COVID-19 tracking and tracing via IoT tools has helped reduce the transmission of this pandemic. Thus, IoT has become a mainstay for test and trace applications, which has accelerated the adoption of IoT technologies [70, 71] provided an analysis of 13 technologies, to spot users with COVID-19 symptoms to fight COVID-19 as well as the possible future pandemics. All over the world, numerous countries have adopted digital test and traceability tools, including South Korea, the UK, Vietnam, Germany, Spain, etc. [72, 73] The UK’s test system has traced 20% of the targets [74]. The Taiwan experiment has successfully used IoT test systems to fight against COVID-19 [56]. These systems are based mainly on two layers:

- Data Acquisition: User mobility data is obtained from multiple sources, such as GSM and GPS data, immigration databases, QR codes tracking, etc. This has enabled the tracking of international and local travelers. In addition, other smart solutions are used, especially CCTV cameras [75], credit card tracking to predict user activities and peak areas [76], and hospital visits tracking systems to facilitate contact tracing [77].
- Data Integration: data from different sources are incorporated and shared with relevant departments [78, 56, 79].
D. Boosted IoT in smart cities

Many facets of human life have been affected by COVID-19, especially the growth of internet operations, disruption of supply chains, energy demand rates, reduction in traffic and use of public transportation, etc. According to ABI Research reports, governments are striving to reform and strengthen their urban resilience to digital transformation to overcome the impact of COVID-19 [80]. To this end, numerous technologies have been deployed to meet new needs that emerged during the pandemic, i.e.: new surveillance tools, drones, digital twins, autonomous freight, and real-time dashboards [80]. Despite the financial implications of COVID-19, governments have moved to invest heavily in technology to support businesses and boost the economy [81]. Figure 3 illustrates the impact of COVID-19 on smart cities. Various insightful strategies are framed where the developed implementation of the used technologies is expected, and the revealed pandemic impacts in such strategies are analyzed. The framed strategies aim to advance the supply chain system, digitalize the energy sector, support the city, and offer a tracking system for the virus spread.

![Image](https://example.com/image.png)

**Fig. 4.** Recent advances in Smart Cities during COVID-19 pandemic

1) Innovations and leading smart cities

In recent years, more people are moving to cities around the world. The increase in urban population is challenging the infrastructure and services adopted. Indeed, cities assemble more than half of the world's population. These inhabitants move, consume energy, water, and other basic needs. This favors the use of the Internet of Things (IoT) technologies to provide the population with new scalable and intelligent systems. These systems ensure a better response to residents' demands and provide more efficient services. Intelligent IoT solutions optimize urban infrastructure to better involve the population in the management and adaptability of services.

Smart cities are based on advanced technologies to enhance life quality, increase efficiency, and ensure economic development and sustainability. These promising technologies support city development including health, energy, and transportation. Smart cities promote societal advancement. Smart cities, which are equipped with a center connected to IoT devices, i.e.: sensors or cameras are better prepared for contingencies such as disasters and pandemics [82]. The world's leading smart cities (e.g. Singapore, Dubai, Oslo, Hong Kong, Seoul, Taipei, etc.) have already had their interests and investments in smart technologies for years to make them livable, resilient, sustainable, and competitive. As a result, these cities had the advantage of acting more effectively, and more quickly during the COVID-19 crisis [83].

"TraceTogether" is an app launched in Singapore to facilitate the search for contaminated individuals by tracking nearby events [84]. "Safe Entry" is also a mobile app, which scans the QR code at the entrance of public places. The data collected is useful for tracking the spread of the corona virus in the city. Categorical surveillance of COVID-19 suspects is implemented in Helsinki via the use of laboratory registry data [85]. COVID-19 precautionary measures are supported in Seoul through the use of a dynamic dashboard collecting important information on confirmed positive cases, including their mobility details [86]. Similarly, Taiwan has implemented additional contact tracing controls that have kept mortality rates low [83].

2) Enhanced Sensing for Sustainable Smart Cities

Since the beginning of the COVID-19 pandemic, sensors are being installed more in smart cities. Mainly, the use of thermal cameras has seen strong growth of 83% [87]. Drones too are being used more not only for delivery [88] but also for social distancing monitoring [89]. In the same context, the SkyNet project in China, with more than 20 million cameras installed and connected, has contributed to the identification and monitoring of densely populated areas in cities [90]. Other countries have adopted surveillance strategies, which respect the privacy of citizens by using radar and LIDAR [91]. For better detection coverage, many researchers have proposed advanced solutions to combat COVID19. For example, the Honghu Hybrid System (HHS), which is designed for COVID-19 data collection, integration, standardization, and analysis, includes several units i.e.: diagnostic labs, a case reporting system, electronic medical records, as well as social media on mobile devices [92].

Smart cities have contributed to the successful management of the COVID-19 pandemic, yet this is not the only pandemic that humanity has faced or will face. So, in the future, there are strong possibilities of recurrent natural disasters, pandemics, and man-
made issues. Since more than half of the world's population resides in urban areas, it is not surprising that approximately 95% of COVID-19 cases have been detected in these areas. The COVID-19 pandemic has highlighted that areas with larger populations are more vulnerable to disasters. This has accentuated the growing interest in developing smart cities that take into account sustainability and economic and ecological efficiency to cope with either man-made disorders or natural disasters. Some smart cities have shown promoting efforts to build sustainable smart cities. A cyclical framework was devised by PwC Middle from the leading smart cities [93]. This framework is meant to ensure the sustainability of environmental, societal, and economic issues in a smart city by covering sustainable energy systems, smart communications, and resilient water networks [94].

E. IoT for Smart buildings

The smart building consists of equipping buildings with intelligent systems based on IoT technologies. The main objective is to ensure optimized energy management, increased comfort of the residents, and improved safety of the whole building. Smart building involves many building trades. Whether in construction or renovation, the real estate developers, as well as the housing designers are concerned, as well as builders, architects, managers, etc. The smart building is a design and contemporary solution in addition to being connected. This technique consists of using advanced technologies to create infrastructure that meet today's needs. Apart from homes, the smart building is also a solution for businesses. Indeed, the connected building allows creating a real ecosystem of services that can be used by employees. The building environment is not managed by the residents but by the employees to optimize the consumption and comfort of the space in which they work.

1) Smart Building Management

The strict sanitary and closing measures have influenced the pedestrian traffic in the buildings, which has caused the bankruptcy of several offline businesses and stores. As COVID-19 has impacted the world economy, it also has an insightful impact on building environments [95]. For this, during the closure, the majority of malls turned into warehouses regarding the growth of e-commerce [96]. This triggered a huge need to expand data center capacity to meet the demand [97], so more data centers were built following the "x from home" trends [98].

![Smart Building Diagram](image)

**Fig. 5. Recent advances in Smart Buildings during COVID-19 pandemic**

With the new needs, new requirements must be considered, for example, intelligent HVAC systems, occupancy tracking/control, social distancing, heating systems, and more stringent cleaning requirements. This has highlighted the importance of IoT in buildings [99, 100], to provide more efficient facility management and support a safer and healthier environment [101]. Yet, investments in this area of intelligent buildings have also been affected due to the financial stress of organizations. As a result, forecasts show a sharp decline in the global smart building market, followed by a recovery in 2023 [102].

Globally, we can infer that despite the short-term decrease of the global investment in intelligent buildings, some applications put at the service of buildings are experiencing an increase in investment (for example, security and health applications). Verdantix conducted a global enterprise survey of 250 executives [103], this showed that 24% of organizations have slowed down their digitization due to the economic impact of COVID-19. 47% are considering new investments in technologies (e.g., thermal imaging, new surveillance visions, etc.) to strengthen their work and ensure their sustainability in the market. Figure 4 illustrates a summary of innovations and work on selected domains, impacted by COVID19, that consolidate the importance of IoT adoption in smart buildings.

2) Smart HVAC Systems

All buildings, whether residential, commercial, or industrial, need an air-conditioning system. When the temperature inside is not high enough, or not low enough, it leads to a drop in productivity, damage to property and equipment, and even breakdowns that can interrupt business. It is therefore essential that you have a perfectly reliable HVAC system. Heating, Ventilation, and Air Conditioning (HVAC) measurement and control systems monitor humidity, flow rates, outdoor and indoor temperatures, differential pressures, and equipment status. HVAC systems can activate and proportionally control valves, boilers, heat exchange units, pumps, fans, and ventilators.

Lighting, air quality, ventilation effect, and much more have been addressed by several studies during the COVID-19 crisis [104]. Indeed, indoor air quality, air conditioning, heating, and ventilation contribute to the reduction of airborne virus transmission [105,
106]. In this sense, different HVAC practices have been proposed to minimize the airborne transmission of the coronavirus [107]. This increased the interest in investments in intelligent HVAC systems in buildings [108]. As it is recommended increasing air exchange to maintain the freshness of indoor air, these HVAC systems rely on UV irradiation to kill viruses [109]. Also, researchers emphasize the importance of flushing buildings at night [110].

Through sensors work, the level of CO2 pollutants and volatile organic compounds can be measured in the indoor environment. Thus, the use of IoT in HVAC systems provides air quality analysis for action plan formulation, progress monitoring, and evaluation of mitigation effectiveness [111]. For example, a digital platform called Neuron was developed by Arup Group developed [108], which can measure indoor air quality to monitor or predict high-risk conditions and allows solutions of UV light, such as ventilation, or air purification to enhance the indoor air quality. Furthermore, Neuron can sense the body temperature to recognize individuals with high temperatures and class them in separate queues for extra screening.

3) Visitor Management

The status of persons present in the building is required for security aims. This data can be viewed at any time in the access control system. The reopening of companies or organizations, after the closure due to COVID-19, has prompted the consideration of the health and safety of visitors. Many jurisdictions legally require the implementation of security plans against this pandemic to prevent the spread of COVID-19 and its. This has emphasized the importance of intelligent visitor management to ensure contact tracing, social distancing, and occupancy tracking. For example, several office buildings are installing new thermal cameras and temperature sensors to perceive employees with fever [112].

Also, a QR code-based contact tracing system has been used in public places such as restaurants, gyms, and coffee shops [113, 114]. A wide range of mobile applications has been deployed recently to track cases and send alerts when needed [51]. As well as advanced techniques are being used to compute the distance between visitors in indoor environments [115] and to make available an indoor navigation for visitors respecting social distancing [116].

4) Facility Management and Cleaning

The COVID-19 pandemic requires strong facility management with a focus on cleanup capabilities to limit the spread of the virus. New standard operating procedures (SOPs) are adopted for cleaning and disinfecting indoor areas [117]. Effective disinfection of interior spaces must be taken into account by intelligent buildings, especially in frequently used areas such as elevators and door handles. For that, enterprises and organizations are adopting robots to disinfect their venues frequently and efficiently [118]. A robot was developed by researchers at CSAIL at MIT, which is based on ultraviolet germicidal irradiation and short-wavelength ultraviolet light to vanish microorganisms, to make sure that spaces are kept clean [119]. Correspondingly, A Robot equipped with LIDAR, which is developed by a subsidiary of Blue Ocean Robotics, establishes a navigation map of patient rooms that need to be disinfected [120].

F. Smart Homes

Making a smart home means first of all, providing comfort and security to its occupants. Through remotely controllable equipment, it is possible to modify the temperature, control the lighting or check that no one is coming home in your absence. Comfort is ensured by a more intuitive use of the devices. A connected home becomes a 100% multimedia home: the radio or music follows you in all the rooms, and you can launch an application using your voice (thanks to smart speakers). Figure 5 describes some existing as well as expected developments in smart homes as a consequence of COVID-19.

As the coronavirus pandemic impacts global economic activity, some sectors are proving more affected than others. This is particularly true of the connected home market, which could reach $85 billion in revenues by 2020, even though equipment sales for 2020 have dropped by nearly 20% from early expectations [80]. This negative impact is estimated to be temporary, so in the long term, the pandemic is expected to have a positive impact by 2026, with a 5% increase over pre-COVID-19 predictions, and revenues rise exceeding $317 billion [80]. This is due to changes in lifestyles and consumer behavior, which have adopted these products, and value their novelties even after the end of COVID-19.

As a future vision, many organizations or companies have announced the adoption of remote work as a long-term policy. For example, Twitter, Microsoft, and Square have announced the possibility of continued remote working even after the pandemic has ended. According to surveys, due to cost savings, 74% of CFOs have adopted working from home as a permanent policy. Also, 50%
of workers liked this vision, because they will be able to save on rent, and cost of living, by moving from big cities like Seattle, New York, San Francisco, and Boston [121].

Across the world, more people will study/work from home, so they need various IoT devices to ensure a more comfortable study or work environment. For example, by 2020, strong growth in sales of such equipment in Australia, such as energy sensors, thermal cameras, security lighting, smart speakers, and HVAC sensors [122].

1) Smart Homes and New Features

In response to the COVID-19 pandemic, numerous Smart Home devices have presented many new features. Home closure has led developers and researchers to explore and deploy new ways to assist the concept “x from home,” i.e., education or work from home, healthcare for home, shopping from home, etc. The impacts on education and online learning of COVID-19 were enlisted by Madhushree et al. [123]. To assist work from home and overcome the current challenges, Google has launched Google Workspace, which is rebranding some existing products with new features [124].

Due to COVID-19 restrictions, Alexa Care Hub was introduced by Amazon, to enable people to make a remote check-in on the family members they cannot visit [125]. Family members must log in to Care Hub, then their activity profiles on the IoT devices are shared among them, this allows them to generate alerts/notifications for sudden or critical situations. A mobile application called Symptom Checker was developed by Infermedica to survey occupants of a home and provide a guide to their current health status. The same medical startup Infermedica has also integrated an Alexa skill into the Symptom Checker [126]. Researchers are also presenting many healthcare systems that support remote healthcare monitoring [127].

Diagnosing COVID-19 using speech analysis is also another promising field, various IoT tools and technologies have been deployed. Voice-based mobile applications have been proposed by the technology company Vocalis to provide healthcare solutions, which study voice signals and detect COVID-19 symptoms, with the possibility of integrating the Alexa skill later [128]. Earlier, Vocalis has industrialized some solutions to detect outbreaks of chronic pulmonary disease by recognizing the signs of breath while speaking.

Although most of these products can be controlled from an application on a smartphone, many users have opted for what is called a home automation hub. Connected to the Internet router, this device acts as a central base: it communicates with all the connected equipment and controls them (some of them also work by voice command), thus allowing to automate the whole connected home. For this, non-informative approaches studied WiFi signals for respiratory rate measurement of COVID-19 patients [129], others based on Alexa [130].

These new features contribute to the advance of research to implement new and increasingly intelligent quarantine solutions [131]. To better analyze the health profile of a home's occupants, different IoT systems analyzing coughing, fever, sneezing, etc. are also presented [132]. Besides, advanced sensors are being adopted to monitor social distancing [133]. These innovations strengthen web dashboards and assist mobile applications for better monitoring and analyzing the health profiles of smart home residents.

2) New Home Energy Management Solutions

The scope of smart homes in terms of energy savings is unlimited as new technologies develop at full speed. The management of energy expenses is made possible by the installation of sensors, to collect information such as temperature, humidity, or human presence, and actuators to send them to the brain of the system, which takes the form of an automaton, a computer, or a home automation box. The variety of functionalities depends on the chosen system. A home automation box is for example more accessible to individuals, but more limited in terms of services rendered. Other more complex installations require the intervention of professionals and, sometimes, of a computer developer.

As today's homes often have multiple energy sources such as solar and battery banks, homes increasingly need smart systems for energy management [134]. COVID-19 has changed people's daily habits, so they spend more time at home. This implies a large increase in home energy consumption [135]. New features have been introduced to support energy conservation. For example, Amazon's Alexa informs users of variations in energy consumption by Echo devices and suggests suggestions for saving energy [136].

Since the appearance of COVID-19, there has been a strong need to install smart sensors and meters. In many countries, the use of smart meters has increased remarkably [137]. Some services based on Alexa have been proposed by different providers for good energy management at home [138]. Similarly, smart thermostats have had more interest [139], for example, Google's Nest which offers a new feature called Savings Finder to help save energy at home [140].

G. IoT and Transportation

The evolution of smart transportation systems is transforming transportation networks through the use of wireless and space-based communication systems, radar, sensors, and other advanced technologies. The smart transportation system market was growing for years [141]. However, to overcome pandemic situations, and their catastrophic results, it has to contribute to the deployment of public transport strategies by promoting public transport through easing user information access and ticketing, optimizing the use of networks through multimodality for passenger and freight transport, improving road safety through automated controls and traffic telematics, and reducing energy consumption and pollution through traffic management systems and communicating vehicles.

The COVID-19 pandemic threatens this important growth of the smart transportation market, which has already slowed down since its appearance. As a result of this pandemic, both transport organizations and passengers have all been severely impacted [142].

In the last year or so, a sudden decline in the number of trips on public transport has been perceived even in metro or Subways. In addition, due to health precautions, closed ports in many countries, closed airports, canceled flights, and operational road networks but with route limitations, caused delays in shipments. These global changes have resulted in increased instability in transportation costs [143]. Figure 6 illustrates the summary of the IoT adoption in transportation.
1) Automotive among Sensing and Analytics

As concerns about climate change and environmental degradation continue to grow, sustainability has become a strategic priority for car manufacturers. Governments, consumers, and investors are pushing manufacturers to change the way they work, their culture, and, of course, their products. This is a long-term commitment for the automotive industry, which despite significant progress must continue its efforts. This has impacted the automotive industry which may impact the recovery of this sector [144].

The current crisis has delayed the adoption of advanced driver assistance systems, as well as autonomous driving in different car lines [145]. Research and development projects are being reduced and the corresponding deadlines have been adjusted. Due to the decline in car sales, research and development projects are being delayed or adjusted. As a result, the majority of LIDAR start-ups have pivoted to non-automotive use cases such as mobile devices and industrial automation. For example, the interest of LIDAR players in the consumer space and smartphones has been revived with the introduction of LIDARs in iPhones. Thus, larger volumes are expected in a shorter time frame given the short design cycles in the consumer segments [146]. Although the smart transportation field has been hardly impacted by the pandemic, there are still some subareas attracting growing interests such as smart logistics and in-cabin analytics.

New features and devices are increasingly integrated into modern cars such as intelligent air conditioning systems, and in-car air quality control systems. To measure CO2, CO, and other pollutants within the cars, several sensors and IoT technologies are being deployed [147]. It was testified that low doses of far-UVC light disable flying corona viruses without injuring human tissues [148]. Several automakers have recommended the use of UV light for vehicle cabin cleaning [149]. Facial mask detection was included in Uber navigation to assure their users that standard health procedures are followed by drivers [150]. IoT Techniques are also being used to monitor air quality in public transport to limit the transmission of COVID-19 [151]. Besides, several IoT solutions are deployed to monitor real-time use on public transport. To inform passengers about the indoor situation and fulfill social distancing requirements.

2) Smart Logistics

The concept of smart logistics aims to provide the sector with greater efficiency and transparency. Thanks to intelligent interconnection, the process becomes more flexible and secure. However, the health crisis has demonstrated more than ever the importance of digital tools for economies. The future of the logistics sector lies in digitalization. The acceleration of the digitalization of the sector will increase the maturity of operators, especially those in the distribution sector. This will strengthen their ability to better anticipate future crises. The development of smart logistics is now a necessity.

In the smart logistics market, a compound annual growth rate (CAGR) of 8.5% is expected from 2020 to 2027 [152]. These predictions are relatively due to the increased need for IoT in smart logistics, which is triggered by COVID-19. As the world’s largest logistics market, China has successively reacted to COVID shock. For example, a Smart Logistic Network based on AI and IoT was built by Cainiao Logistics to ensure fast delivery services [153]. The digitization efforts during COVID-19, which were driven by challenging market conditions, are set to continue and consolidate to address structural failures in transportation and logistics [154]. Similarly, new functionalities, including contactless delivery and inventory tracking, are being introduced in the XPO Connect smart logistics platform of the global company XPO Logistics [155].

Since the start of COVID-19, cold chain logistics has received more attention from scientists and researchers. The development of the cold chain has not only allowed for the safe transportation of vaccines but has also improved existing systems to better preserve pharmaceutical items and food during transportation [156, 157, 158]. Supply chain resilience was classified into two basic categories: reactive strategies, and proactive strategies to provide a framework for exploring supply chain resilience strategies while assessing the impact of COVID-19 [159].

H. Industrial IoT

Mastering the challenges of Industry 4.0 and IoT, during pandemic situations, requires implementation across the entire value chain, enabling the highest degree of optimization and business potential: visioning, management, sales, manufacturing, and product
assembly, digital services, and service management. We provide your company with our expertise and resources to optimize all four pillars of the value chain.

![Diagram showing Smart manufacturing and inventory management and Remote monitoring and control systems.]

**Fig. 9. Recent Increased Adoptions in Industries during COVID-19 pandemic**

The economic impact of COVID-19 has forced several organizations to reduce their Industrial IoT (IIoT) budgets, negatively impacting factory automation. This highlights the need for IIoT growth to ensure sustainability, especially in the event of a pandemic or other disaster. 93% of manufacturing and supply chain professionals anticipate a strong focus on smart and resilient solutions [160, 161]. This demonstrates the importance of IIoT in ensuring a return to business as usual for industries by mixing other technologies like AI and Big Data to reach higher scores by 2027 [162, 163]. Figure 7 recaps the recent advances in some key IIoT areas impacted by COVID-19.

1) **Remote Monitoring**

The ability of the IoT to provide information from sensors, as well as allow devices to communicate with each other, makes a wide range of applications possible. Notably, production optimization through machine monitoring and product quality control. Machines can be continuously monitored and analyzed to ensure that they are operating within the required tolerances. Products can also be monitored in real-time to identify and resolve quality defects. Manufacturers can benefit from the competitive advantage of IoT technologies, and remote monitoring, to implement proactive maintenance of equipment to ensure production continuity even during pandemic situations [135, 164].

IoT is also used for remote operational monitoring of industrial machines [165]. For that, various sensors have to be installed in the predictive maintenance space [166]. In the industrial sector, on-site repair or maintenance is difficult, risky, and costly, especially during the pandemic. For this, it is essential to adopt IoT tools for machine condition predictions, production downtime that can lead to lost revenue, and remote failure identification [167, 135].

2) **Smart Manufacturing**

Today, more than ever, manufacturers must produce customized products in small batches and on-demand, all in uncertain situations. Smart Manufacturing, characterized by cyber-physical systems, enables operations managers to identify and respond quickly to changes in their plants, supply chains, and markets. After the COVID-19 pandemic, manufacturing facilities faced reduced hours, limited staff, and increased demand. This has enhanced the importance of additive manufacturing to meet the demands of various items, including medical equipment and supplies, personal protection, or surveillance tools [168].

As smart manufacturing is playing a promising role in medical applications, different countries can manufacture their crucial medical equipment in a short time [169, 170]. Besides, various collaborative frameworks were presented to improve the viability and the resiliency of the existing manufacturing processes. Due to the highly unstable demands during this pandemic, inventory management has become even more crucial. For that, smart inventory management systems are needed to monitor the available space and items, the needed items, and communicate the data to the concerned team [171].

**IV. DISCUSSION**

The coronavirus pandemic has prompted governments around the world to take drastic preventive measures, at the expense of their economies. The current economic crisis in the world economy is the most serious since the Second World War. In its latest forecast, the World Bank predicts that global GDP will reach only about $84 trillion in 2020 and $87 trillion in 2021, a cumulative loss of more than $10 trillion compared to the situation without the pandemic. The total economic cost of this recession could be even higher, due to the long-term effects on investment and education.

Recovery efforts out of COVID-19 present an opportunity for governments and the international community to use new and emerging technologies to reduce the inequities highlighted by the pandemic. These cutting-edge technologies, which leverage digitization and connectivity, include the internet of things, artificial intelligence (AI), big data, Blockchain, 5G, etc. Therefore, companies and productive sectors must adapt to the profound economic and societal changes, which are caused by the COVID-19, to properly adopt advanced technologies, including IIoT, which has demonstrated several challenges and opportunities since the emergence of the pandemic. Furthermore, many of these changes, caused by COVID-19, could not be restored in the next few years.
due to financial constraints. For this, the adoption of IoT must be well-targeted, more effective, and efficient, and warrants a properly significant return on investment.

A. Key Research Directions and Challenges

The experience of COVID-19 restraint has shown that technology is more than ever at the heart of our daily lives: within the home, on the one hand, with a global smart home market now amounting to $387 billion, up 5% on pre-COVID19 forecasts according to [80]; within companies, on the other hand, which has adapted to keep their business afloat and have shown the diversity of possible solutions. The anecdotal telework has become a real mode of organization, with only 7% of the working population practicing it before the confinement, against 10 to 60% today, depending on the sector.

To promote the economy and respond to potential future crises, IoT technology requires more revolutionary and rapid innovation. Before the pandemic, the global IoT market experienced more or less moderate growth. However, the challenges raised by the pandemic have clarified its shortcomings, and have amplified the need for accelerated IoT development in the vital sectors, which remain the key directions of our research healthcare.

The COVID-19 pandemic has strained health systems and disrupted essential health services. Around the world, countries are working to restore and strengthen key services to better withstand crises and ensure quality care. The health crisis generated by the Covid-19 pandemic has demonstrated the need for urgent health systems reform to ensure that all individuals can benefit from effective, low-threshold care, including testing, diagnosis, and surveillance. The pandemic situation has been exacerbated and raised many new ones.

First, concurrency and ubiquity, which remains crucial. This requires the availability of IoT-supported medical services to meet the increased demand and be accessible to a wider population. Yet, due to the disrupted economic situations, the majority of people do not have the opportunity to have professional medical equipment, so the most affordable devices are smartphones or other wearable devices, which have quite limited healthcare capabilities. Second, the complexity and high cost of medical service processes, which increase the difficulty of using IoT-based services. In addition, most people do not have the capabilities to use new technologies, including dedicated IoT systems for healthcare. Third, the importance of assessing the computational efficiency of the sensors, as well as the energy requirements to ensure the necessary healthcare (such as testing/diagnostics, and continuous monitoring) of high quality.

Based on these challenges, some promising directions for IoT adoption in healthcare:

- **Upgraded Wearable:** It is a fact that it is necessary to update wearable to make them more and more comfortable to carry/wear, to optimize wearable, and to customize the product design according to the different users’ group lifestyle and circumstances [172, 173, 174]. Besides it is also important to enhance energy collecting sensors for wearable devices to overcome the quick drain of battery [175].

- **Advanced IoT technology:** Algorithms running on IoT devices must provide quality equivalent to that provided by medical-grade equipment [176]. The use of AI technologies has not only enabled the processing of massive health data, but also AI has improved the quality of health care. i.e.: telemedicine, screening, and disease diagnosis [177]. Thus, an acceleration of IoT and AI integration is needed. However, the limited memory of IoT devices remains a conundrum to be solved to ensure the deployment of AI models, either via lightweight AI solutions running locally on the client-side [178], or the implementation of network architectures on an ARM CPU [179].

- **Warranted Accessibility:** It’s not easy for everyone to invest in wearable or specialized medical devices. Multifaceted approaches are needed to expand the population eligible for health services [180]. Also, the development of low-cost medical solutions will provide self-help via plug-and-play IoT devices such as home audio systems or smartphones smart-watch, Rapid Diagnostic Tests, and on-device measurement [57, 64, 181, 182].

1) **Smart Cities**

To better manage possible future emergency pandemics, smart cities essentially need to make much greater use of emerging technologies, including IoT. Thanks to smart cities, governments have data from various sources and departments. However, ensuring proper access control while integrating efficiently and effectively data essentially remains a critical challenge. Thus, several future visions are needed to ensure better integration and effective data integrity [183].

First, IoT sensory data has to be encoded according to the open standards for better interoperability. Second, before utilization, the IoT sensory data must be enriched via an ontology assembling domain knowledge in the smart city. Third, to avoid the high cost of restructuring existing data architectures, it is best to facilitate the sharing of sensor data by different authorities by formulating data sharing and integration schemes. The COVID-19 pandemic has impacted various entertainment and retail industries. As people continue to spend more time online, the services provided by the stores need to be innovative to attract more customers and meet their demands. This retail sector should integrate AI technologies, IoT, and big data analysis for a better understanding of customers, locations, and products. Thus, consumer interactions and personalized modeling should be further developed.

2) **Smart Building**

COVID-19 pandemic has forced people to reconsider their way of living, outside, with the wearing of masks and barrier gestures, but also within their homes, which have seen their layout and decoration revised to meet the need for telecommuting and containment in particular. The impact of Covid-19 on housing is not insignificant, and while these were temporary changes at first, many are expected to persist even after the pandemic is over, inspiring some designers. As homes begin to play a larger role in daily life, they have had to adapt to accommodate more activities and services.

Smart buildings have demonstrated good infection control against COVID-19 through non-contact operations performed by intelligent devices or reboots. Despite the success of smart buildings in meeting long-standing needs, several challenges must be addressed. First, the use of robots and smart devices in a building requires consideration of all functional areas as well as the different objects in the small spaces. This requires a mastery of the interior spatial topology to properly manage connectivity and accessibility,
dynamic zone information, and semantics to better serve the people in the building. Second, access policies and privacy require smarter sensor deployment in buildings.

3) Smart Homes

The smart home market is booming, even taking advantage of the appeal of the home equipment with pandemic restrictions. However, the adoption of technologies such as IoT in smart homes is often blocked by two main obstacles: the technical skills needed for home automation, and the high cost. This requires accurate integration and analysis of the collected or generated data from various sources. Thus, currently, investing time and efforts in smart homes is mostly limited to hobbyists and tech enthusiasts. To ease and accelerate user adoption, it’s vital to reduce the setup threshold. Thus, taking into account all user categories, easy plug-and-play solutions to deploy and use are required. Also, there is a huge need to equip home devices with advanced techniques and context-awareness to define accurate operations without human intervention. COVID-19 has changed screw patterns as well as energy consumption rates, so the energy sector must adapt to these variations to continue the current habits of people spending more time at home. Therefore, a shift in energy consumption from commercial/office buildings to homes is needed to overcome the possible challenges.

4) Transportation

COVID-19 has impacted the whole transportation networks in the world in a significant way, in both the urban transport sector and rural (long-distance) transport sector. To respect social distancing and avoid direct contact, transport patterns have been changed. To overcome the pandemic impacts in this sector, and facilitate the activities of both passengers and drivers, fast IoT adoption is crucial to enhance the use of tracking and monitoring IoT skills. Also, accuracy and reliability remain a key challenge while seamlessly integrating data from different sources [184, 185]. Besides, it is important to upgrade the logistics activities to minimize social contact and avoid delays. This requires reconsidering the previous principles and ontologies in the supply chain [186]. To increase the effectiveness of logistics, it is essential to manage, arrange, and optimize the tasks in the supply chain [187]. Furthermore, logistics should be more perceptible, secure, and transparent.

5) Industry

The outbreak of the coronavirus in December 2019 in China and its spread worldwide has had an unprecedented impact. By its nature, the industrial sector is one of the most affected by the crisis, but it is also the one with the best weapons in the fight against the corona virus. The companies that use digital tools the most are probably the ones that have managed to adapt to the global health crisis the fastest and most effectively. COVID-19 pandemic has disrupted the industrial sector so that IoT has become vital to ensure employee safety, business continuity, and remote asset control, etc. To warrant that industries can face future pandemics, the researcher and developers are solicited to advance their works quickly in various ways. Virtual reality and artificial intelligence are becoming more important to ensure remote work or studies, so the industries are brought to adapt the new IoT and AI standards to automate operations, recognize potential equipment failures, and predict the possible scenarios [188].

B. Analyzing the Impact of COVID-19 on IoT

Due to the COVID-19, numerous individuals, companies, and organizations are facing hard financial stress, which remains a key issue negatively impacting fast IoT adoption. Several organizations have limited or stopped completely their investment in the planned new technologies’ adoption such as IoT projects. Under social contact restrictions, another challenge caused by COVID-19 has been raised, which is the increased labor costs for the device installation.

Taking into account the financial constraints caused by the pandemic, it is essential to reduce the costs of implementing IoT systems. Meeting IoT, AI, and cloud services are essential to make the required IoT infrastructure in a virtualized and sustainable way. Moreover, open-source IoT software, analytic tools, AI techniques, and test beds are much needed to help companies and organizations to optimize the cost of outsourcing or developing new solutions.

Currently, it is more important to advance IoT sensors and device development, which are low-priced and easier to install and retain [189, 190]. Besides, it is important to develop cheap new plug-and-play sensing devices [191, 192], which are easy to integrate without additional investment or deployment costs. It is also required to enhance research and work on intelligent human-computer interaction [193] as well as self-adaptation and self-configuration of IoT devices [194] to ease the installation and usage of IoT systems.

**Table 1. Summary of COVID-19 Impact on Short-term and Long-term IoT Adoption in Different Sectors**

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<th>Sectors</th>
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<th>Smart Cities</th>
<th>Smart Buildings</th>
<th>Smart Homes</th>
<th>Transportation</th>
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During the pandemic, various emergency rules have been introduced by many governments such as social distance requirements, limits on people’s movements, and less strict privacy obligations [195]. However, all these regulations have to be reviewed after the pandemic to protect people’s privacy and rights [196]. Summary of COVID-19 impact on short-term and long-term IoT adoption in different sectors.

To overcome future pandemics or emergencies, the researchers need to work on vigorous security protocols, data access policies, and privacy-preserving solutions. Furthermore, rather than using conventional data centers, it is more essential to adopt decentralized data pools to ensure more control for the end-users. Table 1 summarizes the expected short-term and long-term impacts across the studied sectors.

The paper discusses the different works, initiatives, and innovations that being undertaken, during the COVID-19 pandemic, in different sectors:

- Healthcare: COVID-19 has triggered a large unanticipated demand for healthcare for a large number of patients, facilities, premises, and hospital staff. Globally, much investment is being made to overcome the health challenges raised by the pandemic by adopting IoT, something that is expected to be accelerated and amplified at a significant rate in both the short and long term.
- Smart cities: As financial stresses ease, and for better preparation for emergencies or future pandemics, these have become a necessity. This supports the use of IoT in an accelerated manner in the medium to long term.
- Smart buildings: Pandemic restrictions have influenced investment in new IoT projects, so the short-term impact remains negative. However, in the long term, after the financial stress is alleviated, IoT adoption will be accelerated.
- Smart homes: Despite the emerging trend of work/home study, the current financial crisis is holding back IoT adoption in the short term. However, strong accelerated adoption is expected in the long term.
- Transportation: IoT adoption in the transportation sector is mitigated by the sharp decline in individual and public transportation use. The medium- and long-term impact appears to be endured, with an estimate for accelerated but relatively stable adoption in the future.
- Industry: Currently, due to financial and pandemic pressure, industries are struggling to invest in IoT. In the long run, this sector expects accelerated growth to keep industries operational in the future.

V. CONCLUSION

IoT has been unceasingly bringing a progression of changes in human lives through different innovations and applications. There is the countless value of IoT applications in different sectors including healthcare, smart cities, smart buildings, smart homes, transportation, and industry. Notwithstanding the promising advantages of IoT, the COVID-19 pandemic has impacted its adoption. To better analyze the impact of the COVID-19 pandemic on IoT adoption, various interviews were made with numerous experts in different sectors, as well as a thorough analysis of the recent scientific research and reports from leading consulting firms. The paper discusses different works in different key sectors and highlights various challenges that must be addressed to facilitate accelerated IoT adoption.

REFERENCES


AF. Santos, et al., “Best practices on HVAC design to minimize the risk of COVID-19 infection within indoor environments”, Brazilian Archives of Biology and Technology, 63, 2020.


