

Smart Building Technologies in Response to COVID-19

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Abstract: The COVID-19 pandemic has had a huge impact on society. Scientists are working to mitigate the impact in many ways. As a field closely related to human life, building engineering can make a great contribution. In this article, we started with the concept of the smart building as our guide. The impact of COVID-19 on daily energy consumption, information and communication technology, the ventilation of the interior environment of buildings, and the higher demand for new energy technologies such as electric vehicles is an entry point. We discuss how the concept of the smart building and related technologies (refrigeration, measurement, sensor networks, robotics, local energy generation, and storage) could help human society respond to the pandemic. We also analyze the current problems and difficulties that smart buildings face and the possible future directions of this technology.

Keywords: smart building; building automation; ICT; energy consumption; robotics; COVID-19



Citation: Xie, X.; Ramakrishna, S.; Manganelli, M. Smart Building Technologies in Response to COVID-19. *Energies* **2022**, *15*, 5488. <https://doi.org/10.3390/en15155488>

Academic Editor: Dimitrios Katsaprakakis

Received: 18 June 2022

Accepted: 22 July 2022

Published: 28 July 2022

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1. Introduction

The COVID-19 pandemic changed our lives profoundly. Mitigative actions have been undertaken worldwide, including restriction policies, deeply impacting society and lifestyles. The coronavirus is the defining global health crisis of our time and the greatest challenge we have faced since World War II. The pandemic is also a devastating socio-economic crisis. The World Bank says 97 million people will be pushed into poverty in 2020, an unprecedented increase. The International Labour Organization estimates that 205 million people will lose their jobs in 2022, up from 187 million in 2019 [1]. A comprehensive analysis of the effects of COVID-19 has been conducted by Ibn-Mohammed et al. [2], including a discussion of lessons to be learnt and opportunities for the future, e.g., pertaining to circular economy.

During the pandemic, most countries responded by imposing 'lockdowns' that limited daily living to the most basic activities and prevented people from leaving their residential buildings. In addition to affecting the normal functioning of society, this move also led to another problem, namely, the increase in energy consumption in residential buildings. Increased house load consumption due to the COVID-19 situation not only increased the spend on energies, but also impacted residential power distribution strategies. In particular, the load pattern of distribution transformers changed. When changes occur, transformers can be overloaded. Therefore, it is necessary to find solutions to reduce grid load.

Improving the hygiene and sanitation of medical institutions has become another focus, and hospital buildings have become the main battlefield in the fight against the epidemic. In addition, since new viruses can spread quickly through the air, it is important to improve indoor air quality and pay attention to the quality of indoor ventilation systems. We need to find corresponding solutions according to the new requirements.

The challenges of COVID-19 require quick and dynamic solutions. The ‘smart building’ concept is a good solution for today’s situation. Smart buildings use information technology to connect various subsystems, which often operate independently during operation, so that these systems can share information to optimize overall building performance. The idea of smart building is born out of the application and popularization of computers and the internet. By using these technologies, we can organize and monitor the building as a digital system. A brief timeline of the birth of the concept of smart building is illustrated in Figure 1.

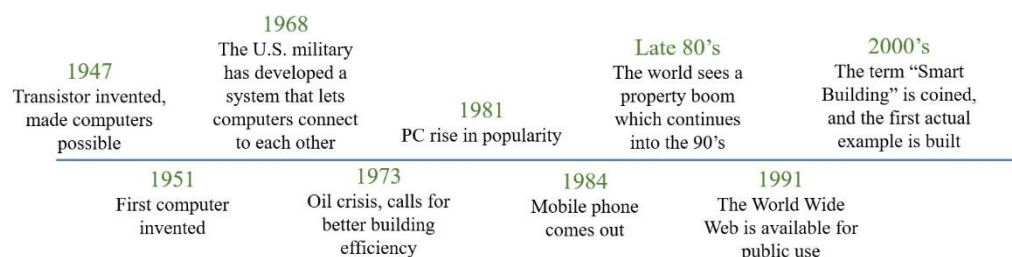


Figure 1. Timeline of main events in smart building history, elaborated from [3].

Smart building technologies can be helpful in several areas. In this work, we review smart building elements as a support against COVID-19. A schematic of approaches is illustrated in Figure 2.

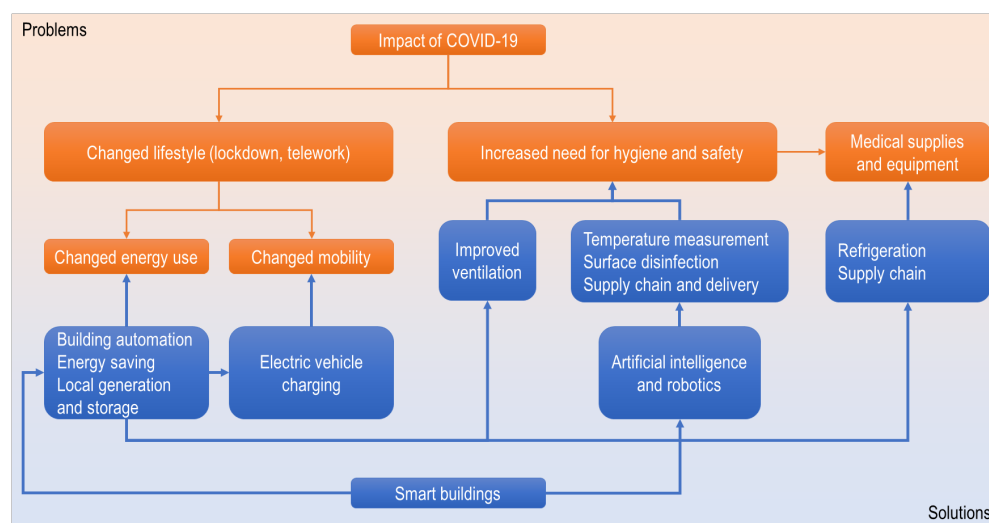


Figure 2. Schematic of smart building approaches as a support against COVID-19 impact.

As noted by Pinheiro et al. [4], on the Web of Science (WoS), the quantity of publications on COVID-19 has increased this year (over 6000 references), but less than 1% of them involve the built environment or buildings [5]. On ScienceDirect, more than 8000 references can be found, but again, less than 1% of them relate to the built environment in any way [6]. As far as scientific research on COVID-19 is concerned, research is concentrated on medicine, the pharmaceutical industry, public health, and related fields. The built environment (buildings and urban areas) can also make remarkable contributions that require research and analysis [4]. The numerosity of papers published per year, author, and subject area are reported in Tables 1–3.

Table 1. Paper number per year and subject area and correlation.

Paper Number						
	<i>‘COVID-19’</i>	<i>and ‘Buildings’</i>	<i>and ‘Robotics’</i>	<i>and ‘Healthcare’</i>	<i>and ‘Automation’</i>	<i>and ‘AI’</i>
2019	62	1		4		
2020	86,013	1019	218	6372	240	472
2021	164,807	3061	540	13,150	666	1418
2022	74,211	1543	191	5978	285	650
2023	43	5		2	2	
2024	2					
Correlation						
		<i>and ‘buildings’</i>	<i>and ‘robotics’</i>	<i>and ‘healthcare’</i>	<i>and ‘automation’</i>	<i>and ‘AI’</i>
2019		1.61%		6.45%		
2020		1.18%	0.25%	7.41%	0.28%	0.55%
2021		1.86%	0.33%	7.98%	0.40%	0.86%
2022		2.08%	0.26%	8.06%	0.38%	0.88%
2023		11.63%		4.65%	4.65%	

Table 2. Top 10 authors by paper numerosity.

<i>‘COVID-19’</i>		<i>‘COVID-19’ and ‘Buildings’</i>		<i>‘COVID-19’ and ‘Robotics’</i>	
Mahase, E.	290	Li, Y.	11	Rocco, B.	7
Wiwanikit, V.	275	Guney, M.	6	Cornejo, J.	4
Lippi, G.	232	Karaca, F.	6	Elara, M.R.	4
Iacobucci, G.	216	Tleuken, A.	6	Hameed, I.A.	4
Mungmunpbtipantip, R.	171	Tokazhanov, G.	6	Nelson, B.J.	4
Dhama, K.	167	Turkyimaz, A.	6	Patel, V.	4
Wiwanikit, V.	164	Aguilar, A.J.	5	Peng, C.	4
Baden, L.R.	151	Aletta, F.	5	Tavakoli, M.	4
Henry, B.M.	147	Chen, W.	5	Ye, R.	4
Rezaei, N.	145	Cowling, B.J.	5	Atashzarm S.F.	3
<i>‘COVID-19’ and Healthcare’</i>		<i>‘COVID-19’ and ‘Automation’</i>		<i>‘COVID-19’ and ‘AI’</i>	
Essar, M.Y.	26	Carroll, K.C.	4	Saba, L.	12
Javaid, M.	24	Dogné, J.M.	3	Suri, J.S.	11
Temsah, M.H.	23	Douxfls, J.	3	Al-Turjman, F.	10
Haleem, A.	22	Franke, J.	3	Viskovic, K.	10
Lin, C.Y.	22	Haleem, A.	3	Agarwal, V.	9
Lucero-Prisno, D.E.	22	Javaid, M.	3	Balestrieri, A.	9
Griffiths, M.D.	21	Lin, W.	3	Fatemi, M.	9
Al-Tawfuq, J.A.	20	Lippi, G.	3	Naidu, S.	9
Bragazzi, N.L.	20	Lutgehetmann, M.	3	Alizad, A.	8
Khunti, K.	20			Faa, G.	8

Table 3. Top 10 subject areas by paper numerosity.

‘COVID-19’		‘COVID-19’ and ‘Buildings’		‘COVID-19’ and ‘Robotics’	
Medicine	191,849	Social Sciences	1807	Computer Science	467
Social Sciences	48,527	Medicine	1746	Engineering	371
Biochemistry, Genetics, and Molecular Biology	29,568	Engineering	999	Medicine	292
Computer Science	26,304	Computer Science	884	Mathematics	149
Immunology and Microbiology	21,084	Environmental Science	748	Social Sciences	120
Engineering	20,159	Business, Management, and Accounting	542	Physics and Astronomy	67
Environmental Science	17,779	Energy	336	Decision Sciences	58
Nursing	14,631	Mathematics	276	Business, Management, and Accounting	52
Psychology	13,642	Arts and Humanities	268	Materials Science	49
Pharmacology, Toxicology, and Pharmaceutics	13,107	Psychology	260	Energy	47
‘COVID-19’ and ‘Healthcare’		‘COVID-19’ and ‘Automation’		‘COVID-19’ and ‘AI’	
Medicine	18,531	Computer Science	468	Computer Science	###
Social Sciences	2128	Medicine	375	Medicine	771
Computer Science	2095	Engineering	371	Engineering	714
Nursing	1922	Biochemistry, Genetics, and Molecular Biology	145	Mathematics	347
Engineering	1637	Social Sciences	142	Social Sciences	301
Biochemistry, Genetics, and Molecular Biology	1621	Mathematics	140	Decision Sciences	280
Immunology and Microbiology	1348	Decision Sciences	115	Biochemistry, Genetics, and Molecular Biology	244
Environmental Science	1184	Business, Management, and Accounting	82	Physics and Astronomy	160
Pharmacology, Toxicology, and Pharmaceutics	1032	Immunology and Microbiology	73	Business, Management, and Accounting	131
Health Professions	901	Energy	69		

The main objectives of building automation are to provide support to persons with special needs and the improvement in healthiness, comfort, and energy use in buildings [7]. These can be very helpful in addressing COVID-19.

In this work, we investigate the bi-directional interaction between a health emergency (e.g., COVID-19) and the built environment: Firstly, how the emergency can affect the built environment, and secondly, how the built environment can be improved to respond to such an emergency. As regards the impact, the focus is on the residential sector because the effect of measures on users was particularly evident to the users themselves (e.g., exacerbation of energy poverty) and because the impact was strictly related to usage scenarios of local generation and storage systems. As regards the response, we try to mention those aspects strictly or widely relating to the built environment (especially to the smart building concept) and arising from different technology advancements.

2. Impact of COVID-19

During the pandemic, the most prevalent response to the spread of COVID-19 was the imposition of ‘lockdowns’ in most countries, limiting activities of daily living to the most basic and preventing people from leaving their residential buildings. This led to a new problem, an increase in the energy consumption in residential buildings. In addition, due to the fast-spreading and airborne nature of the virus, it has become critical to establish high levels of indoor air quality in various buildings.

2.1. Residential Energy Uses

Restrictive measures included stay-at-home and telework policies, which increased residential energy use and decreased mobility and workplace energy uses in the periods concerned. Several studies have investigated how residential load profiles and amounts of energy consumed changed around the world [8–12]. An analysis is presented by Manganelli et al. [13]. It is concluded that daytime energy use increased in general, opening the possibility for the increased use of local renewable generation, energy storage, and electric vehicle charging systems. Examples of key effects on residential energy uses during 2020 lockdowns are as follows. Key aspects and insights are summarized in Table 4.

- An increase of 40% for household cooking, a similar change for entertainment, +60% for heating and cooling, +40% for lighting, and +22% to +95% for energy bills in China [8].
- A decrease of 13% in national electricity use; the morning peak reduced and diluted, and the evening peak also reduced and postponed in cases of studied households in Spain [9].
- Approximately, there was the same peak load but a broader distribution in almost 7000 sample households in Poland [10].
- There was almost the same load profile during weekdays, but an increased evening peak in Australia [11].
- There were major alterations in April–May and minor alterations in June–July in the case of studied social housing in Québec, Canada [14].

Table 4. Key aspects and insights on COVID-19 impact on residential energy usage.

Key Findings	Key Elements
COVID-19 exacerbated energy poverty, combining increased energy expenditures and decreased incomes [15].	Importance of measured data [10].
Low-income users are more exposed to energy poverty and more responsive to energy saving [12,16].	Importance of energy awareness in users [10] and in service providers and governments [11].
	Importance of support measures [17–20].

2.2. Usage of Information and Communication Technology

In addition, the COVID-19 pandemic impacted on the application of information and communication technology (ICT). Microsoft Teams had an increased usage of 775% in March 2020 [21]. A similar situation also happened for the Facebook Group and Zoom [22,23]. This also implies benefits: Ong et al. [24,25] estimated the life-cycle energy and CO₂ cost impact of video conferencing compared to face-to-face meetings. Recent changes in information and communication technology and improvement opportunities are discussed by Manganelli et al. [26].

Digital technologies are advancing at an incredible rate around the world—but not evenly. About 60% of the world’s population is now online, but most of this percentage is in developed countries. In less developed countries, only one in five people is online. Companies such as Google, Amazon, SpaceX, and many countries’ governments are focusing on solving this problem. UNESCO has also made a great contribution [27].

Not only has ICT use increased, but the pandemic has also influenced internet usage. From an investigation by the Irish Central Statistics Office (CSO), it was found, through a comparison between Jan 2020 and Mar 2020 (first wave of COVID-19), that the usage of the internet increased in all age groups [28]. According to the research, people used the internet mainly for communicating, both work and study related, for purchasing items, and for access to information, especially COVID-related.

The pandemic has exposed how the digital divide hurts those without reliable internet [27]. During public health emergencies such as COVID-19, many activities and services (e.g., healthcare, education, and employment) are transformed to being online, and society is more dependent on ICT and digital government systems. This leads to a surge in traffic to online service infrastructure and digital government portals [29].

At the same time, integrated digital government systems may be more vulnerable to cyberattacks and security breaches during emergencies. Therefore, strengthening the data security and e-resilience of ICT infrastructure is more important than usual.

2.3. Increased Request of Ventilation

In most cases, reoccupying a building during the COVID-19 pandemic has not required a new building ventilation system. However, ventilation system upgrades or improvements can increase the delivery of clean air and dilute potential contaminants. The American Centers for Disease Control and Prevention (CDC) presented a list [30] of ventilation interventions that can help reduce the concentration of viral particles in the air, to better protect us during the pandemic. Among the list, several suggestions can be used as guidance for the improvement of ventilation systems in smart building design.

The list of tools that can improve building ventilations is as follows:

1. Increase the input of outdoor air.
2. Use fans as an auxiliary to support the effect of open windows.
3. Ensure that ventilation systems operate properly and provide acceptable indoor air quality according to the current occupancy level for each space.
4. If possible, adjust HVAC systems to increase total airflow to occupied spaces. Disable demand-controlled ventilation controls that could reduce air supply according to occupancy or temperature in occupied hours.
5. Improve central air filtration. Ensure that restroom exhaust fans are operating correctly and at full capacity when the building is occupied.
6. Inspect and maintain exhaust ventilation systems in areas such as kitchens, cooking areas, etc. Use these systems when these spaces are in use.
7. Use portable, high-efficiency particulate air fan/filtration systems to enhance air cleaning.
8. Generate a 'clean-to-less-clean' air movement by evaluating and repositioning, as necessary, the supply louvers, exhaust air grilles, and/or damper settings.

2.4. Mobility Variation and Electric Vehicle Charge

The pandemic forced people to change their levels of mobility and activities. Restrictions and people's concerns affected travel patterns. Cost and convenience have traditionally played a key determinant role when customers choose a shipping or travel method. In the post pandemic world, for both business and private trips, reducing the risk of infection is the number one reason behind travelers' choices, outweighing the time it takes to reach their destination [31]. Mobility and transport have declined, especially with regard to public transport, but there has been an increase in the use of cars, bicycles, and micro-transportation [32,33]. M. Hattrup-Silberberg et al. highlighted major drivers of future mobility and noted that health has become a priority when choosing a transportation method [31].

Before the COVID-19 crisis, urban mobility had begun to be organized globally in a non-standardized manner. The impact of COVID-19 on the global economy has widened regional disparities, with differences in the timing of the crisis and in the response of health systems. Many of these differences will likely remain in the near future. For example, a city that is an infection hotspot may need to implement measures to severely restrict mobility, while other cities in the same region or country may be similar to the precrisis days. The difference could significantly affect the travel options available, potentially making travel truly hyperlocal [31].

The pandemic also reshaped the vehicle industry a little bit, for example, with regard to electric vehicles (EV). Win et al. studied the impacts of COVID-19 on the EV industry in China [34]. Although the study of Wen et al. only analyzed the situation for the EV industry in China, the conclusions can also be applied to the global market. The new drivers shaping future mobility are health, policy and regulation, hyperlocalization, industry consolidation, and a rethinking of innovation. The booming EV industry branch fits this concept in many ways, and, because of this, a strong global uptake of EVs can be expected [31].

The addition of EVs brings another problem, EV charging. EV charging consumes energy directly from the grid. An increase in the number of electric vehicles means an increase in grid load.

Therefore, research into and analysis of electric vehicle charging patterns can better optimize energy transport and distribution. G. McClone et al. [32] studied the EV charging load pattern and charging preferences in Salt City, Utah, US, from February 28 to April 16. After the arrival of COVID-19, the total number of EV charging sessions in Salt Lake City dropped significantly, but the EV charging trend remained similar. These lost charging periods are associated with retail- and entertainment-related public spaces where lockdown policies eliminate visits to these areas.

3. Science and Technology in Response to COVID-19

Help has been sought from technology fields. Major science and technology fields for health are bioinformatics [35], digital health [36], and telehealth [37]. A review of the applications of digital technologies for COVID-19 has been made by Whitelaw et al. [38].

By using a multidisciplinary approach, we could take advantage of smart building technologies and natural resources towards healthy buildings. In a pandemic situation, the role of the smart home has become strategic: the larger the housing unit, the greater the need for smart home systems. In fact, computer systems with the support of detectors and sensors in the environment, as well as mobile interface devices, can enable easy control and management of the building, improve comfort, plan various advance activities, and improve safety by monitoring consumption, activating and deactivating the system when needed or not required, respectively, saves money and energy [39], although the 24/7 monitoring of the system itself requires minimal consumption. However, the presence of home automation in housing units with elderly or sick living alone cannot be ruled out, guaranteeing them greater safety and immediate assistance when needed.

The traditional objective of automation in buildings is to provide support to persons with special needs. Other main objectives are the improvement in healthiness, comfort, and energy use [7]. These objectives can go hand-in-hand with the response to health emergencies such as COVID-19.

A good healthcare system is a priority in health emergencies. Healthcare facilities can greatly benefit from smart building technologies, in terms of efficiency and patients' well-being. Examples of typical building automation applications are reported in Figure 3 [40]. Technologies can extend from smart buildings to smart cities (Figure 4) [41]. The built environment can be studied at different levels. Different types of smart buildings (smart houses, smart hospitals, etc.) can form a smart city, with supporting smart technologies (Figure 5).

Thermostat sensor	Supply/exhaustVenturi air valves	Ante room pressure control
Ante room door switch sensor	Isolation room pressure control	Isolation room door switch

Figure 3. Examples of typical building automation applications for healthcare facilities, elaborated from [40].

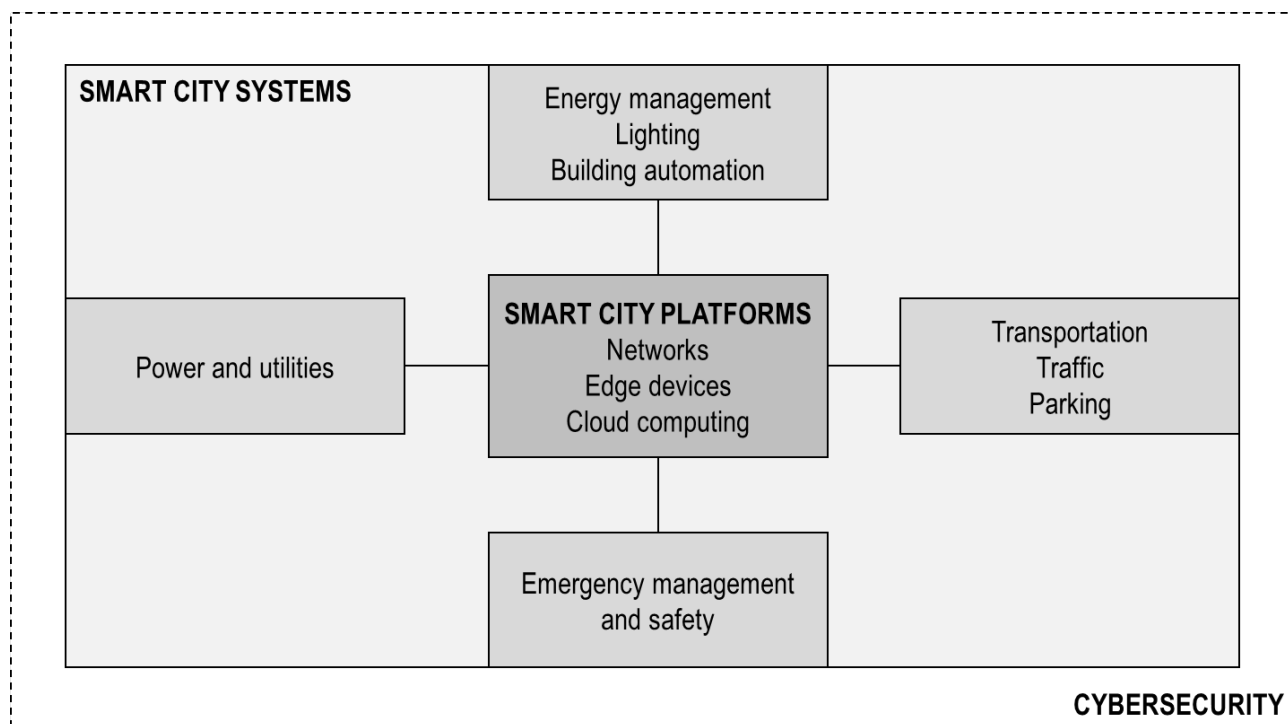


Figure 4. Example of smart city technologies, elaborated from [41].

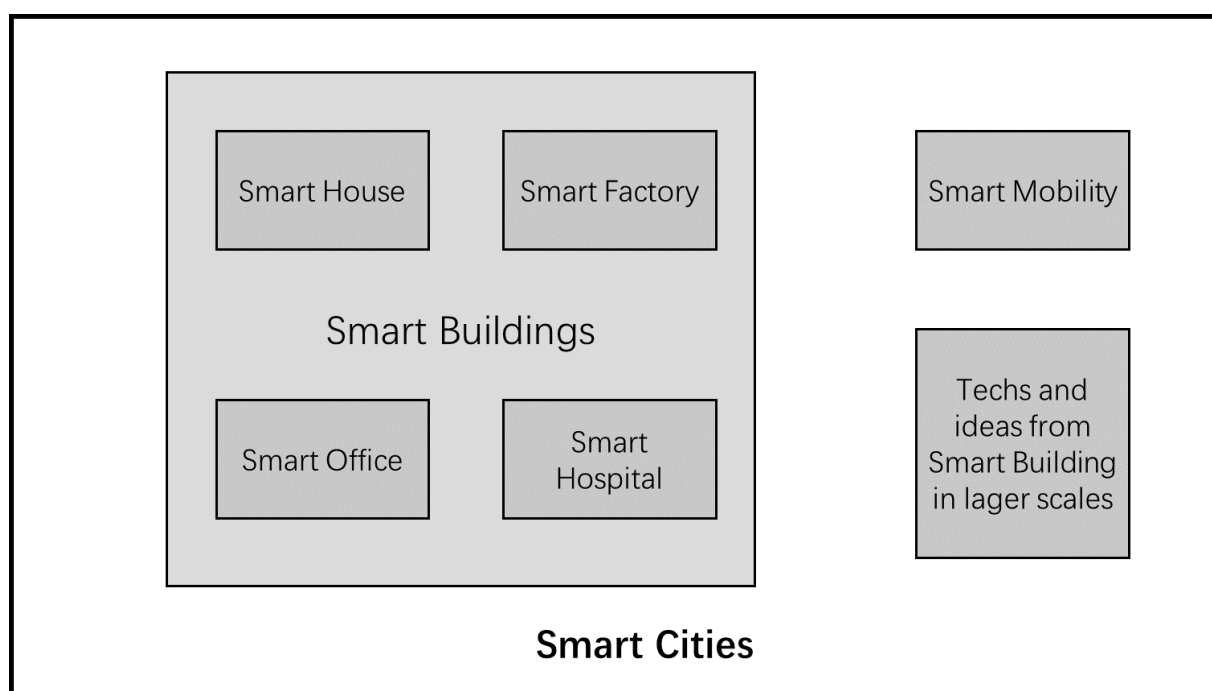


Figure 5. Schematic of relationship between smart built environment levels.

4. Refrigeration and Measurement

A cold chain is essential in the storage and supply of medical equipment. During the pandemic period, the most relevant application of cold chain management has been the distribution of anti-COVID vaccines. Enriko et al. [42] researched the tracking and monitoring of anti-COVID vaccine distribution using IoT. Their study indicates that comprehensive vaccine distribution tracking and monitoring efforts have begun. In this step, the system can ensure that when the temperature of the chiller and the vehicle is above or below the threshold, the relevant personnel will be alerted. In the absence of an alarm, users can rest assured that the vaccine remains effective. Since vaccines are continuously stored and distributed before being injected into patients, future work is required to develop a comprehensive track-and-trace vaccine system. Going one step further, Pargaian et al. [43] studied vaccine wastage in India due to poor cold chain management. According to the World Health Organization, vaccines cannot be kept below 2 degrees Celsius and above 8 degrees Celsius [44]. As such, the cold chain infrastructure is critical, especially during this pandemic period and the rising number of Covid-19 patient cases [45]. The average waste rate for each state in Telangana was 6.50%, and the maximum percentage was 17.60%. As a counter measure, an IoT-based ESP8266 Wi-Fi module was proposed by Pargaian et al. to manage the optimal temperature and humidity of vaccine carrier boxes [43]. The use of IoT-based devices and technologies can ensure monitoring and a reduction in the wasting of vaccines. A similar situation also happened in China; a cold chain system has the problem of large losses. In the context of the imperfect development of cold chain systems, the current epidemic situation and existing opinions have been considered and analyzed. The common problems of cold chain logistics were put forward, combined with these deficiencies, by Zhang et al. who discussed the use of an ISM method to divide the development of cold chain logistics, establish models, and explain them, so as to analyze the relationships between factors. If the cold chain logistics system is improved according to the analysis, the cold chain information system can be effectively improved, thereby promoting the rapid development of the cold chain logistics industry.

5. Robotics

Historically, robots have been used in dull, dirty, and dangerous activities [46]. A catalogue of robots is reported by IEEE [47]. In healthcare, robots are regarded as a promising way to increase the safety of HCWs and patients. A moderate robotization is found to reduce infectious spread [48] in the first place.

A review of robotics application in COVID-19 has been conducted by Javaid et al. [49]. Robots used in the medical field for surgery, rehabilitation, telepresence, sanitation, medical transportation, prescription dispensing, and packaging have been described, e.g., they can perform precision surgery or the packaging of medical devices when there is a risk of contamination.

The types of robots used in the medical field [49] can be classified as per Figure 6.

The advantages and disadvantages of robots in the medical field [49] are shown in Figure 7.

The use of robots in response to the COVID-19 situation [49] is shown in Figure 8.

Robotics applications for COVID-19 have been illustrated by Yang et al. [46], Javaid et al. [49], Guizzo et al. [50], Zhao et al. [51], Sarker et al. [52], and Hooman [53], as follows. The following provides some examples of robot applications in different divisions of labor assisting the fight against COVID.

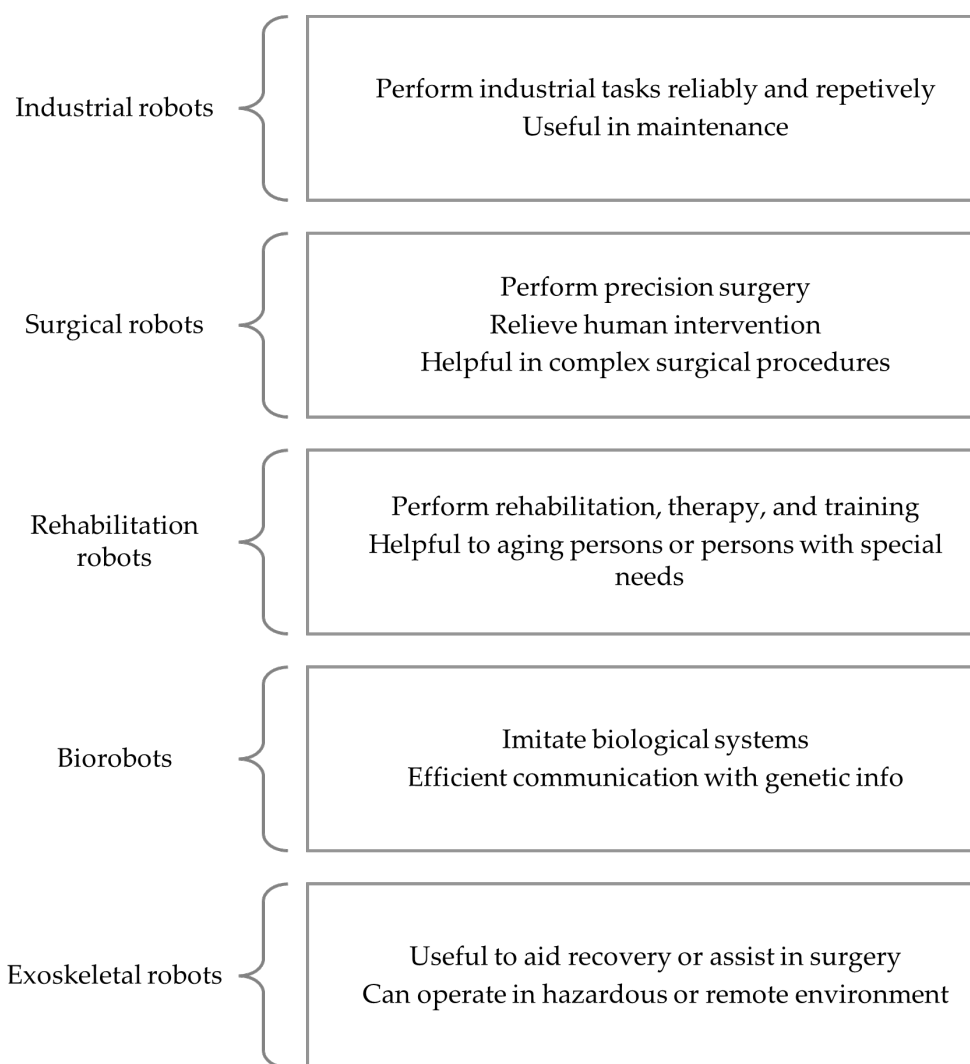


Figure 6. Types of robots used in the medical field, elaborated from [49].

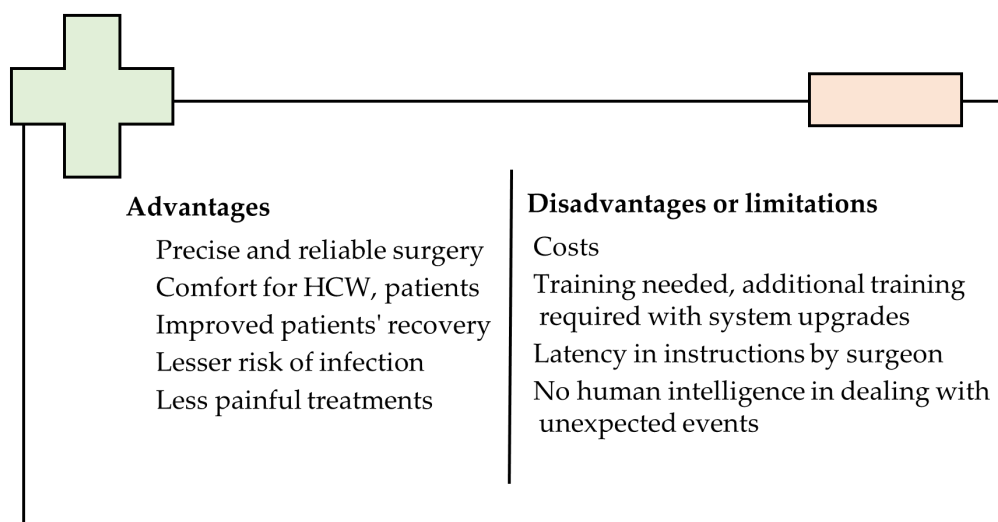


Figure 7. Advantages and disadvantages of robots in the medical field, elaborated from [49].

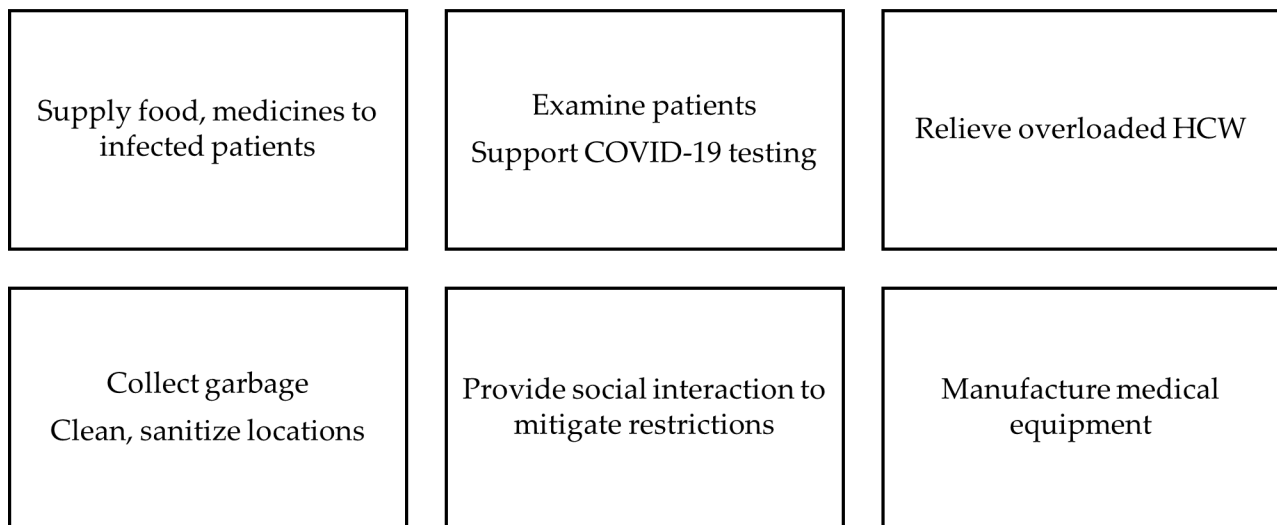


Figure 8. Robot applications in response to COVID-19, elaborated from [49].

5.1. Surface Disinfection

Autonomous or remote-controlled robots can perform inexpensive, fast, and effective non-contact UV surface disinfection, e.g., navigating and sterilizing high-touch surfaces [46]. UVD robots, equipped with lidar and UV-C lamps, are used by Italian hospitals (Sassari, Abano Terme), Boston Dental (Boston, USA and Dubai, UAE), Dolphin Pointe Health Care (Jacksonville, USA), and the Research Institute of the McGill University Health Centre (Montreal, Canada). Abano hospital in Italy reported no new COVID-19 infections among HCWs since the implementation of robotic disinfection [54].

5.2. Temperature Measurement

Robots can perform an efficient, large thermal screening in public areas, e.g., integrating thermal sensors in mobile robots or existing camera systems [46]. Ubtech robots can perform, for example, non-contact temperature measurement, mask compliance detection and reminder messaging, and disinfection [50].

5.3. Supply Chain

Unmanned vehicles can carry medications or make deliveries [46]. Zipline drones are used to deliver supplies among medical facilities. The use of drones is advocated to also transport drugs, samples, and vaccines [50]. Diligent robots carry items in healthcare facilities as a support to HCWs. Robots by Starship Technologies in Hamburg, Germany, and by Rappi in Medellin, Colombia, deliver groceries or takeout. JD uses robots in Changsha, China [50].

5.4. Security

Predicting the spread of the virus to any region will help policymakers to act proactively and take necessary measures accordingly. Patrol robots have the ability to work completely autonomously, and robots that can also work by remote control have great applicability in this COVID-19 era. More recently, robots have been customized to replace manual patrols, especially in hazardous areas (i.e., highly-infected areas). A 5G patrol robot developed by Guangzhou Gosuncn Robotics has been deployed in China to monitor COVID-19 preventive measures [55]. The Singapore government deployed a quadruped robot called ‘Spot’ [56], developed by Boston Dynamics, to patrol local parks to monitor social distancing among tourists.

5.5. Telehealthcare

Telehealth helps lower the spread risk by reducing close interactions between patients and healthcare workers. Many new strategies for the remote monitoring of patients have been introduced in this pandemic. Many hospitals have deployed intelligent chatbots [57–59] to relieve the pressure on the medical department. Previously developed telemedicine technologies, such as [60] robotic nurse Tommy in Italy, physiotherapist Robert in Denmark, and Robotnik in Valencia, Spain, have supported telemedicine facilities during COVID-19.

Moreover, with the help of artificial intelligence (also known as AI), people with medical needs can operate self-service tools by using robotics. Chinese AI technology company SenseTime opened a virtual live room in the biggest streaming platform ‘Huya Live’ [61], hosted by an AI doctor. Viewers can interact with the AI by asking questions and receiving responses.

5.6. Special Applications

A specialized application is in sample handling: Robots can rapidly collect and transport swab and blood samples, increasing speed, reducing infection risk, and relieving staff from routine operations [46]. The first automatic robot for oropharyngeal swab testing was developed in [62]. Wang et al. [63] proposed a low-cost miniature robot for nasopharyngeal swab testing. Such applications fall within medical robotics, which is beyond the scope of this work.

Advanced applications involve the use of social robots and virtual reality, to [46]:

- provide treatments and enable continuous communication with patients, minimizing the exposure of HCWs and the use of protective equipment;
- improve interactions with individuals subject to isolation, to preserve mental health;
- facilitate the rescheduling of events in virtual mode, instead of cancellation.

Sanbot robots with cameras, microphones, and access to patients’ vitals are used at Circolo Hospital in Varese, Italy, as avatars to check on patients. A Zorabots robot in a nursing home in Ostend, Belgium, allows for communications with residents when visits are not possible. Robots were used as avatars in Manila, the Philippines, to hold a graduation ceremony when gatherings were not possible [50,52].

Robots could also be deployed to provide critical services without sending personnel. The cooperation of engineers and health professionals is advocated to be prepared for future pandemics [46].

6. Sensor Networks for Contagion Modeling

Sensors have been used to investigate contacts in hospitals as a route for transmitting hospital-acquired infections, before COVID-19. Hornbeck et al. [64] used small, battery-powered devices (including processor, flash memory, and IEEE 802.15.4 wireless radio), to be carried by HCWs or placed in relevant locations. Mobile devices were packed in recycled pager cases.

Isella et al. [65] and Vanhems et al. [66] used RFID tags in wearable badges, exchanging ultra-low-power radio packets, tuned to detect face-to-face interactions within a threshold distance. Data quantified the number and duration of contacts, among and between classes of individuals, in various periods of the day. The results pointed out the impact as a function of connectedness, i.e., the significant effect of the most-connected workers with respect to the least-connected ones [64–66]. Some individuals (‘super-contactors’) were found to account for most of the contacts, by number and duration [66]. The measurement system was developed by the SocioPatterns project [67], a collaboration research in social dynamics. Resulting works include studies on COVID-19 contact tracing [68,69].

7. Building Automation

As anticipated, building automation can provide a number of functionalities in buildings, some of which can prove very useful in response to health contingencies. The field

includes several disciplines in science and engineering, and in the present form, relies heavily on electronics. The inclusion of automation, ICT, etc., in buildings contributes to the creation of a smart building. To give an idea of this, the main standards that apply in the field and the main communication protocols employed in technical systems are presented as follows.

7.1. Main Building Automation Rating Systems and Standards

Methods for assessing the sustainability of buildings are available worldwide. Classical examples are the UK's BREEAM (Building Research Establishment Environmental Assessment Method) or the US Green Building Council's LEED (Leadership in Energy and Environmental Design), both proposed in the 1990s. Additionally, technical standards are applied on single aspects. Modern day standards are [69,70]:

- EN ISO 16484-1: 'Building automation and control systems project specification and implementation';
- EN 50173-6:2013: 'Information technology—generic cabling systems—part 6: distributed building services';
- EN 50398-1: 'Alarm systems. Combined and integrated alarm systems. General requirements';
- CIBSE Guide H: 'Building control systems';
- EEUMA Publication 191: 'Alarm systems—a guide to design, management and procurement';
- IET 'Code of Practice for Cyber Security in the Built Environment';
- ISO/CD 37173: 'Smart city infrastructure—Development guidelines for information-based system of smart building'.

In addition, many certification and evaluation organizations exist.

7.2. Main Building Automation Protocols

Main building automation protocols are reported as follows [69,71]:

- 1-Wire, from Dallas/Maxim
- BACnet (Building Automation and Control networks), maintained by ASHRAE Committee SSPC 135
- BatiBUS, merged to KNX
- C-Bus, Clipsal Integrated Systems Main Proprietary Protocol
- CC-Link Industrial Networks, supported by Mitsubishi Electric
- DALI (Digital Addressable Lighting Interface), specified by IEC 62386
- DSI (Digital Serial Interface for the controlling of lighting in buildings), precursor to DALI
- Dynet, lighting and automation control protocol developed in Sydney, Australia, by the company Dyalite
- EnOcean, low-power wireless protocol for energy harvesting and very-low-power devices
- European Home Systems Protocol (EHS), merged into KNX
- European Installation Bus (EIB) (also known as Instabus), merged into KNX
- INSTEON, SmartHome Labs Pro new two-way protocol, based on Power-BUS
- KNX (also known as Konnex), resulting from Batibus, EHS, and EIB
- LonTalk, protocol for LonWorks technology by Echelon Corporation
- Modbus RTU or ASCII or TCP
- oBIX (Open Building Information Exchange), a standard for RESTful Web Services-based interfaces to building control systems developed by OASIS
- UPB, two-way peer to peer protocol
- VSCP (Very Simple Control Protocol), a free protocol with main focus on building or home automation
- xAP, open protocol
- X10, open standard for communication among electronic devices used for home automation
- Z-Wave, wireless RF protocol
- ZigBee, open protocol for mesh networks

The numerosity of standards and protocols is explained as follows. Smart buildings require a fusion of technology and disciplines. Solutions found in one discipline may be usefully applied to another discipline. Recommendations for a discipline should be shared across all disciplines that are transferable and applicable. Engineers should also be aware that people in another field are embracing knowledge about their own discipline. With the help of common standards, interdisciplinary communication and integration will become more convenient.

7.3. Buildings Analytics

Building analytics is a powerful method to help you operate your building safely and efficiently during and after the COVID-19 pandemic. Building analytics leverage existing BAS data. Smart analytics solutions will be able to gather these data from buildings and quickly process millions of data samples to provide actionable solutions.

J. Wilson et al. [72] brought up four things that can be considered to keep your building running safely and efficiently during the pandemic or even in the post COVID-19 era. These methods are:

1. consider investing in sensors,
2. fine-tune your existing building analytics platform,
3. introduce compliance reporting,
4. communicate results.

However, it is of course important to make sure your building analytics platforms are configured with reality in mind so that they can be used not only for arc-fault detection devices (AFDD) and energy reporting but also for compliance reporting. It is likely that buildings that are transparent about their performance and communicate with different stakeholders, including building occupants, may stand out as this will help build occupant confidence and gain trust.

7.4. Case Study

Improving the hygiene and sanitation of medical institutions and hospital buildings has become a top priority in the fight against this intense pandemic situation.

In [73], a group of researchers studied the BACS for three healthcare facilities in Denmark. The case study is chosen as it focuses on healthcare facilities, which are particularly stressed in the case of a health contingency such as COVID-19.

The three case study buildings are as follows:

- Case A: healthcare building built in 2001, with subsequent extensions and upgrades to the ventilation system design.
- Case B: healthcare building constructed in 2000, with a deep energy retrofit in 2020/2021, including new ventilation and cooling systems and BACS design.
- Case C: healthcare building completed and opened in 2019.

In such facilities, properly designed, installed, and operated building automation and control systems are critical to achieving energy efficient operation and optimal indoor conditions. The building automation, control system auditing, and intelligence assessment tool IBACSA was used and implemented in the three buildings. The considered domains were as follows: heating, hot water, cooling, ventilation, lighting, dynamic envelope, electricity, and monitoring and control. The tool provides a comprehensive assessment of each of the eight construction areas based on five impact criteria, (1) energy efficiency, (2) maintenance and fault prediction, (3) energy flexibility, (4) comfort, and (5) information to occupants.

The study intended to discuss the influence of the building automation modification on energy performance. Researchers first collected the current BACS auditing data for three sample buildings, and then simulated three hypothetical automation system improvements, which were (1) technical improvements, (2) comfort improvements, and (3) energy efficiency improvements.

The technical improvements focus on low-scoring technical areas and aim to improve a specific area or introduce certain systems that affect multiple areas. The improvement in comfort by this impact standard is crucial in healthcare facilities. In healthcare systems, indoor comfort and air quality are among the highest priorities. This is mainly why the ventilation system is the best performing area in all three cases. The energy efficiency improvements aimed at improving the rating of a building from an energy efficiency perspective, directly affecting the technical and economic performance.

The comparisons of BACS auditing with/without improvements are in Table 5.

Table 5. Improvements in BACS auditing in a case study, elaborated from [73].

	No Improvements			Technical Improvements			Comfort Improvements			Energy Efficiency Improvements		
Domains	A	B	C	A	B	C	A	B	C	A	B	C
Heating	D	B	C	C	B	B	C	A	B	B	A	B
Domestic Hot Water	D	D	D	C	D	D	D	D	D	C	C	C
Cooling	D	B	B	D	B	B	C	A	A	B	B	A
Ventilation	C	A	A	B	A	A	B	A	A	A	A	A
Lighting	E	A	B	E	A	B	A	A	A	A	A	A
Dynamic Envelope	E	C	D	E	C	D	E	C	D	E	C	D
Electricity	D	E	B	D	C	B	D	E	B	D	E	B
Monitoring and Control	C	A	B	B	A	B	C	A	B	C	A	B

Table 5 shows a comparison of the grade scores for the three buildings in different domains in the base case and the three improvement scenarios considered.

Clearly, the three medical buildings scored high in the ventilation system area, while they scored relatively low in the domestic hot water area, highlighting the need for more attention in this area, which is totally reasonable considering that the samples are all healthcare buildings. Compared with Case B and Case C, Case A was the case with the most significant increase in accumulated points due to the low starting level of the building's automation and control. In addition, the implementation of the energy efficiency improvement package resulted in a substantial increase in the energy efficiency score of all three cases. These results show that retrofitting older buildings with new technology can pay off. The energy, and more specifically, the energy efficiency, may not be the primary consideration for healthcare buildings and hospitals, but, in general, there is a very tight relationship between the superior design of BACS and its functionality, and higher energy efficiency performance that could provide better internal comfort and air quality inside buildings, which is critical for public health buildings, especially during the pandemic era.

8. Local Energy Generation and Storage

The pandemic has exacerbated energy poverty, with a dual effect: the lockdowns have led to higher energy spending, along with shrinking markets and lower incomes. However, the changing environment can provide excellent opportunities for local renewable energy generation, energy storage, and power transmission. As an example, researchers studied the impact of an altered environment and the possibilities for the exploitation of a photovoltaic–battery energy storage system (PV-BESS) [74], as in Figure 9.

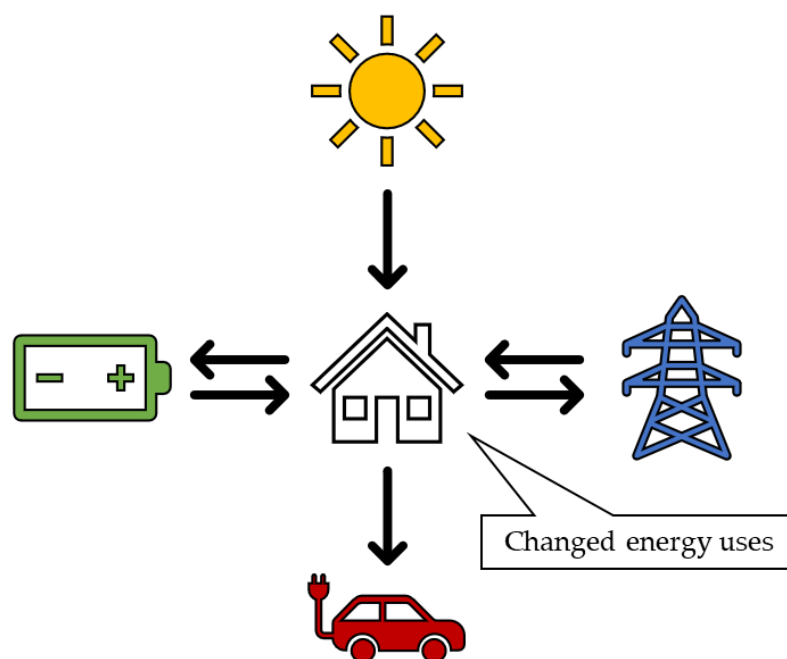


Figure 9. Schematic of integration of local renewable energy generation and storage, in pandemic-changed energy uses.

Case Study

In [74], researchers built a model that relies on the annual average energy exchanged by the system each day, which allows the optimal design for the system to be found and the baseline cost to be determined. This case study is presented as it is a study specifically investigating, in a quantitative way, the different levels of profitability of local generation and storage systems under COVID-19 restriction scenarios. Then researchers built a secondary model that ran on a 15-min baseline with a time-varying profile of the sun, load, EV charging, and purchase/sale costs. It produces reliable estimates of system costs and revenues. The results of the design study were as expected, if the load demand is higher and more sunlight load is used, the PV plant area expands; the battery increases proportionally with the nighttime load. These results suggest that EV adoption and pandemic load require different optimized systems; if the PV-BESS system is tailored to maximum the effective demand, then a pandemic scenario can provide more cost savings than a non-pandemic counterpart. The pandemic has had a major impact on domestic energy use, with electricity bills increasing by more than 9%. The PV-BESS system can significantly reduce the additional energy costs incurred by the pandemic: +36% combined with EV home charging compared to the same setup under normal load, and +40% when an EV is not in use. The main results are reported in Table 6.

Table 6. Comparison of results on average daily energy exchange and yearly energy cost and saving for an Italian household based on the presence of a renewable energy system, an electric vehicle, and lockdown measures, elaborated from [74].

Scenario			Daily Energy (kWh)		Annual Cost (EUR)	Annual Saving (EUR)
PV-BESS	EV	Lockdown	From Grid	To Grid		
No	No	No	13	0	1094	-
No	No	Yes	19	0	1458	-
No	Yes	No	25	0	1860	-

Table 6. *Cont.*

Scenario			Daily Energy (kWh)		Annual Cost (EUR)	Annual Saving (EUR)
PV-BESS	EV	Lockdown	From Grid	To Grid		
No	Yes	Yes	30	0	2225	-
Yes	No	No	6	20	448	645
Yes	No	Yes	7	18	552	906
Yes	Yes	No	16	19	1155	706
Yes	Yes	Yes	17	17	1264	961

9. Discussion

The technology solutions discussed in this paper are summarized in Table 7.

Table 7. Main technology solutions in response to COVID-19.

Solutions	References	Results	Advantages	Inconveniences
ICT	[21–29]	Overcomes the inconvenience for distance working	Working/communication at home, reduce chance of exposition	Not everyone has the proper tools, has requirements on internet
HVAC improvements	[30]	Improved interior air quality	Enhanced air cycle, decrease the chance for infection	Some buildings may have difficulties to carry out modifications on HVAC system; also, some improvements require a specific filter that may be hard to find
Refrigeration/Cold chain	[42–45]	Management and surveillance for storage and supply of medical equipment	Reduce the waste of medical equipment	The system still has space to improve, and not all the countries have high standard cold chain system
Robotics	[46–63]	Help people improve living quality in many ways	Ease the work load for humans; can perform better on some long repetitive tasks or highly dangerous tasks	Significant increase in input costs, need time to train, limit ability to deal with unexpected situation
Sensor networks	[64–66]	Establishing models of contagion; analysis and surveillance of building performance	Help people better understand disease's spread pattern; keep the building work in high efficiency	Cost: different building has different situations; sensor systems may require custom design
Building automation	[73]	Efficient use of energy and optimal comfort	Improvements in energy efficiency and comfort	Not similar improvements in all sectors (needs attention)
Local energy generation and storage/PV-BESS	[74]	Significantly reduced energy consumption	Could reduce annual cost on energy bills; have positive effects on sustainability	PV-BESS require suitable location and weather environment to set, cannot apply globally

Some of the technical solutions presented above have been specifically designed as a response to the COVID-19 pandemic, i.e., robotics for supply, examination, cleaning, social interaction, etc., surface disinfection, temperature measurement, security, swab and blood samples, and sensors for contagion modeling. Other technologies can be successfully exploited in this case.

As mentioned in the chapters above, smart buildings can provide solutions to several difficulties brought about by the COVID-19 pandemic, and the prospect of their actual application seems promising. However, there is always duality for everything, of course, including smart buildings.

For example, to improve the general living conditions and safety of residents, smart buildings must collect a large amount of information about occupant behavior, including personal data. Therefore, managing personal data protection is one of the priority problems for smart building owners and operators to solve. In 2020, smart buildings collected over 37 zettabytes of data globally through an array of sensors and smart connected devices [75]. To mitigate the worries about privacy and data protection safety, smart building technologies should consider privacy and data safety all the time during the establishment process to ensure fulfillment of GDPR and national data protection legislation. Moreover, to improve the analysis method/algorithm, efforts need to be made to decrease the quantity of data needing to be collected. After all, the more data that is collected, the more difficult it is to monitor that the data has been handled using a proper method.

Another important issue associated with the development of smart buildings is the allocation of costs for upgrading buildings using smart technologies. An advanced building with greater technology can provide a much improved living experience, but the cost of the building is usually increased, too. This raises the question as to which party should pay for the increased bill. Even if the investment cost of smart technology is initially borne by landlords, they may pass it on to tenants and/or occupants by increasing rents, which may be deemed unacceptable by tenants and occupants. To solve this contradiction, given that the appliance of smart technologies can reduce energy consumption and utility costs, and even help prevent the spread of infectious diseases such as COVID-19, Tišler et al. [76] believe that national policymakers and the EU need to support the actuarial application of smart buildings with specific financial initiatives to support programs.

The importance of thinking about this aspect when considering the role of buildings in human health is increasing day by day. While this is not an immediate measure to reduce the spread of COVID-19 or even other infectious diseases, in the long term, it is a solution that could benefit public health and may help boost the population's immune system to some extent.

On a different aspect, building holistic, sustainable buildings and urban areas is a burgeoning trend with great potential not only to increase resistance to infectious diseases, but also contribute to facing the challenges of climate change.

These solutions are ranked in Figure 10 in buildings and urban areas, according to the scale and evaluation explained. This categorization can identify solutions that are only relevant to reducing the risk of COVID-19 and others that are also beneficial in other aspects of sustainability (win-win).

Because the smart building is a relatively new concept, there are not many regulations and laws to restrict the related activities, which is worrying many people. However, although the smart building is a new concept, given some time, regulations and levels of supervision will be more complete and more reasonable. The smart building is still a technology for which the pros outweigh the cons.

Figure 11 summarizes the main points regarding smart buildings during the COVID-19 pandemic [76]:

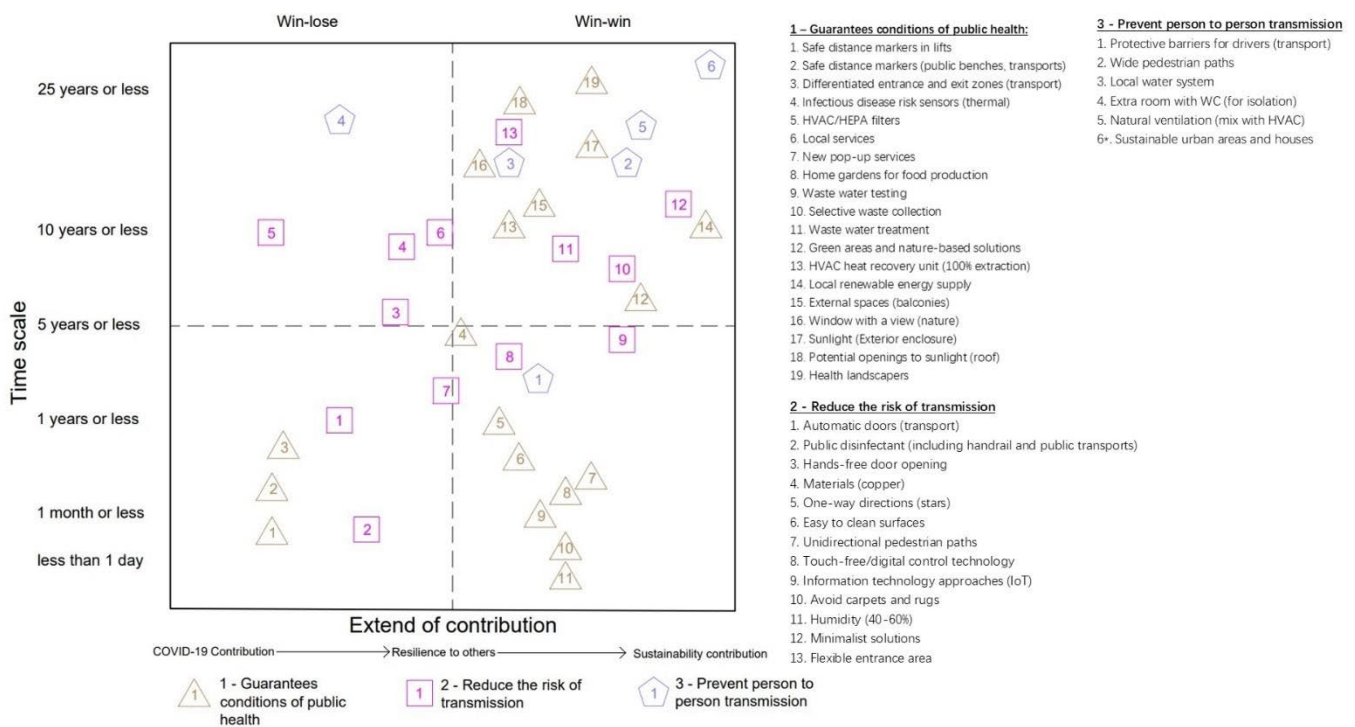


Figure 10. Classification of elements contributing to building healthiness, elaborated from [4].

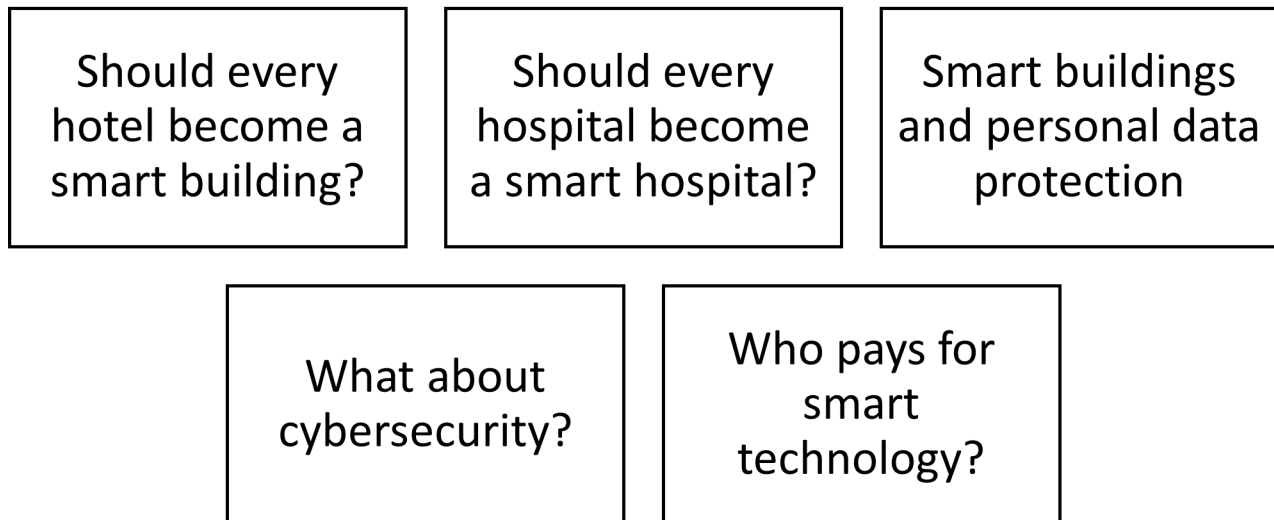


Figure 11. Main points on smart buildings for COVID-19, elaborated from [76].

Economics

The positive influences of smart buildings are not just limited to this special pandemic period. If we take an example of hotel and leisure facilities, using smart building technologies has not only improved hygiene standards and saved on running costs, but has also led to huge advancements in the whole living experience. Many hotels also offer hotel service apps with features including direct booking, quick check-in and check-out, mobile spa and restaurant reservations, mobile room service, and direct guest messaging. As digital and contactless services become the norm, many hotels are already working to digitize core operational processes such as online check-in and check-out, online bill payment, and mobile room keys. It is certain that the changing expectations and habits of travelers will influence this trend in the future [76].

A study, called ‘A New Investor Consensus: The Rising Demand for Healthy Buildings’, coordinated by global real estate group BentallGreenOak (BGO), the United Nations Environment Programme Finance Initiative (UNEP FI), and the non-profit Center for Active Design (CfAD), indicated that the business case for healthy buildings is growing in the global market. Specifically, certified healthy buildings garnered rental premiums of 4.4 to 7.0 percent over their standard counterparts. Companies occupying these buildings benefit from increased employee satisfaction and higher productivity, as well as lower absenteeism and lower turnover of staff [77]. The smart building is not just a technology for personal wellbeing, it also has great potential from an economic aspect, and a bright future even during the post pandemic time.

10. Conclusions

Facing the challenges posed by the pandemic, the whole of human society has worked hard to mitigate the impact of the new situation that has changed our lives.

Since this pandemic is a global event, many fields of science and technology have been asked to help. As one of the most important fields related to people’s daily life, the field of construction is using an emerging concept, smart building technology, to help alleviate the difficulties caused COVID-19. We have seen useful contributions from BACS, local energy generation and storage, and robotics. By using a multidisciplinary approach, we can leverage smart building technologies and natural resources to create healthy buildings. This is also the future direction for construction.

However, nothing is perfect of course, and this is the same for smart building technology. The security of personal data and the increased cost of building programs are all things to consider. However, relative to smart building technologies overall, the pros outweigh the cons. It is a long-term investment worth sticking with. After a period of time, the regulations will be much improved and more reasonable.

The emergence of the COVID-19 pandemic and the possibility of other similar diseases and infections hitting humanity again have led to considerations being made regarding its impact on people’s daily life, and the fact that smart building technology may play a bigger role in the future.

Author Contributions: Conceptualization, M.M.; formal analysis, X.X., S.R. and M.M.; investigation, X.X., S.R. and M.M.; data curation, X.X.; writing—original draft preparation, X.X.; writing—review and editing, S.R. and M.M.; visualization, X.X.; supervision, M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: Part of this work was presented as a dissertation in Sustainable building engineering degree program, chaired by G. Sappa at Sapienza University of Rome, Italy.

Conflicts of Interest: The authors declare no conflict of interest.

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