What, why and when to go virtual: An international analysis of early adopters of virtual building energy codes inspections

Keywords: building energy codes, building energy standards, building inspections, virtual inspections, buildings energy efficiency, international

1. Introduction

Reducing energy consumption is a growing priority for policy makers today to reduce greenhouse gas emissions and costs. Buildings are on the frontline of this issue because of their high energy consumption. Together, the buildings and construction sectors make up more than a third of global final energy consumption and about 40% of total direct and indirect CO_2 emissions [1]. Building energy codes, which are policies that traditionally set minimum requirements for building energy use, are viewed as one of the most cost-effective policies for decreasing energy intensity and reducing greenhouse gas emissions from buildings [2,3,4,5]. For example, building energy codes have reduced energy consumption in buildings by up to 6% in southern European countries [2], by 22% in Germany and the Netherlands [2], and by 13–22% in China [6], and this trend is expected to continue. In the United States from 2010–2040, residential and commercial building energy codes are projected to save about $138 billion in energy costs and prevent about 900 million metric tons of CO_2 emissions [7].

While codes tend to vary in format and approach across nations and levels of government, having effective and efficient methods of checking compliance is critical to ensuring that energy codes are met [8,9,10]. Building energy code inspections have traditionally been performed in person, whereby an inspector visits the building site to determine whether the building and building systems (e.g., lighting, envelope, and heating, ventilation, and air conditioning [HVAC]) comply with the building energy code [8,9]. These inspections take place during various phases of construction: at the design phase (e.g., inspectors check plans to ensure they are code compliant before construction begins), during construction (i.e., ensuring construction is being completed according to design), and before occupancy (i.e., before issuing a permit). While less common, some jurisdictions also perform building energy code inspections after construction (e.g., following a major building renovation) [9]. However, many countries are looking for faster and easier methods to check for compliance and increase reliability in evaluations [11]. This is due to various pressures such as rapid urbanization growth [12], urgency to meet energy efficiency and decarbonization targets [13,14], inspector shortages [15,16], or simply a need to increase code enforcement capacity on a limited budget [15,17]. As a result, some jurisdictions around the world are looking for ways to speed up or automate parts of the code inspection process and see virtual building inspections as a potential means to do so. Moreover, virtual inspections became necessary for many jurisdictions in the past two years due to lockdowns from the COVID-19 pandemic, forcing adoption of virtual inspections [18]. Across the world, there is now increased attention on virtual inspections.

The literature reveals that there are clear drawbacks associated with traditional building in-person inspections. For large or complex inspections, in-person methods are generally labor-intensive, time-consuming, costly, and often inefficient [19]. In addition, in-person inspections are naturally prone to human error. Error rates of 20% to 30% are frequently quoted in the literature across multiple types of inspection tasks [20]. The literature suggests that, with appropriate technological interventions, these errors can be reduced, albeit not entirely eliminated. The literature also highlights important considerations to assess building energy code inspections. One such consideration is the number of inspections performed and at what point in the construction process (e.g., before, during, or after construction) [9]. In a study by Evans et al. [16] looking at the international implications of national and local coordination on building energy codes, five jurisdictions reported that it was essential to understand the tools and technologies available to carry out inspections, as well as the time it takes to complete an inspection, to help inform strategies to increase capacity for undergoing code inspections. Vaughan and Turner [21] also underscore the importance of considering the benefits to customers during code compliance inspections. This study builds on this research to assess when virtual inspections could be beneficial to assess building energy codes.

Only a few studies have looked at the potential for virtual inspections in buildings, even less for building energy inspections. Most of the literature on virtual building inspections has focused on a single region (e.g., [19, 22]) or specific technologies (e.g., [23,24,25]). Other studies (e.g., [26,27,28]) evaluate different technologies including virtual reality cameras, remote sensors, and automatic drones to detect defects in construction and manufacturing. While these studies demonstrate the potential for incorporating technologies to enhance the efficiency of inspections, there are no examples of how these technologies can support (or not) compliance to regulations such as building energy codes. Additionally, the heightened attention on virtual inspections following the COVID-19 pandemic provides an opportunity to assess the viability in the longer run based on experiences across countries. There has not been a study that analyzes how virtual energy code inspections are carried out in various jurisdictions around the world, and this paper attempts to address this gap.

2. Methodology

The study drew information from five countries: Australia, Canada, Singapore, United Arab Emirates (UAE), and the United States. With the exception of the UAE, these countries were selected for the study given their participation in the International Energy Agency’s Energy in Buildings and Communities’ Building Energy Codes Working Group (BECWG). This international group has information sharing on building energy code practices as one of its fundamental objectives [29]; as such, these countries were more willing to share information on their practices and lessons learned. The authors reached out to the BECWG’s 15 member countries. From those countries, the authors interviewed six countries interested in participating: Australia, Brazil, Canada, Japan, Singapore, and the United States. Neither Brazil nor Japan currently conducts virtual inspections; thus, they were excluded from the study. In Brazil, this topic is of interest, but they do not have mandatory building energy codes, although there are plans to make parts of their current building energy labeling program mandatory. In Japan, virtual inspections are not legally permitted. Four of these remaining countries currently conduct virtual inspections and thus were selected for this study. The UAE, while not a member of this working group, has participated in BECWG webinars in the past, specifically on the issue of building codes virtual inspections [18], and so they were included in the study.

From the selected countries, 11 interviews were conducted. Within these countries, jurisdictions were selected and interviewed based on one or more of the following criteria: (1) the jurisdiction incorporated virtual inspections prior to the COVID-19 pandemic; (2) the jurisdiction was on lockdown during the pandemic and switched to virtual inspections as a result; and (3) the jurisdictions represent differing geographies and population growth trends. The selected case studies therefore represent a set of diverse, unique perspectives on building virtual inspections. For instance, the study includes small, condensed local jurisdictions (like the City of Fort Collins, Colorado, U.S.) to megacities with high-rise buildings (e.g., Singapore) to geographically sprawling jurisdictions (such as those belonging to many First Nations communities in Canada). Some jurisdictions have been performing virtual inspections since before the pandemic (e.g., Singapore), while others have adopted virtual inspections out of necessity (e.g., Fort Collins and North Las Vegas, Nevada, U.S.).

All the interviews followed a semi-structured interview approach [30], which allowed the authors to ask specific structured questions and follow-up questions for the participants to elaborate on their unique experiences and perceptions. This allowed deeper exploration of local issues. The structured questionnaire, provided in the annex, focused on parameters built on previous research [9,31,32], which are studies that highlight important considerations in energy codes and inspections. These parameters include: (1) time and financial implications; (2) changes to the scope of inspections; (3) changing practices and technological innovation; and (4) benefits to customers. The questionnaire and parameters were reviewed and edited by experts in the field. Since building code enforcement varies with the country's form of government and inspection method [9], the authors interviewed a variety of people involved in the inspection process, including local government representatives, building inspectors, and certifiers. The authors conducted interviews via video or phone call and asked permission to share results. Questions regarding quantifying cost and time savings were estimated (including travel, inspection, review, and follow up), and additional information was collected via email when additional context was helpful. Questions addressed the systems in place related to virtual inspections and what they required to be effective. The authors transcribed the interviews and grouped the responses based on the four parameters.

Interviews were also accompanied by a literature review. Using the Google Scholar search engine, the following key words were used: "virtual inspections," "virtual inspections buildings energy," "virtual inspections building energy codes and standards," "remote virtual inspections," "teleinspection in buildings."

While the focus of this paper is on verifying building energy codes, the authors also drew information from other types of inspections when applicable and comparable, particularly as evidence of virtual inspections for energy codes is sparse. For example, the research included UAE virtual inspections for fire safety codes, since these are conducted in ways that could be applied to energy code inspections in the future. In addition, the authors evaluated the experience of the National Australian Built Environment Rating System (NABERS), a national rating system that measures environmental performance (including energy efficiency) of Australian buildings. While voluntary, the NABERS program has been highly successful in transforming the energy efficiency of nonresidential buildings in Australia and is a fundamental part of their net-zero national strategy [33,34]. While these inspections are not directly related to mandatory energy codes, the novel technologies and strategies being developed for their own inspection processes can be applied to building energy codes. Table 1 outlines the jurisdictions interviewed.

Table 1: Jurisdictions/groups interviewed

Jurisdiction / Group	**Interviewee Affiliation**	**Type of inspection discussed**
First Nations[1] communities in Canada	FNNBOA (First Nations National Building Officers Association)[2]	Building (including energy code) inspections
Fort Collins, U.S.	Local government	Building energy code inspections
Australia	NABERS (National Australian Built Environment Rating System)	Building energy certification inspections
North Las Vegas, U.S.	Local government	Building energy code inspections
Singapore	Building Construction Authority	Building (including energy standards) inspections
UAE	National government	Building code fire, safety, and building energy inspections

[1] First Nations refers to Indigenous Canadian peoples who are neither Inuit nor Métis.

[2] FNNBOA covers First Nations communities in British Columbia, the Territories, the Prairies (Alberta, Saskatchewan, and Manitoba), Ontario, Quebec, and the Atlantic (New Brunswick, Nova Scotia, Prince Edward Island, and Newfoundland, and Labrador). The FNNBOA represents people in First Nation communities who provide residential, commercial, and institutional construction and renovation technical services, including plans review, inspections, recommending repairs, technical advocacy, and advisory services assisting on reserve construction.

3. Results

The inspection methods surveyed in this study varied across jurisdictions (Table 2). Inspections can be completed by government-affiliated building inspectors or third-party inspectors, with a variety of trainings or certifications. In all jurisdictions, inspections traditionally have the inspector and building owner physically present, requiring scheduling times and travel for the inspector between sites. However, jurisdictions are increasingly implementing virtual inspections as a result of their potential cost and time savings as well as out of necessity from the global COVID-19 pandemic. With the exception of self-certification, virtual inspections often consist of a building inspector who reviews the building from afar while the building owner collects and sends information electronically to the inspector. Depending on the jurisdictional needs and budget, virtual inspections are performed using video inspection software, video calls, high-resolution pictures, and/or self-inspected checklists.

Table 2: Surveyed virtual inspection overview

Jurisdiction/Group	Virtual Inspections Method
First Nations, Canada	Builder takes pictures and sends to inspector.[1]
Fort Collins, U.S.	Inspector holds video call with building owners and reviews permitting documents.
Australia	NABERS third-party inspectors perform video calls with building owner and confirms notes are the same and/or checks other forms of evidence.
North Las Vegas, U.S.	Inspector holds video call with building owners and reviews permitting documents.
Singapore	Building owner sends energy data to inspector and uses the building automation system.[1] Currently, Singapore is piloting inspections that incorporate drones and automation technology.
UAE	Building owners conduct self-recorded or self-inspected checklists against their codes using checklists and video evidence that are verified by inspectors.

[1] Building structural inspections use video platform capabilities.

In many jurisdictions (e.g., Australia, North Las Vegas, Fort Collins), inspectors use popular video platforms such as Facetime, Microsoft Teams, Duo, and Zoom to check for compliance remotely. The video platforms used varied based on jurisdictional needs and familiarity. For example, North Las Vegas currently allows their inspectors to determine what video platform they use to provide flexibility and autonomy to best meet their own and their clients' technological needs. In addition, inspectors typically review approved permitting documents to ensure the building matches the design.

While most code compliance checks are performed before (if reviewing plans), during, or right after construction of a building, the study revealed that Singapore is also implementing virtual inspections to collect energy data after a building is occupied. In 2013, Singapore mandated that all buildings submit general building information and energy consumption data to Singapore's Buildings Control Authority, requiring a higher ('Green Mark') building certification rating [35]. To address this regulation, Singapore sometimes uses a building automation system to directly collect energy data and trends and compare them to Singapore's minimum energy performance standards for buildings. By sending videos and photos of the building automation system information or accessing the system directly, inspectors can verify whether the building is compliant with the standards. Singapore conducts their energy inspections of existing buildings by accessing the building automation system and/or receiving a building's energy bills to ensure compliance with a certain level of energy use intensity in the building.

The UAE conducts self-recorded or self-inspected checklists against their fire safety codes. Building owners will run through an inspector's checklist and film the required tasks for compliance. An inspector then reviews and ensures compliance virtually, thus minimizing the interaction between the inspector and building owner almost entirely.

3.1. Scope of inspections

While the methods of virtual and in-person inspections differ, the scope did not change much between the two; all jurisdictions revealed that the purpose and general outcomes of the inspections remain the same. For building energy codes, the inspections still typically include checks of energy efficiency measures ranging from insulation, fenestration, air leakage control, duct insulation and sealing, to temperature controls and lighting requirements. However, virtual inspections limit the amount an inspector naturally sees and can result in increased visibility challenges. Limitations of virtual inspections can include building owners using the technology improperly (e.g., they do not point the camera properly) or being dependent on the knowledge of the building owner. Yet, virtual inspections may add new capabilities to the inspection process that do not exist for in-person inspections. For instance, virtual inspections could allow inspectors to automate and collect more data that can be useful in new ways, such as creating better documentation and feeding the data into artificial intelligence (AI) and as-built simulation, as is being tested in Singapore.

The accuracy levels of virtual versus in-person inspections are still inconclusive for the jurisdictions interviewed. The main questions are whether virtual inspections result in tampered evidence or are missing aspects that are noncompliant. The quality of virtual inspections is dependent on the accuracy of the information received and the ability of the inspector to verify that information. Different jurisdictions had various viewpoints. In Fort Collins, one building code official explained that virtual inspections provide new opportunities to conceal or tamper with information being sent or shown to the inspector. For example, in a video inspection, if the person holding the camera decides not to show a room or area of the building, the inspector may never notice aspects that are noncompliant with the code. This uncertainty has given some jurisdictions pause for fully embracing virtual inspections; however, in-person inspections can hide information as well. In North Las Vegas, another building code official noted that even with in-person inspections, people find ways to cheat the system by withholding information or providing inaccurate information. According to the official, what is important is how the inspection is conducted to verify the information and the number of checks conducted. For example, obtaining access to a building's floor plan and showing 360-degree views with the camera can ensure all rooms and equipment are inspected, or analyzing equipment nameplates can confirm the accuracy of the information. Another consideration is confirming the location of the building actually being inspected (e.g., through geolocation or visibly confirming the address via video) to ensure the owner does not show a different building entirely.

Determining the accuracy of virtual compared to in-person inspections is a major gap and area of future work. For example, in the UAE, officials felt that self-reported inspections were just as efficient and effective as in-person inspections, though to our knowledge there have been no studies to compare the accuracy of the methods.

3.2. Time and financial implications

Jurisdictions reported experiencing differences in time and financial savings when transitioning from in-person to virtual inspections. Large sprawling jurisdictions (e.g., First Nations communities in Canada and jurisdictions in Australia) saw the most time and financial benefits due to reduced travel expenses.

More condensed jurisdictions (e.g., Fort Collins) did not see time savings so the benefit was minor. Table 3 shows the time and financial implications for the interviewed jurisdictions.

Table 3: Time and Financial Implications

Jurisdiction/Group	**Time Savings**	**Cost Savings**
First Nations, Canada	2-3 days saved for remote communities	Up to $8,000 USD
NABERS, Australia	Full day of travel per inspection	Average of $4,000-$8,000 USD[1]
North Las Vegas, U.S.	Estimated to be twice as efficient due to reduced travel	Estimate not reported but would consist of fuel savings from transportation and labor savings on future inspections
Singapore	Pilot results show 4–8 weeks of the background administrative permitting and building inspection process can be condensed to a few hours of actual working time	Estimate not reported but the initial implementation cost suggested to be relatively high for virtual building inspections
UAE	Too recently adopted for jurisdiction to determine time savings	About 80% of costs from labor and travel

[1]Depending on location and building size

Transitioning to virtual inspections can be more cost-effective by saving inspection, travel, and administrative costs. These time savings allow an increase in capacity for inspections. For example, the UAE estimated that moving to virtual inspections for their building's fire safety codes reduced inspection costs by 80%. In North Las Vegas, a building inspector estimated that transitioning to virtual energy code inspections could allow each inspector to examine twice as many buildings, solely due to removing travel.

Since virtual inspections eliminate the requirement to travel, they can increase capacity to inspect more buildings and, in some cases (e.g., with NABERS in Australia and First Nations communities in Canada), provide the ability to reach more areas. All jurisdictions agreed that virtual inspections eliminate travel times, which can make inspections easier and cheaper for communities with large distances between them and the inspection site. Reduced travel times, and therefore less incurred costs, can make inspections more accessible. For example, the NABERS program in Australia costs money for the owner to get their building certified. However, since NABERS inspectors no longer need to travel far, they can save $4,000–$8,000 USD per inspection, depending on the building size and location. Thus, NABERS can reduce their prices, making building certification more financially accessible to owners across Australia.

Similarly, in the First Nations communities in Canada, virtual inspections in distant communities allow code inspections to become more affordable and accessible in harder to reach places, increasing their inspection range and capacity. The FNNBOA is a nonprofit in Canada that represents people in First Nations communities who provide building construction and renovation services. FNNBOA offers support to those who conduct building reviews and inspections to Indigenous communities on reservations. FNNBOA introduced virtual inspections (referred to there as "teleinspections") in 2015 to reduce travel times and costs, and optimize the number of inspectors available, tackling their two major problems: expensive travel costs and limited number of building inspectors. With COVID-19, virtual inspections also increased in demand as some inspectors could not gain access to communities.

In Canada's First Nations communities, interviews revealed that virtual inspections can dramatically reduce building inspection costs for remote communities. Virtual inspections generally save 2–5 hours of travel time to the communities. For especially distant communities, travel to and from a site can take two to three days and cost between $3,000–$5,000 for a flight and the cost of lodging.[1] In addition, it can take time to schedule inspection visits, which can cause significant construction delays. In certain cases, inspectors also have to factor in that they may face significant weather delays, tying them down for days in remote communities. These are clear examples of when virtual inspections can deliver substantial financial and time savings, eliminating the need to travel at all and providing faster turnaround times.

While the major time and financial savings occur from travel costs, there are administrative savings too through reduced scheduling and use of software and tools. Visiting on site takes coordination and scheduling between the two parties, usually planned weeks in advance, and creates some minor administrative costs. Virtual inspections that use software and automated tools can check compliance and generate reports quickly. This allows a much faster turnaround time, while also having the ability to save and store information for the future. This is especially beneficial for jurisdictions that are building rapidly or can apply economies of scale to see more payback for their investments. In Singapore, switching to virtual inspections can reduce the 4- to 8-week inspection process to only a few hours of initial inspection time due to less administrative and travel times. The inspectors can quickly look for compliance and generate reports immediately after the inspection, allowing builders to construct faster. This concept translates to building energy inspections as well.

However, the study also revealed that virtual inspections are not always more cost and time effective. Fort Collins reported that cost savings were not apparent when they adopted virtual inspections out of necessity following pandemic lockdowns. They transitioned to video calls, but since travel time was minimal throughout their jurisdiction (frequently under 20 minutes), any cost savings from fuel for transportation was minimal. The time saved by going virtual was offset by the time required to train the various contractors to use the video equipment. In general, time savings still exist for smaller jurisdictions from avoiding travel to each site, but just not as beneficial as for more sprawling jurisdictions.

While virtual inspections can save time and costs, the transition to virtual requires initial time and money to build capacity. The amount of capacity building needed varied across jurisdictions depending on their scope and methods of inspections. All interviewed jurisdictions indicated their inspectors had a learning curve transitioning to a virtual environment and all jurisdictions mentioned the benefit of standardizing the process. However, over time, all the jurisdictions became accustomed to using the virtual inspection tools and processes. For example, the NABERS program in Australia is currently developing official training modules for their inspectors now that they have been conducting virtual inspections for over a year. Similarly, First Nations communities in Canada plan to incorporate virtual inspections into their mandatory training for contractors. All jurisdictions mentioned that standardization makes it easier to continue implementing virtual inspections and training inspectors in the future. For example, the UAE and Fort Collins explained that, while it took a long time to adjust to the new tools to conduct video inspections, once the process became standardized it was very simple and natural for the inspectors. Singapore noted that the initial cost for virtual building inspections was rather high for the new technology and trainings, though difficult to quantify. After the initial investment, they could rapidly scale implementation to several buildings making it a worthwhile endeavor.

Jurisdictions that have rapidly increasing construction or a large number of inspections that need to be conducted can greatly benefit from virtual inspections since their initial upfront costs are offset by economies of scale. Smaller jurisdictions were more hesitant to transition to virtual inspections but larger,

[1] For example, in Saskatchewan, a province in Western Canada, a flight from the city of Prince Albert to Fond du Lac, a Dene First Nation, is two hours and costs approximately $1,500 plus another $2,000 for food and car rental.

faster growing jurisdictions were eager to expand their inspection capabilities due to their potential to scale the financial and time benefits from the inspections.

3.3. Customer benefits and impacts

Jurisdictions interviewed reported that customers benefit from virtual inspections as they are more convenient and easier to schedule since inspectors do not need to group inspections by location. This results in timelier inspections and faster turnaround times. Virtual inspections also carry the potential for reduced costs for the customer in some cases. Scheduling a narrow timeslot allows customers to avoid taking days off from work or waiting at length for inspections. All surveyed jurisdictions mentioned that less travel meant faster turnaround times. In addition, by reducing travel costs for inspectors, the cost for customers to obtain NABERS certification also decreased, in some cases by several thousand USD dollars. However, not all jurisdictions are so dispersed so cost-savings vary.

Virtual inspections have changed the educational experience of building owners and contractors. There can be an educational benefit since virtual inspections require contractors and building owners to understand what they are displaying on a video call and why, as identified in Fort Collins. In the case of First Nations communities, FNNBOA explained that traditionally their inspectors played two roles: compliance and education. However, virtual inspections reduce the hands-on advice from inspectors on how to fix aspects of the building. In-person conversations could lead to more organic learning opportunities built from human connection and being physically present on site. With the increasing virtual world, online trainings, seminars, and resources are becoming more widely available. If inspectors notice issues, they can refer building owners and contractors to a construction organization for further virtual training. FNNBOA sees the future of inspections as virtual and using virtual training seminars as an essential educational resource.

Despite benefits to customers, the jurisdictions reported some drawbacks of virtual inspections as well. For instance, privacy can be an issue for virtual inspections with respect to how videos are saved and archived. Some jurisdictions (e.g., UAE) noted this particular concern regarding privacy. In many locations, building permits (and therefore general building information) is public knowledge and easily accessible. However, recording a video of a building during the inspection process may cause concern since videos may generate a higher level of detail of the building and its contents. If hacked or carelessly stored, the videos could unintentionally reveal sensitive information to people who are not approved to see it. UAE officials mentioned that some organizations have previously voiced concern about the security of prerecorded videos during building inspections, despite the videos being archived securely and privately. Jurisdictions require strong computer security protocols on how they gather and store data to ensure the building owner’s privacy during and after the inspection process to avoid leaking sensitive information. If there are security concerns, such as for military buildings, in-person visits can increase the element of trust, and therefore collaboration, since people can meet the inspector who has been granted access to inspect the building and request information, as opposed to an unfamiliar person on the other side of a screen.

Several jurisdictions, such as Fort Collins, North Las Vegas, and Australia, reported that virtual inspections miss the “human component,” not only for customers but also inspectors. Inspectors lose the ability to regularly go out in the field and meet customers face to face, which for some inspectors is a rewarding part of their jobs. Accordingly, the increased time spent on screens could result in lower job satisfaction and impact job retention rates. Table 4 highlights findings on the benefits and drawbacks of virtual inspections from a customer perspective.

Table 4: Reported customer-related impacts from virtual inspections

Jurisdiction/Group	Customer-related benefits	Customer-related drawbacks
First Nations, Canada	- Reduced delays in construction as a result of greater efficiency in inspections (e.g., from reducing inspector travel).	- Customers do not receive hands-on advice on building fixes from inspectors.
Fort Collins, U.S.	- Easier to schedule. - Increased participation of contractors and building owners in the process, thus making the customer more informed on their building energy.	- Some customers prefer in-person interactions over virtual.
NABERS, Australia	- Reduced costs for customers to obtain NABERS rating (by a couple $1,000 USD). - Less time required to schedule. - Faster turnaround times for ratings.	- None reported.
North Las Vegas, U.S.	- Easier to schedule. - Customers saved time and money from not having to take multiple days off from work.	- Some customers prefer in-person interactions over virtual.
UAE	- Prerecorded videos eliminate time waiting for registered inspectors.	- Privacy is an issue for buildings containing sensitive information.

3.4. Technological innovation

Virtual inspections rely on technological innovation to assess code compliance. A jurisdiction's access to technology can be a main factor in the effectiveness of inspections. For instance, many residents in Canada's First Nations communities lack reliable broadband internet and high-quality photo capabilities required to conduct virtual inspections effectively. This limits the ability to reach all communities, making virtual inspections difficult or impossible in certain remote and rural communities. In addition, inspections via video call are dependent on Wi-Fi and phone signal, which tend to be less effective in mechanical rooms where much of the energy equipment analyzed for inspections are located.

Access to more advanced technologies could help increase the accuracy of energy code inspections by minimizing human errors. The current technology in virtual energy code inspections considered in this study include video platforms such as Zoom, advanced building visualization software, building automation systems, and drones and robotics. As technology continues to advance, virtual inspections may become more effective at ensuring compliance by connecting these technologies with advanced digitalization efforts and controls.

Video and inspection software can also connect many project elements with data to automate and archive the inspection process, streamlining documentation and implementation, and eliminating the use of handwritten notes that may impede traceability. Recording videos and taking photos allows archiving client information, which can be helpful for reference in the future. However, if clients have sensitive information, performing virtual inspections can present risks. This forces jurisdictions to think about how they can incorporate measures to protect client privacy. For example, inspectors can ask clients to avoid showing people in their videos or providing sensitive information unrelated to building energy. With the aim of automating inspections entirely in the future, Singapore's Building Construction Authority is exploring data privacy solutions such as the use of blockchain. Blockchain stores data in blocks that are then linked together with cryptography to help protect the data. Another consideration is the increased amount of memory space needed to store inspection-related documentation and photos. Virtual inspections will require more processing, storage, and network resources, which may be cost-prohibitive for some jurisdictions.

New technologies and platforms can be expensive, and many jurisdictions do not see the need for cutting-edge software when videos and high-quality images can pass along the information adequately. For instance, North Las Vegas mentioned how using video inspection software would be convenient, especially for its archiving capabilities, but not essential to effectively carry out their building energy code inspections. Fort Collins planned to return to in-person inspections and therefore did not see the need to invest in new technology to perform virtual inspections.

Drones and digitalization

Drones coupled with thermal cameras and digitalization technologies, such as AI, have the potential to be applied to building inspections since they enable looking into hard-to-reach places and provide opportunities for increased automation. While not yet applied to building energy code inspections, Singapore and the United States are starting to test the implementation of drones for other types of building inspections (e.g., structural codes) to increase the time and efficiency—for instance, by eliminating the need for scaffolding or harnesses and allowing the drone operator to remain in one place. Drone technology is already being applied in other industrial areas such as for inspecting solar farms or safety dams [36,37,38,39]. Advances in technologies that combine thermal cameras and drones could make it possible to use drones in building energy code inspections. Thermal cameras (also known as infrared cameras or thermal imagers) have gained popularity in the past few decades as a tool for surveying building energy efficiency [40]. Modern thermal cameras have the capacity to measure temperature, assess heat loss, identify missing or degraded insulation, and locate sources of moisture. Coupled with drones, this technology could, in theory, make energy inspections more efficient, reliable, and automated, which would be especially beneficial for growing megacities like Singapore.

The Singapore Land Authority and Housing and Development Board is already starting to collaborate with the private sector to explore the use of drones combined with digitalization capabilities for building inspections citywide [39]; however, the focus is on building inspections, not specifically energy code inspections. With demand for building inspections growing rapidly in megacities, combining drones with other digital technology could make inspections more autonomous and efficient. The Singaporean government aims to entirely automate inspections in the future, developing and using AI. The government is exploring technologies that combine drones and digitalization capabilities such as autonomous charging shelter systems and data hubs that allow drones to be recharged autonomously and be linked to the internet [39]. This technology would permit inspectors to focus on the inspection results rather than sorting through hundreds of images and videos.

These technologies could result in substantial time and cost savings. For example, in-person building inspections in Singapore high-rises traditionally take 4–8 weeks at a cost of about $2,000 per day, but pilots combining drones with digitalization technologies promise to reduce the process to several hours of inspection-related work and the cost by 60–70%. While the initial investment for this technology is expensive, pilots suggest that the investment could be made more profitable in the long term by reducing inspection time and associated labor costs considerably, especially due to economies of scale.

While these technologies hold a lot of promise, there are several barriers such as privacy and cost. Using drones can generate privacy concerns like inadvertently capturing video of neighboring buildings that are occupied. With data as a backbone to policy, data security is critical, resulting in many organizations considering technologies such as blockchain to protect the rapid increase of data. Another concern is that filming is currently very expensive, so jurisdictions like the UAE believe that drones for building inspections should only be used when necessary. However, developments in drone technologies are accelerating and may be more affordable in the future, especially when applied at a large scale, thus furthering cost savings from less labor.

Drones also have technological limitations. Future technological development includes expanding drone capabilities for longer flights—from 30 minutes to several hours [39]. This would significantly expand the radius of inspections, allowing inspections of even harder to reach places, and drone services could be outsourced by neighboring countries and cities. However, these capabilities could also present further privacy and permitting challenges.

Another barrier to drone deployment relates to air space safety as drone location is currently not visible to regulatory bodies. This makes it challenging to monitor and protect the air space. However, new solutions using software capability, tracking and registration systems, and cybersecurity may render drones more visible to regulatory bodies in the future. For example, in Japan new legislation in 2022 will create an online drone registration system to allow flying commercial drones in populated areas, greatly reducing the time and paperwork currently required to receive a permit while still tracing vehicles and owners. This change is targeted at creating drone delivery services but is necessary for opening the way for drones to be used in building inspections. Similar drone registration schemes are already in place in Australia, China, France, the United Kingdom, and the United States [41].

It is also not entirely clear the extent to which this technology can be applied to inspect compliance of building energy codes. For example, drones combined with thermal cameras would allow inspectors to see missing or damaged installations, external electrical issues, failed windows, and other energy-related issues in buildings. However, the infrared capabilities of the cameras may, for the most part, be useful once the building is operating and therefore only be primarily helpful for compliance checks of building energy performance standards rather than building energy codes. Energy performance standards are specifications that limit the amount of energy that may be consumed by a building system, so their inspections are common post construction. For building energy codes, once the building is constructed, building envelopes are typically too costly to fix. However, one study in Canada [40] suggests a link between thermal cameras and British Columbia's building energy code, where inspectors can potentially use the cameras to detect air flow and locate missing insulation to verify newly constructed buildings comply with code. In the case of combining drones and thermal cameras, jurisdictions will need to assess whether the current limited applications of this technology for virtual building energy code inspections justifies the cost.

Another consideration is that the digitalization of building inspections can take a long time and require collaboration between many different parties (e.g., regulators, industry, and building inspection accreditation bodies). Most jurisdictions interviewed, such as the local U.S. governments of Fort Collins and North Las Vegas, do not see the need for using drones in building energy inspections presently, but can envision a future where drones are cheaper and more widely used for automation. While not currently implemented, drones have enormous potential to revolutionize the way building inspections and building energy analysis are performed.

Other emerging technologies

Other forms of technology are emerging that can advance virtual inspections. There is increasing interest within the building energy codes community in advancing virtual inspections by modeling after technologies and methods from other types of inspection processes. These technologies, which came up during the interviews and/or are cited in other studies [23,42,43] include archiving or organizational software, advanced cameras, and robots coupled with AI, sensors, and other software. Although some of these technologies have a high initial upfront cost, they may have a high return of investment when applied at a large scale and as a result of an increase in use. Analyzing these technologies in detail, such as how AI is incorporated and rolled out, is outside the scope of this paper.

Visibility is a critical part of virtual inspections. Advanced cameras, such as those that create 360-degree digital photos of buildings or stitch together panorama photos, increase visibility of the building and can make it easier to detect flaws in building systems. Combined with software, advanced cameras such as those with stitching capabilities, can capture more data on a building with minimal time and effort from a person on site. Advanced cameras could also be coupled with various design software programs and archiving capabilities, tracking progress and changes more efficiently by showcasing the entire building or job site. The United States is currently implementing different types of 360-degree cameras and software, such as HoloBuilder, at some construction job sites to track progress of construction projects virtually [44]. While this has not been deployed in building energy inspections, attaching thermal capabilities, such as infrared cameras that capture heat flow, could allow for tracking and investigating energy flows.

A related emerging capability is intelligent project tracking software that can automate project management tasks such as organizing and labeling photos and tracking project updates. This software has the capacity to capture data in real time. For example, it could be applied to track changes to construction projects to ensure continued code compliance. Across the world, companies are adopting this new category of intelligent construction software for project tracking (e.g., StructionSite), which also combines cameras and AI to track construction work [45].

Like drones, robots have the potential to play a role in the future of building energy code inspections. For example, inspectors could deploy automated robots to navigate through buildings, follow routine inspection tests, and collect data more reliably and accurately. There are robots currently used for construction sites or to routinely inspect industries that are more hazardous, such as oil, gas, and mining. One example that exists for building inspections is “Spot the robot dog” developed by Boston Dynamics [46], which can navigate through construction sites, create digital twins of buildings, and compare as-built conditions to Building Information Modeling[2] data autonomously. Similarly, a quality inspection and assessment robot in Singapore (QuicaBot) [43] can autonomously scan an entire room using cameras and laser scanners to pick up building defects, such as cracks and inclinations. An early study of this technology [43] found that the autonomous assessment conducted by the robot resulted in better inspection accuracy when compared to manual assessments. While these have not yet been applied to energy code inspections, there is potential to use robots with thermal cameras to facilitate building energy inspections, similarly to what is envisioned for autonomous drones. Naturally, these would share some of the same challenges as drones related to cost, privacy concerns, and scalability.

4. Discussion

Inspecting buildings for compliance with energy codes is necessary to ensure energy efficiency measures are incorporated into new buildings. In this report, the jurisdictions interviewed identified several important indicators of successful remote inspections. The authors assessed virtual inspection practices in

[2] Building Information Modeling consists of computer files that support decision-making regarding a built asset and integrates multidisciplinary data to create detailed digital representations that are managed in an open cloud platform for real-time collaboration. It is used to generate and manage data during the design, construction, and operation process of a building.

the selected jurisdictions based on four parameters: (1) time and financial implications; (2) changes to the scope of the inspections; (3) changing practices and technological innovation; and (4) benefits to customers. Based on this analysis, the research team identified criteria under which virtual inspections can add value and when they do not. Major themes included time required to reach inspection sites, pace at which jurisdictions are developing new construction, technological accessibility, privacy implications, and initial motivations. These criteria are discussed in more detail in the following sections.

4.1. Time required to reach inspection sites

The time required to reach inspection sites is a key determinant in whether virtual inspections would add value. For instance, in remote locations or geographically dispersed jurisdictions, travel costs can be significant. Virtual inspections in these jurisdictions greatly reduce travel time and costs, providing large savings and benefits over on-site inspections. Where distances are small, the travel time savings and benefits are less and likely the scheduling issues are less complex as a result. Jurisdictions with a large number of inspections (e.g., North Las Vegas) and those that require traveling long distances to inspection sites (e.g., in First Nation communities in Canada) benefit more with virtual inspections. For some jurisdictions, such as Fort Collins, it makes sense to keep inspections simple as the jurisdiction is smaller, requires short travel distances, and has fewer inspections.

4.2. New construction rate

The pace of construction and urbanization in a jurisdiction have an impact on whether virtual inspections have more benefits over on-site inspections. For megacities like Singapore, virtual inspections are beneficial due to economies of scale. Investing in new technologies pays off quicker since they can be implemented faster and wider. The more inspections that need to be completed, the faster the payoff for investing in more advanced technologies. Some jurisdictions, like the UAE, noted that rapid building construction benefits from virtual inspections because they result in quicker approvals due to less travel and administrative time.

4.3. Technology accessibility

A jurisdiction's access to technology can influence whether an on-site inspection is more beneficial than in person. The jurisdiction is less likely to use a new technology if it has high upfront costs or requires additional capacity to use. However, technological advances in robots, digitization, and AI have the potential to revolutionize building energy inspections and may allow more collaboration across borders. Advances in drone automation and range could expand inspection radiuses, but the companies developing such capabilities remain for the most part in the testing and development phases when it relates to buildings' energy efficiency. Digitalization efforts, such as using web tools that streamline compliance checking and permitting processes, have the potential to reduce human errors. Perhaps one of the largest potential impacts of technological innovation on energy codes is digitalizing the entire code inspection process and collecting data that can then be used to influence policy.

4.4. Privacy and security implications

Depending on the technology, virtual inspections could potentially present security or privacy concerns by inadvertently collecting sensitive information. For energy code inspections, the main security concern would be revealing vulnerabilities of the buildings since they are conducted preoccupancy. Drones coupled with intelligent software could inadvertently capture information from nearby occupied buildings during an inspection. Or there may be cybersecurity concerns related to inspections of military facilities or other buildings at risk of attack if information regarding vulnerable spots is captured. For on-site inspections of locations with security concerns, the building owners may require limitations of camera abilities (e.g., taking photos of equipment only) and need greater coordination beforehand to receive building access (e.g., approval from higher-ups to conduct the inspection). The security concerns of virtual inspections remain the same as on site (having information that could expose security risks), except when addressing issues such as archiving information, downloading data, and using unsecure servers that can be hacked. These barriers of insuring secure code inspections, and safe retrieval and viewing of data or images, are frequently overlooked but still present risks. As the age of cybersecurity and cyberthreats increase, keeping data and records secure will remain an increasing concern.

4.5. Motivations behind virtual inspections

While many countries were forced to adopt virtual inspections due to the pandemic, some jurisdictions were motivated by time and cost savings, better access to remote areas, and contributing to the advancement of automation and technology. In the case of Singapore's Building Construction Authority, for example, their motivation was to increase the accuracy of inspections by reducing opportunities for human error as well as the time and labor required for inspections. By making code inspections as efficient as possible through digitalization and automation, they hope to enhance their capacity to collect data, draw analytics, understand trends, and thus introduce more informed polices to reduce building energy consumption. Overall, countries want to improve reliability in the evaluation of code compliance to ensure energy-efficient measures are actually being implemented [11]. These motivations influence their decision on how they carry out inspections.

4.6. Moving forward and broader implications

As the need for virtual inspections due to the pandemic dwindles, those jurisdictions that adopted virtual inspections out of necessity now debate whether to continue performing them, return to on-site inspections fully, or implement a hybrid of the two. Most jurisdictions and inspection groups (NABERS in Australia, North Las Vegas, Singapore, UAE) are looking to continue with virtual inspections even when the pandemic no longer requires it and plan to continue to standardize and fine-tune their inspection process. Some jurisdictions (Fort Collins) do not plan to continue with fully virtual inspections since they do not see it as sufficiently beneficial. However, they view having the capability and knowledge as a good thing and may still incorporate virtual inspections in their procedures to some degree.

Many countries in the world have not adopted virtual inspections for regulatory reasons. For instance, building energy codes in Brazil are voluntary, so they naturally do not perform virtual or other inspections to check for compliance, and Japan's regulatory barriers prevent them from performing virtual inspections. Moving forward, both jurisdictions intend on adopting virtual inspections in their code inspection processes. Brazil aims to mandate their codes and streamline their inspection processes by adopting aspects of virtual inspections to increase capacity and have lower inspection costs. This would be "leapfrogging" the intermediate step from in-person inspections straight to virtual inspections. Virtual inspections could be conducted with readily accessible technologies such as mobile phones that can take photos and videos. Expanding capacity for enforcing building energy codes is one of the largest challenges facing code implementation, particularly in jurisdictions that do not have a long history with building energy codes. Thus, virtual inspections could have an enormous global effect in reducing building energy consumption, especially as much of the world is rapidly constructing.

Though virtual inspections can be beneficial, they are not a be-all-and-end-all solution. For First Nations communities in Canada, for example, remote inspections can be beneficial since they have limited inspectors available and could more efficiently access communities. However, while FNNBOA helped develop a process for virtual inspections in First Nations communities, there has been a lack of uptake mostly because of disputes concerning who has the authority in these communities. In addition, some of the officials conducting training lack accreditation and qualifications to carry out building energy code inspections. While virtual inspections can provide benefits in jurisdictions with a limited number of inspectors and long travel distances, other issues such as those faced by First Nations communities still need to be addressed to make verifying compliance effective.

5. Conclusions

Faster and more effective code compliance is more critical than ever to ensure building energy savings. Jurisdictions can use virtual inspections as a tool for helping to expand capacity for enforcing building energy codes, if conducted properly. Jurisdictions find the most benefit when they are geographically dispersed or rapidly constructing new buildings. Jurisdictions should also consider their access to effective technology and privacy or security concerns when deciding to conduct virtual inspections. There are many promising technologies that could make virtual inspections more appealing by potentially increasing their reliability, accuracy, and affordability, and providing creative ways to track and document progress. While some of these technologies are already being piloted in other areas, more research is needed to assess their validity for building energy code inspections. Virtual inspections, like most technological developments, are not inherently good or bad and their effectiveness is highly dependent on how they are implemented. While the pandemic accelerated the need, virtual inspections are gaining momentum due to their efficiency benefits. In many cases, virtual inspections, or many aspects of them, are here to stay.

Quantifying the accuracy of an inspection is difficult because it requires knowing what measures the inspection missed. This is a significant gap that must be addressed in future work to determine if virtual inspections are a viable option in the long run. In addition, future work could include further quantification of cost and time savings across various types of jurisdictions. This analysis will be more easily accessible as more jurisdictions adopt or continue virtual inspections for building energy codes.

6. References

[1] International Energy Agency, 2020. https://www.iea.org/topics/buildings (accessed 22 April 2022).

[2] J. Deason, A. Hobbs, 2011, Codes to cleaner buildings: Effectiveness of US building energy codes, Climate Policy Initiative. https://www.climatepolicyinitiative.org/publication/codes-to-cleaner-buildings-effectiveness-of-u-s-building-energy-codes/ (accessed 22 April 2022).

[3] O. Lucon, D. Ürge-Vorsatz, A. Zain Ahmed, H. Akbari, P. Bertoldi, L. Cabeza, N. Eyre, A. Gadgil, L. D. D. Harvey, Y. Jiang, E. Liphoto, S. Mirasgedis, S. Murakami, J. Parikh, C. Pyke, and M. Vilariño, 2014: Buildings. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

[4] D. Ürge-Vorsatz, N. Eyre, P. Graham, D. Harvey, E. Hertwich, Y. Jiang, C. Kornevall, M. Majundar, J.E. Mcmahon, S. Miragedis, S. Murakami, A. Novikova, S.T. Herrero, 2012, Energy end-use: Buildings. In Global Energy Assessment: Toward a Sustainable Future, Chapter 10 (pp. 649-760). Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

[5] J. Zhang, R.A. Athalye, P.R. Hart, M.I. Rosenberg, Y. Xie, S. Goel, V. Mendon, B. Liu, 2013, Energy and Energy Cost Savings Analysis of the IECC for Commercial Buildings, PNNL-22760. Pacific Northwest National Lab, Richland, WA (United States).

[6] S. Yu, J. Eom, Y. Zhou, M. Evans, L. Clarke, 2014, Scenarios of building energy demand for China with a detailed regional representation. *Energy*, *67*, 284-297.

[7] M.T. Tyler, D.W. Winiarski, M.I. Rosenberg, B. Liu, 2021, Impacts of Model Building Energy Codes–Interim Update, PNNL-31437. Pacific Northwest National Laboratory (PNNL), Richland, WA (United States).

[8] R. Bartlett, M.A. Halverson, D.L. Shankle, 2003, Understanding building energy codes and standards, PNNL-14235. Pacific Northwest National Lab.(PNNL), Richland, WA (United States).

[9] M. Evans, V. Roshchanka, P. Graham, 2017, An international survey of building energy codes and their implementation. Journal of Cleaner Production, 158, 382-389.

[10] H. Misuriello, S. Penney, M. Eldridge, B. Foster, 2010, Lessons learned from building energy code compliance and enforcement evaluation studies. Proceedings of the 2010 ACEEE Summer Study on Energy Efficiency in Buildings, 8, 245-255.

[11] A. Delgado, A. Mott, M. Evans, 2021, Best practices for building energy codes compliance, PNNL-32155. Pacific Northwest National Laboratory, Richland, WA (United States).

[12] P.K. Ng, N. Mithraratne, H.W. Kua, 2013, Energy analysis of semi-transparent BIPV in Singapore buildings. Energy and buildings, 66, 274-281.

[13] M. Schwarz, C. Nakhle, C. Knoeri, 2020, Innovative designs of building energy codes for building decarbonization and their implementation challenges. Journal of Cleaner Production, 248, 119260.

[14] E.M. Franconi, J. Lerond, C Chandrasekharan Nambiar, D Kim, M.I. Rosenberg, J. Williams, 2020, Opening the Door to Grid-Interactive Efficient Buildings with Energy Codes (No. PNNL-SA-151838). Pacific Northwest National Laboratory, Richland, WA (United States).

[15] A. Delgado, A. Mott, M. Evans, 2021, Best practices for building energy codes compliance, PNNL-32155. Pacific Northwest National Laboratory, Richland, WA (United States).

[16] F. Liu, A.S. Meyer, J.F. Hogan, 2010, *Mainstreaming building energy efficiency codes in developing countries: global experiences and lessons from early adopters* (Vol. 204). World Bank Publications.

[17] M. Evans, S. Yu, A. Staniszewski, L. Jin, A. Denysenko, 2018, The international implications of national and local coordination on building energy codes: Case studies in six cities. Journal of cleaner production, 191, 127-134.

[18] EBC, 2020, "Building Energy Issues and the COVID-19 Response", EBC Building Energy Codes Working Group Webinar, https://www.iea-ebc.org/Data/Sites/1/media/docs/working-groups/building-energy-codes/EBC_WG_BECs_Webinar_05_May_2020_COVID-19_Buildings.pdf

[19] M.H. Shariq, B.R. Hughes, 2020, Revolutionising building inspection techniques to meet large-scale energy demands: A review of the state-of-the-art. Renewable and Sustainable Energy Reviews, 130, 109979.

[20] J.E. See, 2012, Visual inspection: a review of the literature, SAND2012-8590. Sandia National Laboratories, Albuquerque, NM (United States).

[21] E. Vaughan, J. Turner, 2013, The value and impact of building codes. *Environmental and Energy Study Institute White Paper*, *20*, 501-517

[22] K. Morse, S. Kolegraff, A. Kline. "Initial Perceptions of Remote Virtual Inspections in the residential Construction Industry Sector".

[23] E. Barreira, R.M. Almeida, M. Moreira, 2017, An infrared thermography passive approach to assess the effect of leakage points in buildings. Energy and Buildings, 140, 224-235.

[24] W. Cai, X. Wen, S. Wang, L. Wang, 2019, A real-time detection method of building energy efficiency based on image processing. Journal of Visual Communication and Image Representation, 60, 295-304.

[25] M. Fox, S. Goodhew, P. De Wilde, 2016, Building defect detection: External versus internal thermography. Building and Environment, 105, 317-331.

[26] K.A. Korkmaz, S.I. Mohammed, 2020, Evaluating the Use of Drones in the Area of Transportation/Construction. Journal of Architectural Environment & Structural Engineering Research, v. 3, n. 1, p. 1-4. <https://ojs.bilpublishing.com/index.php/jaeser/article/view/1787> (accessed 22 April 2022). doi:https://doi.org/10.30564/jaeser.v3i1.1787.

[27] Z. Asgari, F.P Rahimian, 2017, Advanced virtual reality applications and intelligent agents for construction process optimisation and defect prevention. Procedia engineering, 196, 1130-1137.

[28] O. Maghazei, T.H. Netland, D. Frauenberger, T. Thalmann, 2021, Automatic drones for factory inspection: The role of virtual simulation. In IFIP International Conference on Advances in Production Management Systems (pp. 457-464). Springer International Publishing, https://doi.org/10.1007/978-3-030-85910-7_48.

[29] Energy in Buildings and Communities (EBC), 2021, Annual Report 2020, International Energy Agency Energy in Buildings and Communities Program. https://www.iea-ebc.org/publications/annual-reports (accessed 22 April 2022).

[30] K. Newcomer, H. Hatry, J. Wholey, 2015, Conducting Semi-Structured Interviews. John Wiley & Sons, Ltd.. Web.

[31] S. Cox, 2016, Building energy codes: Policy overview and good practices, NREL/TP-6A20-65542. National Renewable Energy Laboratory, Golden, CO (United States).

[32] M. Rosenberg, D. Jonlin, S. Nadel, 2017, A Perspective of Energy Codes and Regulations for the Buildings of the Future. Journal of Solar Energy Engineering, 139(1), 010801.

[33] P. Bannister, 2012, NABERS: lessons from 12 years of performance based ratings in Australia. Paper presented at 12th International Conference for Enhanced Building Operations, 23-26 October 2012, Manchester, UK.

[34] R. Cohen, P. Bannister, 2017, Why is Australia better than the UK at building energy efficiency? Energy World, 19.

[35] Global Building Performance Network (GBPN). Singapore: Country Profile (2021). https://library.gbpn.org/beet-3/country-infosheets/singapore (accessed 22 April 2022).

[36] E. Ciampa, L. De Vito, M.R. Pecce, 2019, Practical issues on the use of drones for construction inspections. Journal of Physics: Conference Series, Vol. 1249, No. 1, p. 012016. IOP Publishing.

[37] D. Day, 2017, Drones for transmission infrastructure inspection and mapping improve efficiency. Natural Gas & Electricity, 33(12), 7-11.

[38] J.F. Falorca, J.C.G Lanzinha, 2020, Facade inspections with drones–theoretical analysis and exploratory tests. International Journal of Building Pathology and Adaptation.

[39] H3Dynamics, 2021. https://www.h3dynamics.com/ (accessed November 2021).

[40] A. Plowright, 2016, Using thermal cameras to promote energy efficiency in buildings. Vancouver: University of British Columbia.

[41] R. Tobita, 2019, Japan to Open Skies to commercial drones with Flexible Rules. Nikkei Asia, Nikkei Asia. https://asia.nikkei.com/Politics/Japan-to-open-skies-to-commercial-drones-with-flexible-rules (accessed 22 April 2022).

[42] D. Lattanzi, G. Miller, 2017, Review of robotic infrastructure inspection systems. Journal of Infrastructure Systems, 23(3), 04017004.

[43] R.J. Yan, E. Kayacan, I.M. Chen, L.K. Tiong, J. Wu, 2018, QuicaBot: Quality inspection and assessment robot. *IEEE Transactions on Automation Science and Engineering*, *16*(2), 506-517.

[44] HoloBuilder 2021. https://www.holobuilder.com/ (accessed November 2021).

[45] StructionSite, 2021. https://structionsite.com/ (accessed November 2021).

[46] Boston Dynamics, 2021. https://www.bostondynamics.com/products (accessed November 2021).

7. Annex

Virtual Inspections Questionnaire

Overview of practice

1. Can you describe how your jurisdiction currently performs inspections (the scope, the cadence, tools used)?
2. Who performs the inspections (e.g., local government officials, third-party inspectors)?

Scope changes

3. Have you changed practices (i.e., gone remote) because of the pandemic? How long have you conducted virtual inspections?
4. As a result of switching to virtual:
    - How long does a virtual inspection take versus in-person? Has there been changes to the number of inspections? Can you approximate percent change in number of inspections condcuted in a day/week/month?
    - Has the inspection reach to different parts of your jurisdiction/region stayed the same or changed (e.g., reach to remote areas)?
    - How has the scope of the inspections changed? Anything added/left out compared to in-person?
    - Has the follow-up to inspections changed?
5. Do you find cases where in-person inspections are still necessary? Do you see potential for this to change (e.g., resulting from technology advancement)?
6. Is there resistance to change resulting from company/organizational culture?

Time and financial savings

7. How much time is saved switching to virtual (time for travel, inspection, review, follow-up)? Have you identified other efficiencies? Can you approximate time savings?
8. Have there been assessments on financial savings? Can you approximate a percent estimate of money saved?
9. What capacity building have you established to switch to virtual inspections?

Changing practices and technology innovation

10. Are there new capabilities/technologies for virtual inspections (e.g., virtual conferencing; drones/robots/other; filming/recording; data integration into building energy models; collection of building energy management system data remotely; other)? How is it being applied to address virtual inspections?

11. Have you acquired new software? What are some remaining needs (e.g., technological needs)?
12. What have you learned from switching to virtual inspections? Other advantages/disadvantages to performing virtual vs. in-person inspections?

Benefits to consumers

13. Have customers benefitted from the change to virtual inspections? Are there any disadvantages to the consumers?
14. Has scheduling become more or less convenient for customers?
15. Have costs to customers changed?

Follow-up

16. Can we reference and credit you in our paper? Are there any sensitivities in the shared information?
17. Is there anyone you recommend talking to for learning more, or potentially helpful documents or resources?