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Review

Sensors in Civil Engineering: From Existing Gaps to Quantum Opportunities

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Abstract: The vital role of civil engineering is to enable the development of modern cities and establish foundations for smart and sustainable urban environments of the future. Advanced sensing technologies are among the instrumental methods used to enhance the performance of civil engineering infrastructures and address the multifaceted challenges of future cities. Through this study, we discussed the shortcomings of traditional sensors in four primary civil engineering domains: construction, energy, water, and transportation. Then, we investigated and summarized the potential of quantum sensors to contribute to and revolutionize the management of civil engineering infrastructures. For the water sector, advancements are expected in monitoring water quality and pressure in water and sewage infrastructures. In the energy sector, quantum sensors may facilitate renewables integration and improve grid stability and buildings' energy efficiency. The most promising progress in the construction field is the ability to identify subsurface density and underground structures. In transportation, these sensors create many fresh avenues for real-time traffic management and smart mobility solutions. As one of the first-in-the-field studies offering the adoption of quantum sensors across four primary domains of civil engineering, this research establishes the basis for the discourse about the scope and timeline for deploying quantum sensors to real-world applications towards the quantum transformation of civil engineering.

Keywords: civil engineering; infrastructure; sensor; quantum sensing; smart city; future city

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1. Introduction

The cities of the future will face a range of complex and multifaceted challenges, including climate change, rapid urbanization, resource scarcity, social and economic inequality, and many more. These challenges require an integrated and holistic approach to urban planning and development. Since the last decade of the 20th century, the concept of smart cities has been broadly studied in various disciplines and continues to dominate in civil engineering and urban planning discussions [1,2]. A prominent catalyst in this transformative discourse has been the emergence of cutting-edge sensing technologies [3]. The integration of sensor technologies is forging a trajectory towards intelligent and sustainable civil infrastructure, augmenting functionality across all aspects of the value chain [1]. An extensive spectrum of information ranging from temperature, pressure, and humidity to water and air quality, digital imaging, acceleration, spatial positioning, strain measurements, radiation, and more becomes imperative in forecasting, situational cognizance, and informed decision-making processes. However, the quality and availability of information about civil infrastructures and related environments are constrained by the present state of sensor technology.

This study aims to understand how quantum sensors might assist in addressing the challenges of the civil infrastructures of future cities. Quantum sensors use quantum phenomena to achieve high precision and accuracy in detecting various physical quantities [4,5]. These phenomena, including superposition, tunneling, and entanglement, are based on fundamental principles in quantum physics. Superposition refers to the capacity of particles to exist in several states simultaneously. In turn, tunneling refers to the ability of particles to traverse energy barriers [5]. Entanglement is a unique quantum phenomenon where particles become interlinked, and one particle's state instantly affects another's state, regardless of the distance between them [6]. This property is exploited to enhance measurement sensitivity and accuracy beyond what classical sensors can achieve. Entangled particles in quantum sensors can detect subtle changes in physical environments, making them highly effective for applications such as gravitational field detection or magnetic field measurement [4,5,7–10]. Another critical property of quantum sensors is coherence—the ability of a quantum system to maintain its state over time [11]. This property ensures the stability of the quantum state against external perturbations, leading to more accurate and reliable measurements. Preserving coherence enables quantum sensors to perform precise measurements even in environments with high levels of noise and disturbance, which is particularly relevant in the challenging conditions of civil infrastructure applications.

Within the scope of this research, we articulate the extant constraints of sensing technologies across the pivotal domains of civil engineering: construction, transportation, energy, and water. Then, we introduce the concept of quantum sensing as an innovative solution to bridge the gaps in existing technologies' sensitivity, accuracy, resistance to harsh environments, and reliability. In addition to the potential of overcoming the challenges of conventional sensing technologies in civil engineering sectors, we discuss how this concept unveils novel capabilities hitherto unattainable for modern cities.

We deployed narrative review as the research method for this study. The narrative review is particularly useful for provoking scholarly dialogue [12] and developing a vision for new technology [13,14]. Since quantum sensing applications in real-world use cases are still very limited [4], and there is not yet enough literature about the practical application of quantum sensing for civil infrastructures, the outcomes of this review may serve as a ground base for initiating both academic and practitioners' discussions and raising additional perspectives. The conceptual framework used in this review is based on the consensual foundational constructs of civil engineering infrastructures presented in section two.

This research makes several significant contributions to the field of civil engineering, primarily related to the advanced sensing technologies, management, and operation of future cities' engineering infrastructures. The paper's innovative nature lies in its forward-looking perspective on future developments in the field of civil engineering. Based on the comprehensive sectoral analysis of four primary civil engineering domains, this study highlights limitations in current sensing technologies and establishes a foundation for discourse about the scope and timeline for deploying quantum sensors in real-world applications. Being one of the first-in-the-field studies advocating for adopting quantum sensors across four primary domains of civil engineering, it paves the way for the quantum transformation of civil engineering.

The remainder of this paper is organized as follows. Section 3 constitutes the core of this paper. This section contains four parts covering the primary domains of civil engineering infrastructures. For each one of the domains, we discuss the most urgent needs for the cities of the future, provide a comprehensive review of sensing-related challenges related to those needs, and discuss how quantum sensing might be helpful to overcome these limitations. In Section 6, we summarize and discuss the study's findings and call for a broader debate about the scope and timing for leveraging the potential of quantum sensing in various civil engineering infrastructures and applications.

2. Civil Engineering for the Cities of the Future

Civil engineering infrastructure supplies the needs of and supports daily activities in the urban environment. The concept of smart cities has emerged as an instrumental approach to tackling challenges and enhancing the performance of civil engineering infrastructures by deploying technological innovations [1,15]. Despite tens of definitions of the smart city [16], scholars and practitioners are in consensus that the term is dedicated to addressing the primary demands of the cities of the future, including infrastructure, transportation, energy, waste, and water management systems [17,18]. According to the UN's recent report, policymakers and municipalities should be ready to manage these demands while promoting sustainability, resilience, and social equity for all residents [19].

Several international standardization institutes also acknowledged the crucial role of infrastructures in successfully deploying smart cities. ISO/TR 37152 [20] and ITU-T Y.4201 [21] are examples of standards that specifically deal with smart city infrastructures. The ISO/TR 37152 outlines a common framework for developing and operating smart community infrastructures, including energy, water, transportation, waste management, information and communications technology, etc. The framework applies to all smart community infrastructures' life cycle processes from conceptual design through planning, development, operation, maintenance, redevelopment, and feedback [20]. According to ISO, this framework can be adopted by planners, developers, business operators, and suppliers engaged in planning, developing, and operating smart community infrastructures. ITU-T Y.4201 is dedicated to planning, designing, constructing, deploying, managing, and maintaining smart cities and communities. The ITU-T Y.4201 provides high-level requirements and a reference framework for smart city platforms. It aims to support all the services and applications of a smart city, including infrastructure life-cycle management, inter-system communication, security support, maintenance support, processor controls, decision-making support, real-time dissemination of public information, resilience, and interoperability [21].

In addition to standards, during the last years, significant effort has been invested in classifying smart city infrastructures to create a holistic perspective and overview. For example, eight main elements in civil engineering were identified: transportation systems, water systems, air quality, energy infrastructure, solid waste management, construction engineering and management, structures, and geotechnical systems [1]. Another recent study classified smart city infrastructures into ten themes: energy, security, transportation, smart city network architecture, health, construction, land use, hydrology, government, and population [22]. Table 1 exemplifies the consensus in the literature and corresponding standards about the primary civil engineering infrastructural domains.

Table 1. Primary domains of civil engineering infrastructures.

Author	Title	Energy	Transportation	Water	Construction
Berglund et al., (2020) [1]	Smart infrastructure: A vision for the role of the civil engineering profession in smart cities.	✓ *	✓	✓	✓
Bohloul (2020) [16]	Smart cities: A survey on new developments, trends, and opportunities.	✓	✓		✓
Kasznar et al., (2021) [22]	Multiple dimensions of smart cities' infrastructure: A review.	✓	✓	✓	✓
Rozario et al., (2021) [17]	Creating smart cities: A review for holistic approach.	✓	✓	✓	
Puliafito et al., (2021) [23]	Smart cities of the future as cyber physical systems: Challenges and enabling technologies.	✓	✓	✓	✓
J. Wang et al., (2022) [2]	Progress of standardization of urban infrastructure in smart cities.	✓	✓	✓	✓
Yusuf & Suleiman (2023) [18]	Smart cities: The cities of the future.	✓	✓		✓
ISO/TR 37152 (2016) [20]	Smart community infrastructures—common framework for development and operation.	✓	✓	✓	
ITU-T Y.4201 (2018) [21]	High-level requirements and reference framework of smart city platforms.	✓	✓	✓	✓

* An infrastructural domain is detailed in the document.

Based on Table 1, the conceptual framework for this study consists of four primary civil engineering infrastructure constructs: energy, transportation, water, and construction. While multiple challenges exist for each type of infrastructure, the common issue for all domains is data availability, quality, and timely analysis [23,24]. Sensors constitute the primary data source in smart cities [1]. However, the collection of infrastructure and environmental data may be limited by sensor technology or the sensor's location. While fixed sensors provide only limited information about the system, real-time sensors measuring environmental parameters require frequent calibration and monitoring, which increases operational and maintenance limitations. In turn, wireless sensors are constrained by power, communication range, and bandwidth [25,26]. In the next section, we discuss future cities' specific infrastructural needs and the limitations of conventional sensing technologies. Then, for each type of infrastructure domain, we discuss the potential of quantum sensing and particular types of sensors that might help overcome the existing limitations.

3. Civil Infrastructures Sensing: Challenges and Opportunities

3.1. Civil Infrastructures—Energy

3.1.1. The Challenges

Buildings account for a significant portion of energy consumption in cities. According to the economic reports, 36% to 40% of global energy usage and over 40% of CO_2 emissions come from commercial and residential buildings [27,28]. The challenge lies in improving existing buildings' energy efficiency through retrofitting measures and boosting energy-efficient design and construction practices for new buildings. However, retrofitting older structures to meet modern energy standards can be costly and technically challenging. While sensors are crucial in monitoring and controlling buildings' energy consumption, conventional sensors are limited in accuracy, sensitivity, and resolution, which affect energy management systems' effectiveness [29–31]. For example, traditional temperature sensors may have limited precision and inability to capture localized variations in temperature within a building [32,33]. These limitations hamper the precise monitoring and control of thermal conditions, leading to difficulty in detecting thermal inefficiencies in specific areas and optimizing energy consumption in real time. In turn, occupancy and light sensors may have limited accuracy, coverage, and responsiveness. For instance, occupancy sensors based on passive infrared technology may struggle to detect occupancy in cases of obstructions or slow-moving occupants [34,35]. Light sensors may not provide precise measurements of ambient light levels, leading to suboptimal control of lighting systems [36,37]. Finally, conventional gas sensors may lack the sensitivity to detect low levels of volatile gases which affect indoor air quality [38,39].

The integration of renewable energy sources into the grid relies on accurate and timely data from sensors. Conventional sensors used for renewable energy integration and forecasting, such as solar irradiance sensors or wind speed sensors, have certain limitations in capturing real-time data and providing accurate forecasts [40,41]. For example, conventional solar irradiance sensors, such as pyranometers, have limitations in accurately measuring solar radiation under varying weather conditions [42,43]. In turn, solar irradiance sensors based on silicon photodiodes may have limited spectral responses, making them less accurate in measuring solar radiation under specific wavelength ranges [44]. The lack of precise measurements under cloudy skies or during fluctuations in atmospheric conditions also affects the accuracy of solar energy forecasts. These restrictions complicate solar energy resources management and integration of solar energy into the grid. Conventional wind sensors, such as cup anemometers or wind vanes, may have limitations in capturing subtle changes in wind speed and direction, particularly in complex wind flow conditions or at high altitudes [45,46]. As a result, inaccurate wind energy predictions lead to suboptimal utilization of wind power resources.

Ensuring the resilience and reliability of the power grid requires continuous, accurate, and reliable monitoring of electrical power quality parameters, such as voltage, frequency, and harmonics. Providing this information relies heavily on sensors [47,48]. However, conventional sensors have limitations in capturing detailed power quality data or detecting transient events that can affect grid stability and power delivery [48,49]. For example, conventional voltage sensors, such as electromechanical or electronic voltage transformers, may be limited in accurately capturing small voltage fluctuations or harmonic distortions [48,50]. Some of these sensors may also have limited frequency response, preventing the detection of high-frequency transients or disturbances that can impact grid stability [51,52]. In turn, current sensors may not provide sufficient sensitivity to detect small irregularities or transient variations in current flow [53,54]. Conventional frequency sensors, such as frequency meters or phase-locked loop devices, may have limitations in accurately capturing subtle frequency variations, especially during dynamic grid conditions or transient events [55]. These limitations can hinder the timely detection and response to frequency deviations, affecting the grid's stability and power quality.

3.1.2. The Potential of Quantum Sensing

In the field of energy efficiency and building retrofitting, quantum sensors have the potential to mitigate or resolve several energy-related challenges related to occupancy, temperature, and light sensor limitations. For example, quantum temperature and gas sensors offer unprecedented precision and sensitivity in measuring temperature, humidity, and gas concentrations [56,57]. The temperature sensors based on the single photon interferometer allow for the precise monitoring of thermal conditions within buildings with a sensitivity of 0.00115 °C and a temperature resolution of the entire sensing system of 0.029 °C [56]. The localized and precise temperature readings help identify the areas of inefficiency, facilitate more accurate energy usage monitoring, and enable targeted retrofitting measures in buildings. In turn, quantum-dot-based gas sensors enable high sensitivity, selectivity, and fast dynamics at low or room temperatures [58,59]. These sensors can detect and measure gases at ultra-low concentrations, thus providing more accurate information on indoor air quality and pollutants. Finally, the recent developments in the field of quantum imaging, including 3D quantum cameras, behind-the-corner cameras, low-brightness imaging, and quantum laser imaging, can overcome multiple limitations of conventional occupancy and light sensors [4]. Quantum imaging enables unprecedented accuracy and responsiveness in monitoring occupancy and light levels within buildings, thus ensuring better control and optimization of lighting systems for energy efficiency.

Quantum sensing can also aid in renewable energy forecasting, enabling better planning and management of renewable generation sources [60]. For example, quantum solar irradiance sensors utilize quantum principles to measure solar radiation across a broad spectrum, providing more accurate and comprehensive data even in challenging weather conditions [61,62]. These sensors can provide more reliable and detailed data, aiding in integrating renewable energy into the grid and improving the accuracy of renewable energy forecasting. Moreover, some quantum sensors can be directly powered by solar energy, thus reducing traditional energy consumption. For example, sunlight-driven quantum magnetometers can utilize solar energy instead of high-power-consuming equipment such as lasers or microwave amplifiers [63].

Quantum sensors provide higher sampling rates, broader frequency ranges, and improved accuracy [4], which promise more comprehensive power quality monitoring, facilitating grid resilience and proactive maintenance [7,64]. In particular, quantum voltage and quantum frequency sensors offer higher accuracy, sensitivity, and broader frequency ranges [65–67]. These capabilities allow for the improved identification of grid disturbances, including fluctuations, harmonic distortions, and transient events, thus enabling the measures to ensure high power quality and grid resilience.

Finally, there is a growing discussion in the literature about the potential of quantum technologies and sensors to revolutionize energy storage systems. Although the crucial role of these systems in enabling sustainable and resilient cities is well studied, energy storage technologies face several challenges, including cost, limited capacity and lifespan, safety, and environmental impact. Quantum-based energy storage and conversion techniques promise unprecedentedly low costs and solutions with a low ecological footprint. For example, carbon quantum dots and graphene quantum dots are already used in semiconductors, photovoltaic energy storage, supercapacitors, electrocatalysis, and energy conversion applications [68,69]. However, one should emphasize that despite great promise for the energy industry, implementing quantum sensing in energy technologies still encounters challenges, particularly related to the mass production of quantum materials [70]. Figure 1 summarizes the potential of quantum sensors for energy infrastructures and applications.

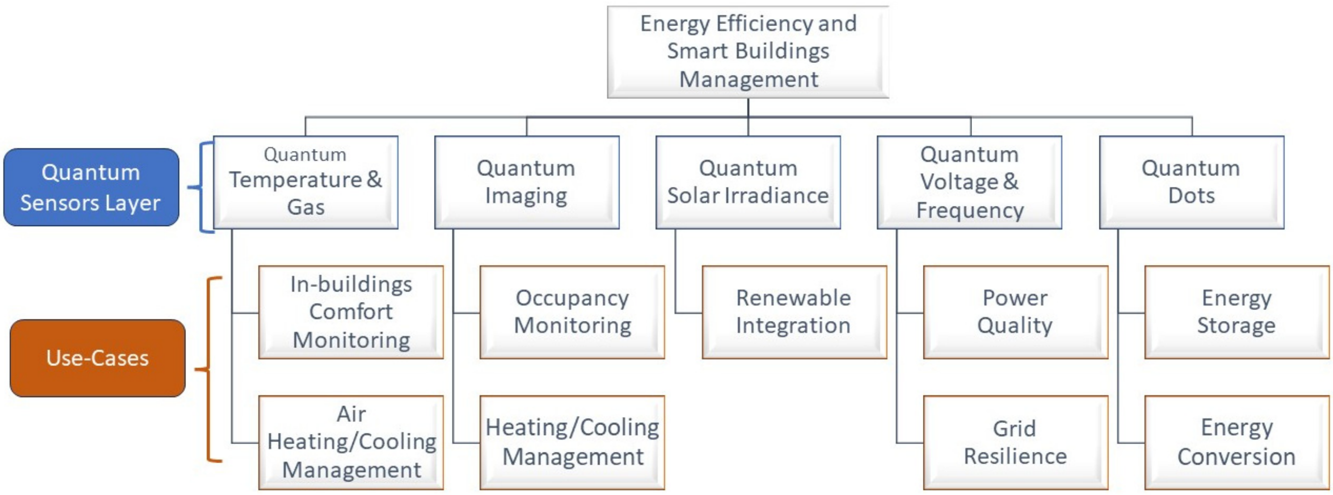

Figure 1. The potential of quantum sensors for energy infrastructures and applications.

3.2. Civil Infrastructures—Transportation

3.2.1. The Challenges

To facilitate the development of transportation infrastructure, enable efficient traffic management, and improve the sustainability and safety of transportation solutions, cities should have advanced sensor infrastructure [71–73]. Moreover, to allow for informed traffic management and real-time optimization decisions, the data from sensors should be precise and reliable [74]. However, conventional sensors have several limitations. Traffic sensors, such as inductive loops or radar detectors, provide traffic management data at specific intersections or road segments. Some of these sensors require physical infrastructure installation, which can be expensive and time-consuming, especially when considering the need to dig up roads and other infrastructures [71]. Moreover, while the lack of comprehensive coverage of the entire road network limits the ability to monitor traffic flow across the city [71,75], the shortcomings in the durability and resilience of these sensors affect their long-term functionality.

Transportation sensors are exposed to harsh environmental conditions, such as extreme temperatures, moisture, or vibrations. Weather conditions, such as heavy rain, snow, fog, and dust, also affect the accuracy and reliability of sensors. Periodic maintenance and calibration are needed to ensure sensor accuracy and performance over time [76,77]. In addition, traditional sensors may have limited data granularity, which can be insufficient for detailed traffic analysis and planning. For example, some sensors may not identify specific vehicle types and their occupancy or do not supply comprehensive data on particular transportation means, such as cyclists or micro-mobility devices [78]. Moreover, some conventional sensors may defer data reporting, leading to less accurate real-time information about traffic conditions [79].

As a city grows, scaling innovative mobility systems is necessary to handle increased data volume. However, new sensor deployments required to reach comprehensive coverage across all transportation modes and routes can be difficult and costly [77], potentially leaving some intermodal connections unmonitored [80,81]. Integrating, coordinating, and synchronizing data from multiple sensors in various transportation modes, such as trains, buses, bikes, and ride-sharing services, can also be challenging because of different sensor technologies, interfaces, data formats, and exchange protocols [24]. Moreover, some sensors may be restricted in providing real-time data, thus causing delays in the availability of the information to users [81].

Concerning traffic safety and security, certain sensor technologies, such as cameras, may have blind spots or limited field of view, leaving areas without surveillance coverage [82]. While some cameras' image quality and resolution may not be sufficient to capture fine details, poor lighting conditions or adverse weather conditions can also impact the sensor's performance and compromise the visibility of traffic events [83]. Moreover, connected sensor systems may be vulnerable to cybersecurity threats, especially those involving video surveillance, raising privacy concerns as they may capture identifiable information about individuals. Balancing security needs with privacy rights is in itself a complex challenge in the field of traffic management.

3.2.2. The Potential of Quantum Sensing

Quantum sensors can revolutionize intelligent transportation systems by providing highly accurate real-time data for adaptive traffic control, dynamic route planning, and preventive maintenance of infrastructures and transportation means [4,84]. Leveraging the unique precision of quantum sensors, cities can optimize the broad range of transportation operations, thus leading to more efficient and sustainable urban mobility. In the following paragraphs, we discuss several examples of how specific types of quantum sensors can contribute to the transportation challenges of modern and future cities.

Quantum accelerometers and quantum strain gauges can continuously monitor and detect structural defects in transportation infrastructure [85]. Noticing potholes or cracks in bridges and roads will enable real-time alerts to authorities, drivers, and commuters about road surface conditions. Furthermore, continuous monitoring allows for timely maintenance, thus prolonging infrastructure lifespan and enhancing road safety. In turn, integrating quantum magnetometers and quantum gravimeters into traffic management systems can offer precise and real-time data on vehicle movements, traffic density, and congestion patterns [11,60]. These data will enable dynamic traffic control, including optimized signal timings, better traffic management, and predictions. An additional possibility for gathering accurate real-time data on traffic conditions is the combination of quantum magnetometers and quantum cameras. This combination can enable traffic control centers to adjust signal timings and lane configurations, thus optimizing traffic flow and reducing congestion [6,86]. The data from these sensors can also be used to design more effective road networks, traffic management, and optimization strategies.

Utilizing quantum cameras or LiDARs for intersection management might help detect vehicles, cyclists, and pedestrians, create alerts, and enable faster intervention and collision prevention, thus enhancing safety for all road users [6,87]. In addition, detecting transport means and pedestrians may be used to adjust signal timings in intelligent intersection management systems and contribute to the overall optimization of traffic flow at intersections [88]. Finally, integrating quantum sensors into public transport enables coordination with traffic signals, prioritizing public transport at intersections, improving overall public transport efficiency, and attracting more commuters to use sustainable transportation options [81].

In the field of smart mobility solutions, quantum gyroscopes and quantum magnetometers can enhance passengers' intermodal experience by providing seamless navigation and orientation assistance [89]. In addition, deploying quantum accelerometers for micromobility services can optimize vehicle performance and improve rider safety [90,91]. Once integrated into ride-sharing platforms, the data from these sensors might be used for dynamic ride demand prediction and optimization, more efficient matching of riders and drivers, reducing empty trips, and overall carbon footprint [92]. Parking space management is an integral part of smart mobility solutions. Quantum cameras and LiDARs can revolutionize parking space management by providing accurate and continuous occupancy data [24,81]. These sensors can accurately detect and monitor parking space occupancy and guide drivers to available parking spots. Once integrated with the city's parking applications, this functionality will reduce the time and energy spent searching for parking spots and minimize congestion caused by drivers searching for parking.

Quantum accelerometers or quantum gyroscopes can also be applied in freight logistics to monitor cargo conditions and optimize transportation routes [93,94]. By accurately tracking cargo movements and environmental conditions, freight logistics can be streamlined, leading to more efficient and sustainable transport of goods. These types of sensors can also assist in optimizing vehicle fleet management for various transportation services [95]. For example, quantum gyroscopes or accelerometers might help monitor driving behavior and vehicle performance [96]. Additionally, quantum radars can bolster security in freight transportation by detecting potential threats or unauthorized access to freight containers or cargo. Finally, quantum radars or LiDARs can be applied for precise vehicle positioning and spacing, ensuring safe and efficient freight vehicle platooning operations, reducing aerodynamic drag, and consequent fuel savings [97].

Quantum gas sensors can monitor traffic-related emissions in urban environments, improving the ability to detect pollutants and greenhouse gases [56,57]. By deploying these sensors, cities can gain better insights about air quality and emissions, dedicate efforts to mitigate environmental impacts, and promote sustainable transportation practices. In turn, quantum thermometers and humidity sensors can assess in-cabin conditions, enabling on-the-go air quality monitoring and improving passenger comfort [57,98]. Finally, quantum microphones can be deployed to monitor noise pollution levels in urban areas, identify hotspots, implement noise reduction strategies, and create quieter and more-livable urban environments [99]. Figure 2 summarizes the potential of quantum sensors for transportation infrastructures and applications.

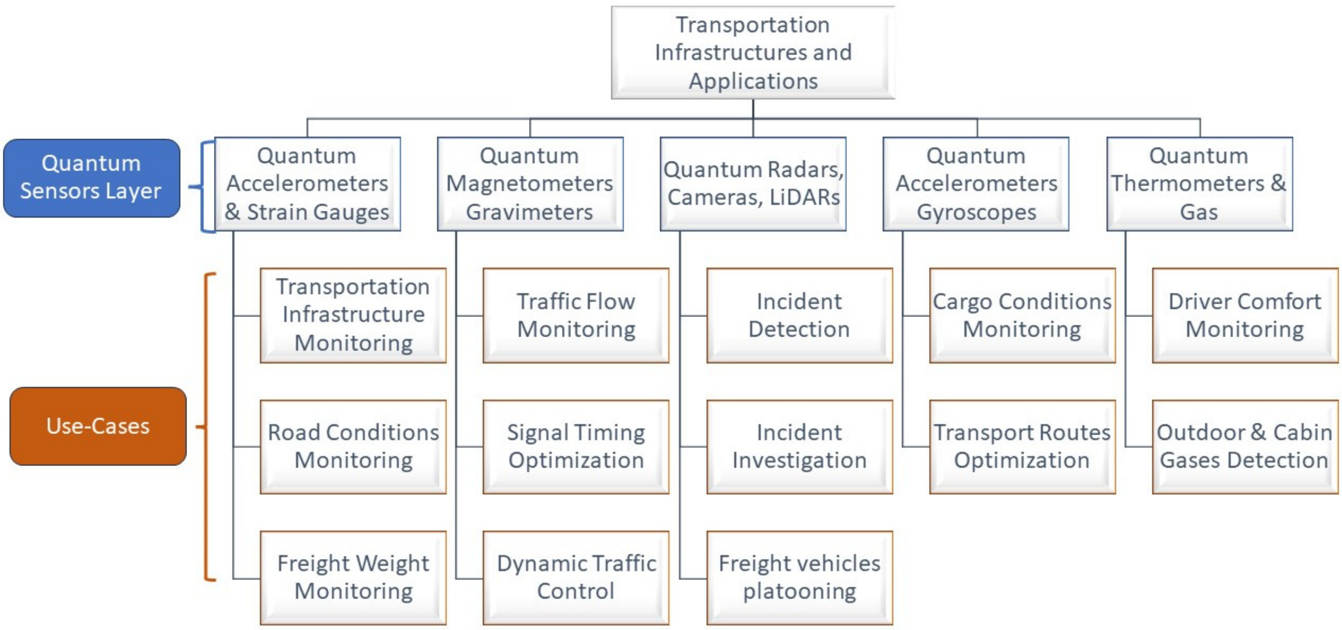

Figure 2. The potential of quantum sensors for transportation infrastructures and applications.

3.3. Civil Infrastructures—Water

3.3.1. The Challenges

Smart water management systems are crucial for cities' daily operation and resilience to extreme weather events such as droughts and floods. These systems enable the efficient use of water resources, reducing water scarcity and ensuring sustainable water management practices [100,101]. Advanced technologies and real-time monitoring should allow decision-makers to follow up on water quality parameters, optimize distribution, respond promptly, and minimize water losses [102,103]. In turn, wastewater management systems should enable optimized treatment processes, reducing energy consumption and improving treatment efficiency [104,105]. Among others, real-time monitoring of wastewater parameters should allow for automatic detection of pollutant loads or equipment malfunctions, thus leading to more effective and reliable treatment. However, the implementation of intelligent water and wastewater poses several challenges.

First, upgrading existing water infrastructure to accommodate smart technologies is challenging due to cost, technical feasibility, and integration with legacy systems [101,106]. Second, the success of smart water systems relies on active engagement and collaboration among multiple stakeholders, including water utilities, city governments, technology providers, and citizens [100]. To seamlessly integrate sensors, meters, control systems, and data platforms, there is a need for standardization and interoperability among various components and systems [100,101]. Third, cities and water utilities should adopt advanced data analytics techniques to process and interpret large volumes of data generated by new systems, including machine learning and artificial intelligence [105–107]. Data privacy and cybersecurity are significant concerns for smart water management systems [102,104]. According to the literature, there is a clear need for robust privacy measures, data encryption, and secure communication protocols to protect sensitive water-related data from cybersecurity threats [107,108].

Determining the optimal locations for sensor deployment within the water infrastructure is essential for capturing representative data. However, identifying appropriate monitoring points and deploying sensors in hardly inaccessible places, such as underground pipes or remote areas, is difficult [109,110]. Moreover, sensors may face interference and crosstalk from nearby sensors or environmental factors in complex water and wastewater systems. The interference can arise due to electrical noise, temperature variations, or signal overlapping, impacting the reliability and precision of sensor measurements [111,112]. Even though some of the data generated by the sensors can be partially processed on the spot, some data should be transmitted to a management system. In addition to the need for reliable network connectivity, one should address data latency issues, ensure data transmission security, and manage the large volumes of data generated by the sensor network [113,114].

Ensuring the reliability and accuracy of sensors is crucial for effective water management [105,115]. Sensors must provide precise measurements of parameters such as water quality, water level, flow rate, and pressure [103,106,116]. However, sensors in water and wastewater systems are susceptible to fouling, where particles, organic matter, or biofilms accumulate on sensor surfaces, leading to measurement inaccuracies and reduced sensor performance [117,118]. Specifically, the growth of microorganisms on sensor surfaces, known in the literature as biofouling, poses a significant challenge [119,120]. Hence, sensor calibration, preventing sensor drift, and ensuring long-term reliability in harsh environmental conditions are critical for the sensors' reliable operation.

Sensors require regular maintenance to provide reliable operation. However, sensor maintenance can be time-consuming, costly, and require specialized expertise [116,121]. The cost-effectiveness of maintaining a large-scale sensor network is an important parameter to consider before deploying advanced water and wastewater systems. Sensors deployed in water and wastewater systems should exhibit longevity and durability to withstand harsh environmental conditions, chemical exposure, and mechanical stresses [122,123]. In addition, since providing power sources in remote or hardly inaccessible areas is challenging, enhancing sensor energy efficiency is crucial to extending battery life, reducing power requirements, and minimizing sensor networks' environmental footprint [113,124]. Hence, ensuring sensor longevity is vital to minimize the need for frequent replacements and maintenance, reducing overall operational costs [125].

3.3.2. The Potential of Quantum Sensing

Concerning reliability and accuracy, quantum sensors, such as quantum magnetometers, atomic spectrometers, or fluorescence sensors based on carbon quantum dots, offer high precision and accuracy in measuring physical parameters [4,60]. These types of sensors can provide more reliable and accurate water quality measurements [126,127], flow rate, and pressure [128,129], thus surpassing the limitations of traditional sensors. In addition, quantum sensors may better detect low concentrations of contaminants in water or wastewater compared to conventional sensors. Recent studies in quantum-enhanced spectroscopy and quantum cascade lasers have shown that quantum sensors can provide enhanced sensitivity, enabling the detection of trace contaminants at lower concentration levels [119,130]. Moreover, these sensors can simultaneously measure various parameters, offering a multidimensional view of water and wastewater systems [131].

Due to high precision in measurements, quantum sensors can reduce data transmission requirements, thus alleviating several challenges related to data latency, communication bandwidth, and transmission security within a sensor network. Thanks to the principles of quantum entanglement, these sensors can offer higher immunity to external interference, such as electromagnetic fields or environmental noise [4,132]. Quantum sensors, particularly those based on solid-state systems, can have longer lifespans and require less frequent calibration than traditional sensors, thus reducing maintenance efforts and costs associated with sensor replacement or recalibration [4]. Hence, although not all challenges of smart water management systems could be resolved by quantum sensing, the issues of maintenance, durability, and longevity also seem to be addressable as soon as these sensors' technological readiness for deployment in the operational environment matures. Figure 3 summarizes the potential of quantum sensors for water and wastewater infrastructures and applications.

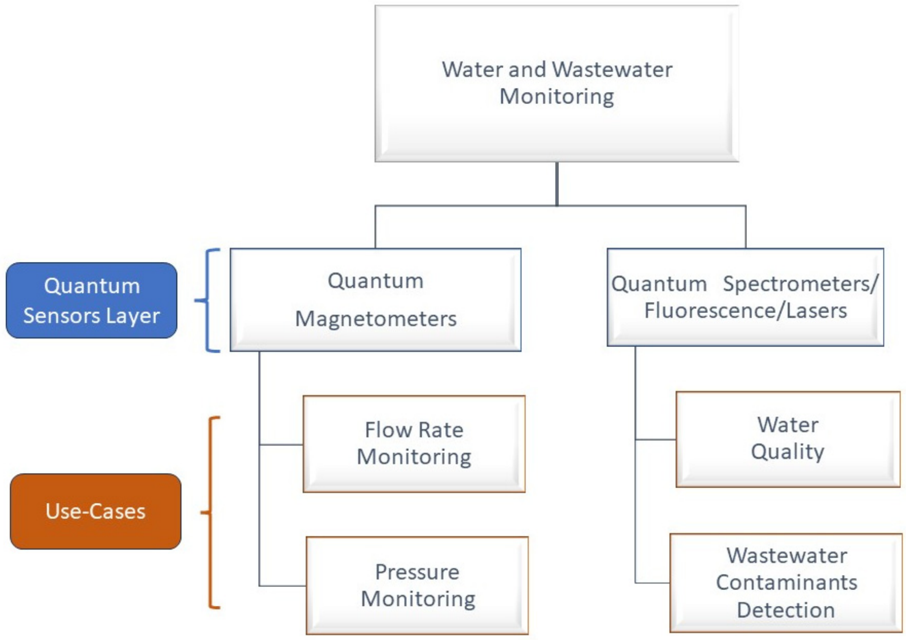

Figure 3. The potential of quantum sensors for wastewater infrastructures and applications.

3.4. Civil Infrastructures—Construction

3.4.1. The Challenges

Numerous studies have acknowledged the importance of detailed information and automated processes for improving the effectiveness and security of construction projects. Monitoring underground utilities is necessary for improving planning and construction efficiency, maintaining and managing infrastructures, ensuring safety, protecting the environment, complying with regulations, as well as preparing and responding to disasters [133,134]. During the execution phase, knowledge of the precise location of underground utilities is necessary to prevent delays and additional costs caused by unexpected utility encounters or relocations [134–136]. However, the automated monitoring of construction sites still represents a formidable obstacle [137,138].

Existing sensors face several challenges and limitations that hinder their efficiency in the construction domain. The primary disadvantage of the existing sensors is their robustness, which is negatively affected by the harsh conditions at construction sites [139]. Dust, moisture, extreme temperatures, electromagnetic interference from machinery, and mechanical vibrations—all these, and additional conditions typical for construction sites, can diminish sensors' performance and result in inaccurate data [25,37,140]. For example, there can be issues regarding the long-term stability and drift of geotechnical sensors, such as those utilized to monitor soil conditions or structural strain [141]. Sensor drift necessitates periodic calibration, which can be challenging to perform on a construction site. In addition to the difficulty of installing sensors in the field [142], many sensors used in construction, such as load cells, strain gauges, and accelerometers, are susceptible to non-linear response and hysteresis [143]. Sensors embedded in structures or used in geotechnical applications are sensitive to mechanical stress, which can degrade their performance or cause failure over time [144].

The complexity of underground networks complicates each utility's locating and mapping precisely. Moreover, descriptions and maps of underground utilities are frequently outdated or inaccurate, which limits our ability to rely on them to uncover underground utilities. Performing detection and mapping underground utilities for every new construction project can be time-consuming and costly, especially when utilizing traditional sensing technologies that require multiple passes or additional equipment to produce satisfactory results. Some detection methods, such as excavating test pits or using trenching equipment, can be invasive and cause damage to the environment, pavement, or other infrastructure components [145].

Cities implement the currently available technologies to improve the ability to locate and manage underground infrastructure, reduce the risks associated with utility strikes, and enhance urban planning and development processes [146]. Some of these technologies employed for detecting underground utilities are ground-penetrating radar (GPR) and electromagnetic induction (EMI) sensors [147]. However, the low resolution of GPR and EMI sensors makes data interpretation problematic [148]. In addition, due to their limited sensitivity, GPR and EMI sensors have difficulty detecting small or non-metallic utilities, such as plastic pipes and fiber-optic cables. Different soil and ground conditions can attenuate electromagnetic signals used by GPR and EMI sensors, thereby reducing their detection range and precision [149]. The data collected by GPR and EMI sensors can be affected by moisture content and other subsurface objects [150]. Moreover, measuring minute changes in gravitational fields for subsurface imaging or detecting minute shifts in building structures necessitates an incredibly high degree of precision that existing sensors may struggle to provide [151].

3.4.2. The Potential of Quantum Sensing

In the construction domain, quantum sensing can offer a range of improved or new procedures and applications, primarily due to enhanced precision, resilience to environmental noise, and unique quantum properties [4]. For example, by leveraging quantum entanglement, quantum sensors can reduce the impact of environmental noise, which is a significant benefit in the challenging conditions typically encountered on construction sites [152]. Moreover, quantum sensors employing entangled particles could be used on construction sites to measure parameters such as gravitational variations, magnetic fields, temperature, pressure, and vibration with high precision, even under harsh conditions. The reduction of sensitivity to environmental noise, which typically interferes with the measurements of existing sensors, will result in more precise and reliable data. Using quantum error correction techniques will further improve the accuracy and reliability of quantum sensor measurements [153].

Quantum sensing reveals the new capability for high-precision subsurface imaging [154]. Quantum gravimeters use atom interferometry principles and quantum states' superposition to measure gravitational acceleration with exceptional precision [155]. These sensors can help detect minute variations in the subsurface density, indicating the presence of underground structures or variations in soil and rock types. Thus, these sensors could be utilized for high-resolution subsurface imaging, assisting in detecting underground utilities, voids, or geological features.

Quantum sensing can also offer several advantages over GPR and EMI sensors for detecting underground utilities, especially in densely populated or cluttered subsurface environments [4]. Because quantum magnetometers are less affected by soil conditions and ground composition than conventional GPR and EMI sensors, these sensors promise less signal attenuation [156]. As a result, quantum magnetometers can measure magnetic fields with extremely high sensitivity, allowing them to detect small or weakly magnetic objects at greater depths, such as small metal pipes or buried utility lines [4,157]. It might be possible to design quantum sensors to be less susceptible to electromagnetic interference from external sources, thereby enhancing their ability to detect and distinguish utility signals from background noise [158,159]. In turn, quantum gravimeters can detect variations in gravitational fields caused by underground changes in mass distribution, thereby enabling the detection of non-metallic utilities such as plastic pipes and fiber-optic cables [160].

Since changes in stress alter the magnetic properties of a material, magnetic field sensors can be used to detect corrosion, which is a leading cause of structural failure in steel structures [161,162]. On construction sites, quantum magnetometers can provide advanced environmental monitoring for detecting buried metallic objects or infrastructure, assist with directional drilling, and monitor the magnetic emissions of electrical equipment. In turn, quantum thermometers utilize the quantum properties of specific materials to measure temperature with a high degree of accuracy [98]. Their resistance to environmental noise makes them ideal for noisy construction environments where precise temperature readings are essential for materials handling, worker safety, and more. For example, quantum temperature sensors can monitor concrete curing temperature, which is crucial for its strength and durability [163].

Using quantum superposition and entanglement, quantum gyroscopes can accurately measure rotation [164]. This may be essential for tasks such as aligning structures, monitoring the stability of cranes or other heavy equipment, and confirming the angular position of construction elements. Because quantum gyroscopes can detect minute vibrations and rotations, they can provide crucial data about the structural integrity of buildings under construction or after they are built [165]. In turn, quantum accelerometers use supercooled atoms to detect even the tiniest changes in acceleration [166]. This can enhance a building's structural health monitoring during construction and operation. Finally, because quantum gas sensors are much more sensitive than traditional sensors, they can detect even the smallest leaks of dangerous gases, such as radon and methane [56,57]. This can aid in the prevention of accidents and the protection of construction workers. Figure 4 summarizes the potential of quantum sensors for construction-related infrastructures and applications.

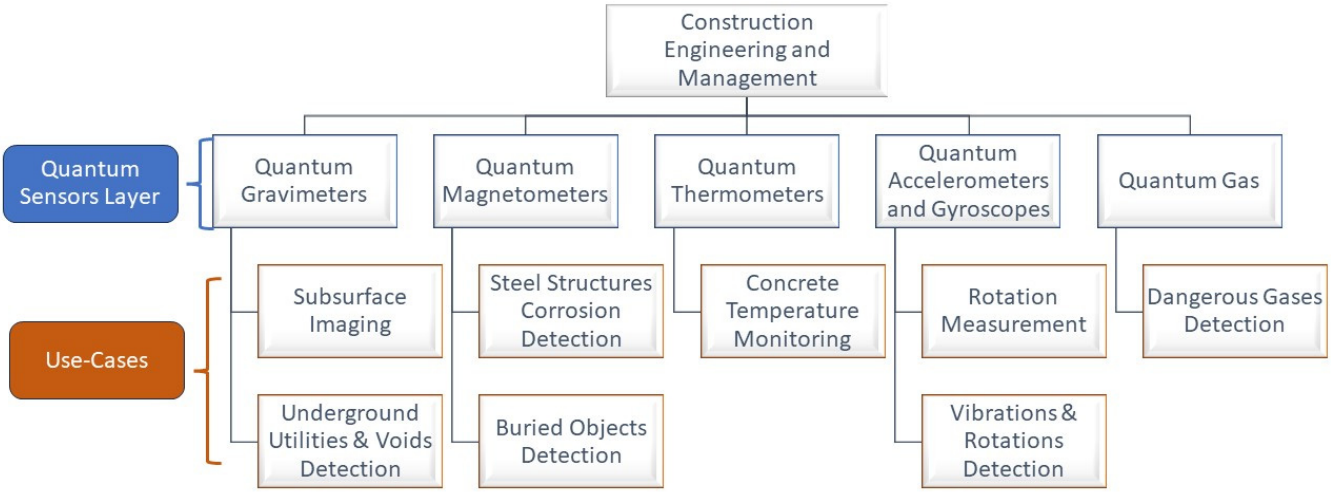

Figure 4. The potential of quantum sensors for construction infrastructures and applications.

4. Research Findings

This study has led to several significant findings on applying quantum sensors in civil infrastructures. According to the conceptual framework of this study, the summary is systematized based on the primary domains of civil engineering: energy, transportation, water, and construction. It was revealed that quantum sensors hold immense potential to enhance the efficiency and accuracy of civil engineering practices across various domains. With their superior sensitivity and precision, these sensors can address traditional sensors' limitations, thereby significantly improving data quality and operational efficiency. The combinations of quantum magnetometers with gravimeters, gyroscopes, cameras, and spectrometers can be used in various applications for three main civil engineering domains—transportation, construction, and water. Since quantum magnetometry is the most advanced sensing technology [4], its application to the transportation and construction sectors seems to be the most promising.

In construction, quantum sensors emerged as game-changers in detecting and imaging subsurface structures and utilities. Their ability to provide precise imaging can significantly reduce the risks and costs associated with unforeseen underground obstacles—one of the common challenges in urban construction projects. In addition to facilitating safe and efficient construction, this capability is crucial for urban planning and maintaining existing infrastructures. Moreover, the integration of quantum sensors may be utilized for precise directional drilling and monitoring electrical equipment's magnetic emissions.

The study also found that quantum sensors could revolutionize the transportation sector. Their application in traffic management, smart mobility solutions, and infra-structure monitoring could lead to safer, more efficient, and environmentally friendly transportation systems. The results demonstrated that these sensors could provide real-time, highly accurate data on traffic flow, road conditions, and structural integrity of transportation infrastructures. Such data are essential for developing mobility solutions and enhancing road safety. This is especially pertinent given urban transportation networks' growing complexities and demands.

For the water sector, these sensors have the potential to significantly improve real-time monitoring of water and wastewater flow rate and pressure in various aquatic environments. Quantum sensors employing carbon quantum dots surpass conventional sensors' detection limits and exhibit the unprecedented capability to identify trace amounts of pollutants or contaminants in water or wastewater. The ability of these sensors to detect minute contaminants and changes in water systems can significantly enhance the safety and reliability of water supply and sewage systems, thus contributing to urban water management and environmental protection.

Metrological sensors such as temperature, gas, irradiance, accelerometers, gyroscopes, strain gauges, electricity, and audio and their combinations seem promising for three of four civil engineering domains—energy, transportation, and construction. In the energy field, these sensors promise to contribute to power quality, grid resilience, solar energy forecasting, and energy efficiency by precisely monitoring solar irradiation, indoor temperature comfort, and air quality parameters. Temperature, air quality, and comfort parameters also might be helpful in the transportation sector for improving drivers' safety and passengers' comfort. Similarly, the functionality of identifying dangerous gases and their concentration is also relevant for the energy, transportation, and construction sectors. Finally, combining accelerometers with strain gauges and gyroscopes offers a broad range of improvements in monitoring road surfaces, micro-mobility services, fleet, and cargo management. Nevertheless, the most promising result of integrating these three types of sensors seems to be in the construction sector with respect to tracking the position, structural health, and integrity of buildings and constructions, as well as vibration monitoring and stability and the angular position of heavy equipment.

Quantum optic sensors, including cameras, radars, and LiDARs, are currently the most suitable for energy and transportation sectors. For the energy sector, these sensors might be helpful for energy efficiency by precisely monitoring buildings' occupancy and lighting optimization. In the transportation domain, the combinations of these sensors may help in intersection and road safety, parking space management, improve freight safety, and even facilitate advanced freight vehicle platooning. Based on the range of possibilities, and considering the current state of quantum sensor development, we assume that the transportation and construction sectors will become the first adaptors of the technology, followed by the energy and water industries. Table 2 delineates the transformative potential of quantum sensors in various civil infrastructure domains, emphasizing how their integration can vastly enhance energy, transportation, water, and construction capabilities.

Table 2. Quantum sensors' potential for civil infrastructures and applications.

Quantum Sensors	Energy	Transportation	Water	Construction
Temperature Gas Humidity	energy efficiency indoor air quality buildings' retrofitting	air quality emissions control passenger comfort	-	detecting dangerous gases monitoring curing temperature
Accelerometers strain gauges	-	road surface conditions monitoring	-	-
Accelerometers Gyroscopes	-	micro-mobility services rider safety fleet management freight logistics cargo conditions	-	stability of heavy equipment angular position of constructions structural integrity of buildings vibration
Magnetometers Gyroscopes	-	smart mobility solutions navigation and orientation assistance	-	-

Table 2. *Cont.*

Quantum Sensors	Energy	Transportation	Water	Construction
Magnetometers Gravimeters	-	traffic density, congestion dynamic traffic control, traffic management, and predictions	-	detecting underground utilities, voids, or geological features detecting buried metallic objects monitoring the magnetic emissions of electrical equipment
Magnetometers Cameras	-	dynamic traffic signal timings and lane configurations traffic management strategies and optimization	-	-
Magnetometers Spectrometers	-	-	flow rate, pressure water quality detection of contaminants	-
Cameras LiDARs	occupancy lighting optimization energy efficiency	intersection management road safety parking space management	-	-
Radars LiDARs	-	freight safety vehicle platooning	-	-
Voltage Frequency	power quality and grid resilience	-	-	-

5. Discussion

Contemporary smart city solutions mainly rely on the binary computational paradigm [167]. Despite the permanent advancements of existing sensors in the analysis and monitoring of civil infrastructures, the current state of conventional technologies imposes limitations on the quality and accessibility of data. The sensors' accuracy, sensitivity, reliability, and resilience limitations lead to diminished efficacy, increased operational costs, and scalability restrictions. Quantum sensing, a burgeoning technology field, holds great potential for revolutionizing multiple civil engineering sectors. As outlined in Table 2, quantum sensors are highly suitable for a diverse array of civil engineering applications and have the potential to enable tasks that were previously deemed unattainable or unfeasible. However, although quantum technologies lead to groundbreaking advancements and practical applications in many industries, their potential for civil engineering is still largely unexplored. Some of the reasons relate to the understanding of technological maturity and the cost–benefit viability of these technologies [8]. The concept of the technology readiness level (TRL) was originated by the American National Aeronautics and Space Administration (NASA) in the last decade of the 20th century as a means of measuring how far a technology was from being deployed in space [10]. Since then, the TRL concept was adopted by ISO and, among others, became mandatory for most publicly funded EU programs as an indicator to align with the EC's expectations regarding the development level of a specific technology. The basic principle of the TRL measure is simple—the higher TRL means that the technology is closer to commercial maturity. However, utilizing the TRL concept alone without application or discipline-specific guides may create confusion rather than clearly indicate the technology, product, or systems' commercial readiness and viability [8,10].

To address the drawbacks of the generic nature of the TRL concept and enable the evaluation of the readiness of specific quantum technology, one of the recently offered concepts is quantum technology readiness levels or QTRLs [8]. Since performing the precise evaluation of the technology and its intended applications is crucial, it is reasonable to utilize QTRL to assess the readiness of individual branches of quantum technologies or a particular product based on the specific technology. One of the evident advantages of QTRLs is the special requirements for the technology and the performance metrics needed to assess its levels, such as the level of technical feasibility, the maturity of the design, the level of testing and validation, and the readiness for deployment.

Particularly for quantum sensing, here are the main principles of QTRLs as defined by Purohit et al. [10]. QTRL 1 refers to researching basic principles of quantum phenomena such as quantum superposition, entanglement, and coherence. QTRL 2 stands for developing a particular quantum technology concept or application. QTRL 3 is about the feasibility of the technological concept proven through the analytical or experimental evidence achieved in laboratory experiments or simulations. One of the essential elements of QTRL 3 is demonstrating potential advantages over conventional technologies. QTRL 4 tests the integration of individual quantum components into a more extensive system and asses their performance, reliability, and scalability. QTRL 5 focuses on validating the system's performance in environments that imitate real-world conditions—e.g., assessing the performance of quantum sensors in realistic settings. QTRL 6 requires demonstration of a fully functional system or subsystem within a relevant environment—e.g., a quantum sensor deployed in the field. QTRL 7 is about presenting the technology in an operational real-world environment—e.g., deploying a quantum sensor for environmental monitoring. QTRL 8 is achieved when the system has been completed and qualified through rigorous testing and demonstration. QTRL 9 is reached when quantum technology has been successfully deployed and used in practical, real-world applications or missions—e.g., quantum sensors are widely used in various businesses. Based on the recently published literature sources, Table 3 presents a comparative analysis, the current evaluation of QTRL, and expectations for reaching QTRL 9 for the main categories of quantum sensors as of the end of 2023. As shown in Table 3, the practical application of quantum sensors in real-world field conditions is still developing [4,8,9,167,168]. To fully harness the potential of quantum sensors for civil engineering, it is imperative to overcome the substantial obstacles associated with their widespread deployment.

Table 3. The main categories of quantum sensors.

Sensing Technology	Conventional Performance	Quantum Performance	Current QTRL	QTRL 9 Expectation
Magnetometers	Sensitivity : $\approx 10^{-12}$ T Noise $\approx$ pT/$\sqrt{\text{Hz}}$	Ultra $-$ high sensitivity $< 10^{-15}$ T Very low noise < fT/$\sqrt{\text{Hz}}$	QTRL8	<5 years
Gravimeters	Sensitivity : 1 cm/s^2, Drift : 0.01 µm/s^2/h	High Sensitivity; low drift Sensitivity : 50 nm/s^2; Drift : 1 nm/s^2/h	QTRL8	5–10 years
Accelerometers	Precision: 10 nm/s^2, Noise: 100 nm/s^2	High Precision, low noise Precision: 1 nm/s^2, Noise: 10 nm/s^2	QTRL8	5–10 years
Gyroscopes	Accuracy: up to 0.01°/h Drift: up to 0.001°/h	High stability, low drift Accuracy : $< 1 \times 10^{-6\circ}$/h, Drift : $< 1 \times 10^{-6\circ}$/h	QTRL7	5–10 years
Acoustics	Resolution: 10 cm	High resolution, low noise Resolution: 1 mm	QTRL4	5–10 years
Imaging	Resolution: ≈1 cm@10 m	Sub-wavelength resolution Resolution: <1 mm@10 m	QTRL4	5–15 years

First, quantum sensors still exhibit a significant drawback due to their high cost, impeding their extensive adoption. The cost–benefit analysis (CBA) assists in making informed decisions about whether to invest in specific technologies or projects based on their overall value proposition during a specified timeframe for a particular application or industry. In CBA, benefits and costs can be classified as either estimable or stochastic [168]. The estimable CBA can be performed based on available information about the technology and accompanying costs, assuming that the project will develop as expected. In turn, stochastic CBA considers the uncertainty in project outcomes [169]. In both methodologies, one should have enough information about various solutions, vendors, and more to make informed decisions. For conventional sensors, the costs include evaluating the expenses incurred in acquiring, deploying, and maintaining sensors against the benefits derived from their use. Because the most advanced readiness level is currently estimated as QTRL 8, it is premature to discuss the costs of these sensors.

Due to the apparent complexity of performing conventional CBA for disruptive technologies, such as quantum sensing, as a preparatory stage, Purohit et al. [164] offered quantum commercial readiness levels (QCRLs) to provide a framework for evaluating the commercial viability and market readiness of these technologies. While QTRL 9 can already be reached within five years for some sensors, to understand the market readiness of quantum technology better, one could utilize the QCRLs [164]. According to Purohit et al. [164], the QCRL scale is defined from QCRL 1 to QCRL 5, where QCRL 1, described as problem-solution fit, corresponds to QTRL1 till QTRL 3. QCRL 2 refers to minimal viable product (MVP) readiness. In turn, market validation is defined as QCRL 3. From the point of view of technology readiness, these steps are mapped from QTRL 4 to QTRL 5. Once the technological readiness reaches the demonstration stage of QTRL 6 to QTRL 7, one could claim that the product–market fit is established, which is QCRL 4. Lastly, when the technology is ready for full commercialization and scaling, i.e., QTRL 9, QCRL 5 is also achieved. By mapping QCRLs to QTRLs, stakeholders can make informed decisions and manage the risk required for the later phase of CBA. However, one should consider that significant barriers could still exist, including operability in diverse contexts, standardization for achieving compatibility among various vendors, regulation, specialized training, and more [169].

Notwithstanding these obstacles, the advancement of quantum sensors for civil infrastructures represents a propitious domain that can substantially influence future cities. With the ongoing maturation of technology, it is anticipated that quantum sensors will witness a decline in cost, accompanied by enhancements in user-friendliness and robustness. This will enhance their acceptance and utilization across diverse applications within civil infrastructures. To further exploit the full potential of quantum sensors, it is imperative to advance knowledge about these technologies, particularly within practical civil engineering applications. Given the currently high costs of quantum sensors, it is crucial to prioritize the development of more economically viable approaches for their production and implementation. Because of the absence of universally recognized benchmarks for these sensors, it is essential to establish standards that guarantee compatibility and comparability across various sensor categories. In light of the complex characteristics inherent in quantum sensors, one should develop comprehensive training programs that cater to the needs of civil engineers and additional relevant professionals. These programs are essential to equip individuals with the necessary skills and knowledge to effectively utilize and maintain these sophisticated instruments.

The limitations of this study are typical for the method of narrative review. Since quantum sensing applications in real-world use cases are still minimal and there is not yet enough literature on the application of quantum sensing for civil infrastructures, it might be that some needs or limitations of existing sensors were not included in the analysis. Considering the goal of this paper to present a vision and provoke dialogue on how quantum sensors might assist in addressing the challenges of the civil infrastructures of future cities, we consider the limitations of this study to be acceptable.

6. Conclusions

The advancement in quantum sensing, characterized by quantum entanglement and superposition, brings about sensors with unprecedented precision and sensitivity. These sensors are poised to revolutionize construction, transportation, energy, structural health, water, and environmental monitoring. The potential of quantum sensors extends beyond mere technical enhancements; they pledge smarter, more sustainable urban development and a proactive approach to global challenges such as climate change. The advent of quantum sensing for civil engineering heralds the beginning of a transformative era. The quantum transformation is more than a technological upgrade; it represents a fundamental shift in how data are gathered, processed, and utilized in civil infrastructures. However, this transformation is not without challenges. The costs, operational complexities, and the absence of standardized benchmarks for quantum sensors in civil engineering are significant hurdles. Addressing these requires concerted efforts in research, development, and policymaking. Moreover, integrating quantum sensors with existing technologies necessitates a strategic approach, balancing innovation with practicality. Preparing the workforce for this quantum leap is crucial and emphasizes the need for specialized training and education programs in civil engineering. As we stand on the brink of this quantum revolution in civil engineering, it is imperative to navigate these challenges thoughtfully, ensuring that the potential of quantum sensing is fully realized in building the resilient and efficient infrastructures of the future.

The study is innovative in several aspects. First, it provides a comprehensive analysis across four main sectors of civil engineering—construction, energy, water, and transportation—through identification and discussion of the limitations of traditional sensors in these sectors. Second, it explores the potential of quantum sensing technology for these four civil engineering sectors. The research extends its innovative reach by delving into a technology not yet extensively researched in this field. The scope of the study demonstrates the versatile applications of quantum sensors across diverse and interconnected domains within civil engineering, highlighting quantum technology's multifaceted potential. Third, the study further explores quantum sensors' potential to revolutionize these sectors. It meticulously outlines how these sensors can address distinct challenges in water quality monitoring, energy grid stability, construction processes, and transportation management.

It is one of the first comprehensive studies advocating the strong rationale for considering road mapping toward adopting quantum sensors in civil engineering. This aspect is inherently innovative, setting a precedent for future research and development in the field. Fourth, by establishing a foundation for future discourse on the deployment of quantum sensors in real-world applications, this study plays a crucial role in shaping the trajectory of technological advancements and quantum transformation in civil engineering. This contribution is particularly important as it paves the way for quantum sensors' practical application in solving real-world challenges for the cities of the future. Finally, this study serves as the basis for intellectual discourse among academics and professionals about the scope and timing for leveraging the discussed potential within the primary fields of civil engineering infrastructures. We believe that integrating scholarly inquiry, pragmatic implementations, and technological progress will serve as the fundamental basis for future cities, guaranteeing their preparedness to address the requirements and complexities of the upcoming decades.

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