

different aspects such as distress, unevenness, rutting and cracks [34]. Asphalt 3D printing technologies could also be installed on drones to fill cracks in pavements [35].

Another major use-case for drones is post-disaster reconnaissance. Fires, explosions, and natural disasters such as earthquakes, floods, hurricanes, tornadoes, and landslides can cause unavoidable damage to buildings and infrastructure. Drones can be used to perform comprehensive damage assessment through identifying damage evidence ranging from cracks to complete collapses, and enhance the processes of rescuing, cleaning, rehabilitation, and retrofitting [12,23]. Damage evidence can also be helpful when filing for post-disaster insurance compensations [36].

4 IMPLEMENTATION OF DRONES IN CONSTRUCTION PROJECTS

4.1 Benefits

The different applications of drones across the construction project lifecycle discussed earlier highlight major social, economic, and environmental benefits.

From the social perspective, the ability of the drone to manoeuvre over hazardous areas and dangerous heights for important tasks like inspection or surveying makes the technology a safer alternative than human labour. Land surveyors and inspectors can fly drones over their areas of interest instead of performing their surveying or inspection tasks physically and getting exposed to risks [12]. Drones can also add an extra layer of security to the job site through identifying breaching of parameters or entrances to no-go zones faster [19]. This becomes especially important for site visitors and pedestrians commuting around the jobsite. Moreover, the use of drones for inspecting highway infrastructure such as bridges, roads, and tunnels, can decrease the hardships of traffic control [37].

From an economic perspective, the different use-cases of drones – discussed in the applications section above – show that drones can (1) simplify reporting through capturing and footage in real time for project stakeholders present inside and outside the job site, (2) enhance decision making through remote site access, (3) provide accurate calculation tasks such as earthwork volumes, (4) track progress on construction site with high accuracy and compare it to design to develop as-built statuses, (5) track the movement of materials and resources anywhere on the job site, (6) replace the need for heavy equipment and truck cranes or elevating platforms to inspect hazardous area, and (7) reduce liability through resolving disputes faster [16,18,21,23,32]. All those benefits translate into productive job sites with efficient communication and

collaboration among stakeholders, and significant time and cost savings in a construction project [12]. Moreover, the use of drones allows companies to gain competitive advantage whether when bidding on projects or seeking new clients.

From an environmental perspective, drones do not rely on fossil fuels and are mostly electric-motor driven. Thus, drones release significantly lower levels of carbon dioxide emissions when compared to construction equipment, making them an environmentally friendly alternative for aerial work – i.e. land mapping, photography, and surveying [12]. Further environmental benefits are also perceived through reducing congestion, for drones will decrease the number of human labour and equipment needed to perform critical tasks [28]. Moreover, the use of drones can contribute to sustainable development and construction when monitoring energy projects like pipelines, wind turbines, or solar farms [12].

4.2 Challenges

Despite the different benefits perceived from the use of drones, several challenges remain at the technical, social, and legal standpoints.

From a technical standpoint, technological constraints such as the limits on the battery life can shorten the time of flights and operations [38]. Battery life is affected by factors such as the take-off weight, which in turns affects the types of cameras and sensors that can be used [34]. Another technical constraint is the effect of environmental factors like severe weather conditions and rough terrains; terrains like mountains and hills or underground tunnels and severe weather conditions like extreme temperatures, accumulation of ice, high wind speeds, and heavy rains may hinder signals and connectivity [34,38]. Moreover, drone take-off location and flight paths should be away from large metal objects or heavily reinforced concrete structures since electrical sensors like gyroscope and magnetometer can be affected by communication interference if there are magnetic sources around the drone [39]. Furthermore, even though researchers are studying the ability of drones to perform aerial drone-based construction tasks, material such as bricks or blocks or voxels might require to be altered to meet the drones capabilities [40]. Finally, while drones excel at outdoor environments. Several limitations remain for using drone in indoor environments with the absence of GPS and lack of predefined parameters necessitate more intricate sensing abilities and sophisticated supporting algorithms [38]. To overcome such technical issues, cross-industry cooperation is required between the manufacturer and client to enhance product research and development and improve the capabilities of drones for the construction industry [23].

From a social standpoint, operating drones comes with the risk of collisions with people, objects, and other aerial vehicles [34]. Many reasons can cause the drone to malfunction such as the sudden discharge of the battery, unpredicted weather occurrences like unknown winds aloft, unexpected hazard events like forest fires or earthquakes, loss of command and control link, loss of visual contact with the drone, and loss of navigation control [37]. Even though the probability of such risks may be low, they become more possible when using drones on large scale entails [41]. Noting the labour intensive nature of the construction industry and the critical location of many construction sites in populated areas, drone malfunctions may lead to crashes crash into on-site personnel, pedestrians, vehicles, or structures resulting in bodily injuries and/or property damages [38]. Other social challenges include security and privacy concerns. Drones are equipped with cameras, night vision device, and various sensors that give it the ability to track objects and observe them in different perspectives. Such capabilities can facilitate snooping and capturing unauthorized images of persons or private property, which in turn raises privacy concerns from citizens [38,41]. Moreover, many law enforcement agencies have voiced security concerns on the use of drones since drone operations can be vulnerable for GPS jamming and hacking, making drones prospect for malicious users to conduct cyberterrorism and other unlawful activities [9]. Such social challenges may be maintained by strong security firewall systems and ethical guidelines for drone operations to clearly define the objectives of the flight, the data that should be gathered for analysis, time of data residentials, possible privacy violations, and proper risk and safety mitigation plans and strategies [23].

From a legal standpoint, different aviation rules may restrict the potential of drones. For example, in USA, while the FAA regulations are important to guarantee the safety of people and property, other regulations may cause operation restrictions. Examples of restricting regulations include: the weight of the drone including payload at take-off should not cross 25 kilogram (55 pounds), flying at or under 120 meters (400 feet), flying at or under 160 kilometres per hour (100 miles per hour), staying 8 kilometres (5 miles) away from airports, remaining in Class G airspace, keeping the drone within the visual line of sight of the operator, and yielding the right of way to other aircrafts. It is worth to note that restrictions, aside staying in Class G and the take-off weight of the drone – may be waived by the FAA upon submitting a waiver. It is also worth to note that the restrictions of flying over moving vehicles, flying over people who are not protected by a shield and/or part of the operation, and flying at night were lifted by the FAA as of April 2021 [6]. Other legal challenges come in the

form of liabilities [26]. The absence of common industry standards for risk allocation and mitigation may cause potential liabilities on who might be responsible for the incurred injuries or property damages in the case of a drone malfunction [26]. This becomes especially important because the FAA does not mandate insurance for drone operations, but requires operators to report all drone incidents, which may lead to revoking licenses and jeopardizing the company from using drones in their operations [26]. Thus, insurance companies should develop policies to clearly define and integrate drone usage into the insurance coverage of construction projects and create ideal insurance cost models that account for the accident rates and safety risks for drone operations [23].

4.3 Lifecycle Cost

The lifecycle cost of implementing drones can be broken down into three phases: procurement and acquisition, operations and management, and retirement and disposal [42]. The procurement and acquisition phase is related to the permits needed to buy and operate the drones, and the cost of purchase. Factors that affect the cost of the purchase include the drone's weight (i.e. battery, propellers, motors, controllers, frame, take-off elements), its payload capacity (i.e. gimbals, cameras, sensors), and endurance (i.e. battery service) [42]. Other cost factors include the required software for navigation and flightpath automation, to control, monitor, communicate, and navigate the drone, in addition to gathering, storing, and sharing data [42]. The operation and management phase is associated with incurred costs to operate the drones at regular intervals of time. Examples of operation costs include the lifespan of propellers and batteries, software adaptability, insurance, and operating crew [42]. As for the retirement and disposal phase, it is derived from the recuperated capital at the end of the drone's lifespan [42].

5 Implementation Practices and Recommendations

Several companies have published success stories of the use of drones in the construction industry, whether through webinars, academic papers, or blogs. A number of those resources were reviewed to comprehensively compile a list of common practices needed for implementing drones [12,36–38,43–48,50]. It is worth to note that the practices should be treated as guidelines instead of an official standard for implementing drones.

To begin with, construction companies should understand the need for drones before starting the implementation process. As seen in the applications section, drones have multiple purposes across the entire

lifecycle of a project. Thus, it is important for companies to communicate with project stakeholders and assign one or more champions to define the areas of interests, the type of data needed, the timelines of acquiring and analysing the data, the proper methods to share the data, and the expected deliverables. Another reason for including multiple stakeholders is that one drone flight may serve multiple teams. Thus, understanding the needs of every team helps better understand the use-cases that drones can fulfil. For example, images can be shared with superintendents to note and understand

Since the construction industry is resistive to change, a transition to implement drones in construction processes may not be easy. Thus, it is important for champions to highlight the value of using drones by sending newsletters, conducting webinars, and sharing videos with those who are hesitant to change. Return on Investment (ROI) is also a common practice to show value; champions can perform preliminary analysis by comparing the current incurred costs (such as the current-state labour wages and equipment needed to collect the data and perform analysis) to the drone investment cost (i.e. the Lifecycle cost explained before) and the expected savings (both tangible such as the equipment's replaced by drones, and intangible such as the dollar value of the time savings). Another way to show value is to conduct different pilot test on a small-scale construction product with the help of a third party and gather feedback from involved personnel.

Another important practice is to review the regulations and necessary authorizations to operate drones. While the FAA is responsible to regulate the operations of drones in USA, several states and cities have created their own rules and regulations, with some imposing regulations limitations that are stricter than others. Thus, a company should invest time in understanding the local and federal rules and regulations in their areas of operation.

As discussed in the challenges section, the drone operations are associated with serious safety risks. Thus, it is important for companies to develop risk assessment plans and standardize checklists for drone operators and on-site personnel to use before, during, and after the flight operation. Such practices are also valuable for the involved lawyers and insurance companies.

Finally, the global drone market is increasing and currently involves a growing number of hardware, software, pilot, training, insurance, and distribution partners. With such a strong global partnership network, and with drones successfully exceeding their expectations on construction projects, companies have the support that they need to confidently start their drone initiatives.

6 CONCLUSIONS

This paper recapped the use of drones in the construction industry. Using the 5W2H method, the paper presented the different applications of drones across the lifecycle of a construction project, discussed the benefits of using drones and elaborated on the challenges, and provided an overview of the lifecycle costs. The paper also presented a comprehensive assessment of common practices derived from several successful implementations of drones in the construction industry. Findings in this paper can set a baseline for both construction academicians and practitioners for the state of drones in the industry. Further studies can build on this study by providing industry use-cases and elaborating on other Industry 4.0 technologies that can be integrated with drones to maximize its use.

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