UAV-Based Delivery Systems: a Systematic Review, Current Trends, and Research Challenges

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The rising popularity of drones significantly impacts package delivery services, offering both unique opportunities and challenges. This survey explores the diverse applications of drones for last-mile deliveries, highlighting their capacity to access remote areas and create new business prospects. Use cases, ranging from critical medical deliveries to addressing COVID-19 pandemic needs, underscore the transformative potential of drone technology. While recognizing drones' eco-friendly attributes in eliminating harmful gas emissions, the survey addresses battery constraints, necessitating an investigation into physical energy models to extend flight autonomy. This becomes crucial for operational capabilities, especially in adverse weather conditions. A reliable communication infrastructure is crucial for the success of drone operations in package delivery, especially during unexpected events, as seamless connectivity plays a key role in facilitating efficient control and monitoring between ground stations and drones. This enables dynamic rerouting, enhancing overall delivery reliability. The survey explores innovative approaches, including collaborations with other vehicles like trucks, trains, and buses, optimizing the last-mile delivery process. Despite the transformative potential, concerns about privacy, security, safety, and risk management in drone delivery are acknowledged. The work also emphasizes responsible and ethical implementation, considering diverse concerns associated with widespread adoption.

In contrast to existing survey articles focused on specific technical aspects, this comprehensive survey broadens its scope. It covers ethical issues, sustainability aspects, healthcare systems, physics models, innovative approaches, reliable communications, security and safety concerns, and real test-beds in drone-based delivery systems. The survey not only identifies potential applications and tackles technical challenges but also integrates broader considerations. In addition, this work extensively explores the motivations, lessons learned, and future directions in the realm of drone delivery. Analyzing existing literature, it provides valuable insights for researchers, industry professionals, policymakers, and stakeholders keen on understanding the dynamic evolution of drone technology in the package delivery domain.

CCS Concepts: • **Networks** → *Network algorithms*; • **Computing methodologies**;

Additional Key Words and Phrases: Unmanned aerial vehicles (UAVs), drone delivery, sustainable delivery, transportation of blood and organs, drone energy models, delivery safety and security

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1 INTRODUCTION

Nowadays, unmanned aerial vehicles (UAVs) or drones have experienced an exponential rise in popularity and have become an integral part of both the research and industry communities [137]. They can be used for a wide range of civilian applications, including smart agriculture [19, 93],

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monitoring [56, 76], search and rescue [23, 113], data collection [18, 24], and last-mile package delivery [15, 96]. In the last decade, research has focused on the UAV assistance paradigm [5], leading to improved interaction between ground networks and flying UAVs. Moreover, the widespread use of embedded wireless interfaces has simplified its deployment. UAVs, with their controlled mobility and adjustable altitudes, are considered ideal for enhancing performance and overcoming ground network limitations. Simultaneously, the Internet of Things (IoT) generates extensive data, requiring collection and transmission to a central controller for processing. Therefore, UAVs could serve as auxiliary devices, leveraging their advantages such as flexibility in movement, alleviating IoT communication burden, reducing data collection delays, powering IoT devices, and ensuring efficient delivery of collected data [97]. In essence, the UAV assistance paradigm proves indispensable for groundbreaking research and innovative applications.

By leveraging their capabilities, drone delivery has the potential to revolutionize logistics, creating new business opportunities, particularly in the efficient transportation of goods to remote and hard-to-access locations [8]. Since drones are battery-powered, drone delivery promotes environmental sustainability by eliminating the emission of harmful gases [117] associated with traditional delivery methods, such as trucks. This eco-friendly attribute has obtained significant attention and support from environmentalists and policymakers alike [32]. Also, their ability to potentially bypass traffic congestion makes them invaluable for time-critical deliveries [80], such as transporting organs or blood for medical purposes [118], particularly in congested urban areas.

On the other hand, the onboard battery significantly impacts and limits the flight time and autonomy of drones [34]. Therefore, it is crucial to extend their flight range and duration. It is worthy to investigate their physical energy models, enabling optimization of energy consumption and implementation of advanced path planning strategies considering current weather conditions [153]. Furthermore, establishing a reliable and robust wireless communication infrastructure is crucial to ensure seamless connectivity and control between ground stations and drones throughout the entire delivery process [58]. This becomes especially critical in handling unexpected events, allowing drones to be dynamically rerouted.

To enhance the efficiency and scalability of drone delivery systems, novel approaches such as collaborating with other vehicles have been explored [144]. In fact, through symbiotic relationships with private trucks or public transportation like trains or buses, drones can leverage existing ground transportation networks to optimize the last-mile delivery process. These collaborative efforts not only help increase the number of deliveries and reduce overall delivery time but also to address potential challenges related to battery life, payload capacity, and regulatory compliance.

Although the prospect of widespread and extensive drone delivery is exciting for the aforementioned reasons, it also raises concerns in several areas [91, 147]. Issues of privacy, security [59], and the potential safety risks associated with accidents or improper use require careful consideration [4]. Addressing these concerns is crucial to ensure the responsible and ethical implementation of drone delivery systems [55].

Paper Contribution and Organization: This paper presents the first comprehensive survey that explores and discusses the significant challenges of drone delivery. By analyzing existing literature, it aims to provide a comprehensive understanding of the current trends, opportunities, challenges, and future perspectives in this field. This survey provides valuable insights for researchers, industry professionals, policymakers, and stakeholders who are interested in the potential impact of drone technology on the delivery landscape.

In the following, we explore various aspects related to drone-based package delivery (summarized in Table 1). Section 2 provides an overview of the existing surveys in this domain. Then, we consider the ethical considerations concerning drone delivery in Section 3, emphasizing the importance of ethical practices and responsible implementation. Section 4 focuses on the sustainability aspects of drone delivery, highlighting its potential to reduce environmental impact. The role of drones in healthcare, specifically in medication delivery (Section 5.1) and addressing challenges during the COVID-19 pandemic (Section 5.2), are discussed in Section 5. The physics of drone delivery, including energy models (Section 6.1) and the influence of weather factors (Section 6.2), are examined in Section 6. The significance of robust communication infrastructure in ensuring efficient drone operations are explored in Section 7. Section 8 covers different approaches to drone deliveries, including exclusive drone-based delivery (Section 8.1), integration with public transportation systems (Section 8.2), and collaboration with trucks (Section 8.3). Concerns related to security and privacy (Section 9.1), as well as safety, risk, and reliability (Section 9.2), are addressed in Section 9. Finally, in Section 10, we explore innovative and test-beds and attempted real implementations that enhance the effectiveness and efficiency of drone-based package delivery. The paper concludes with a summary of the lesson learned, key findings, open challenges, and future directions in Section 11, and conclusions in Section 12.

Table 1. Taxonomy organization.

Category	**Section**
Ethics	3
Sustainability	4
Health	5
Medications	5.1
Pandemics	5.2
Physics	6
Energy Models	6.1
Weather Factors	6.2
Communications	7
Deliveries	8
Drones Only	8.1
Public Transportation and Drones	8.2
Trucks and Drones	8.3
Concerns	9
Security and Privacy	9.1
Safety, Risk, and Reliability	9.2
Test-beds and Implementations	10

2 RELATED WORK

Many articles provide a review of the use of drones for last-mile delivery, delving into different aspects such as routing problems, optimization approaches, delivery concepts, and energy supply management. They suggest potential research directions for future studies, emphasizing the critical importance of developing efficient and sustainable solutions for last-mile delivery, as exemplified in [52]. However, this work distinguishes itself by considering a comprehensive range of issues, including ethics, sustainability, health, physics, communications, concerns, and real test-beds in drone-based delivery systems.

Macrina et al. [92] explore the use of drones for delivery and focuses on routing problems. The authors categorize state-of-the-art works on drone routing, and eventually give suggestions for future opportunities. They also note the growing interest in using drones for many applications, supported by advances in technology and intelligent autonomous control.

Chung et al. [36] review optimization problems in the application of drone and drone-truck combined operations in various delivery based applications such as construction, agriculture, transportation, security, and entertainment. The paper examines current investigations into models, solution approaches, coordination mechanisms between vehicles, and challenges encountered when implementing these systems.

Boysen et al. [21] survey the current last-mile distribution concepts, with a focus on drones and robots. The paper also highlights the problems of congestion and pollution caused by increasing parcel delivery volumes, and the need for efficient and green solutions. It systematically presents the different delivery concepts and discusses the problems involved in their setup and operation.

Liang et al. [87] offer an analysis of the truck-drone routing problem, which involves a coordination to efficiently deliver packages to customers. The paper introduces two fundamental models for the traveling salesman problem (TSP) and the vehicle routing problem (VRP) incorporating drones. Furthermore, the authors categorize the existing works based on the constraints and characteristics they address.

Rajabi et al. [116] discuss the potential of drones for delivery, and the need to optimize their energy consumption for efficient implementation. The article reviews different power sources for drones, including fuel cells, batteries, solar cells, and supercapacitors, and discusses the importance of selecting the appropriate energy management system for optimal performance. The article concludes by identifying potential research areas for drone energy-supply management and strategic systems.

Benarbia et al. [12] present a survey of existing literature, examining critical research topics, solutions, and conceptual frameworks proposed in the field of drone delivery systems. The authors also delve into the performance levels of these approaches and address the key challenges they aim to tackle.

Raivi et al. [115] conduct a survey that examines the latest routing algorithms for delivery systems based on drones. The focus of the study focuses on trajectory planning, energy charging mechanisms, and security considerations. Additionally, they compare the routing algorithms in terms of their main concepts, advantages, limitations, and performance aspects. The paper concludes by presenting open research challenges to inspire further exploration and advancement in this field.

Finally, Eskandaripour et al. [47] examine the technical hurdles associated with last-mile drone delivery, including routing, optimizing cargo distribution, managing batteries, ensuring effective data communication, and safeguarding the environment. These challenges are interconnected and must be tackled collectively to attain a last-mile drone delivery system that is both eco-friendly and resource-efficient.

Table 2. Addressed topics in other survey papers.

Paper	[92]	[36]	[21]	[87]	[116]	[12]	[115]	[47]	**This**
Ethics		✓				✓		✓	✓
Sustainability			✓					✓	✓
Health							✓		✓
Physics		✓		✓	✓		✓		✓
Communications		✓	✓						✓
Deliveries	✓	✓	✓	✓	✓	✓	✓	✓	✓
Concerns		✓					✓		✓
Test-beds									✓

In contrast to other survey papers, our work comprehensively addresses various facets within the UAV-based delivery context. We not only delve into aspects such as ethics, sustainability, energy models, and communication but also prioritize considerations related to privacy, security, and safety. Moreover, this study consolidates insights from the surveyed works, offering valuable lessons learned, and puts forth numerous open challenges that warrant attention, along with suggesting future directions for research.

Table 2 presents the topics discussed in other state-of-the-art surveys related to drone-based package delivery applications, also highligthing our topics too. Finally, Figure 1 illustrates the proposed taxonomy, emphasizing categories, addressed aspects, and outstanding challenges. In the following sections, we will review the most recent and relevant works concerning this field.

3 ETHICS

Nowadays, drones are used in almost every civilian application, including package delivery. However, despite the support from the research and industry communities, it is not necessarily true that people would welcome the sight of drones hovering over them every day for regular tasks like delivery. This ethical aspect is particularly emphasized if people would not rely on drones in the future at all. Several papers have already addressed these issues and highlighted the importance of understanding public perceptions and concerns regarding drone technology. Table 3 summarizes the reviewed papers.

Using drones for parcel delivery offers faster, cheaper, and more eco-friendly delivery options, but the adoption intention of customers is uncertain despite pilot tests conducted by companies like Amazon and Google. A study of 296 US consumers showed that factors such as speed, environmental friendliness, complexity, performance risk, and privacy risk affect drone delivery adoption, and adoption determinants vary by the customer's area of residence [151]. In the US, the parcel delivery sector holds a substantial value of $200 billion annually, and there are high expectations for the rapid growth of drone-based deliveries. It is expected that this form of delivery will replace a significant portion of in-person deliveries, thereby enabling the transportation of larger or time-sensitive payloads using drones. While drones have the potential to enhance delivery efficiency and reduce costs, their widespread adoption is hindered by existing technological and human limitations. Nevertheless, if current trends persist, these limitations are expected to be overcome in the near future. As a result, practical and widespread drone delivery is anticipated to become a reality in certain areas [49].

Drone delivery technology is a new and unfamiliar concept for retailers in many countries, including Pakistan, where there is limited research on consumer perceptions [74]. In order to assess the level of acceptance and concerns of Pakistani consumers towards drone delivery, a quantitative survey was conducted with 307 residents from two Pakistani cities, predominantly from the middle and upper class. The survey findings suggest that privacy concerns are a key consideration for Pakistani consumers when it comes to drone delivery. The study also identifies consumer segments that retailers can target through the use of drone delivery technology. To address these concerns, retailers could incorporate privacy parameters during the service design and deployment stages of the drone infrastructure. In a study presented in [26], factors influencing the acceptance of drone delivery services in emerging market economies, particularly in Thailand, were investigated. The research shows that personal innovativeness and opinion passions impact users' perception of ease of use, but not the usefulness of drone delivery services. Privacy risk negatively affects the link between ease of use and adoption, but does not affect the relationship between usefulness and intention to adopt. Perceived ease of use positively influences adoption intention, while perceived usefulness does not have a significant effect. These findings underscore the importance for retailers in emerging markets to understand these factors to gain a competitive edge in last-mile delivery.

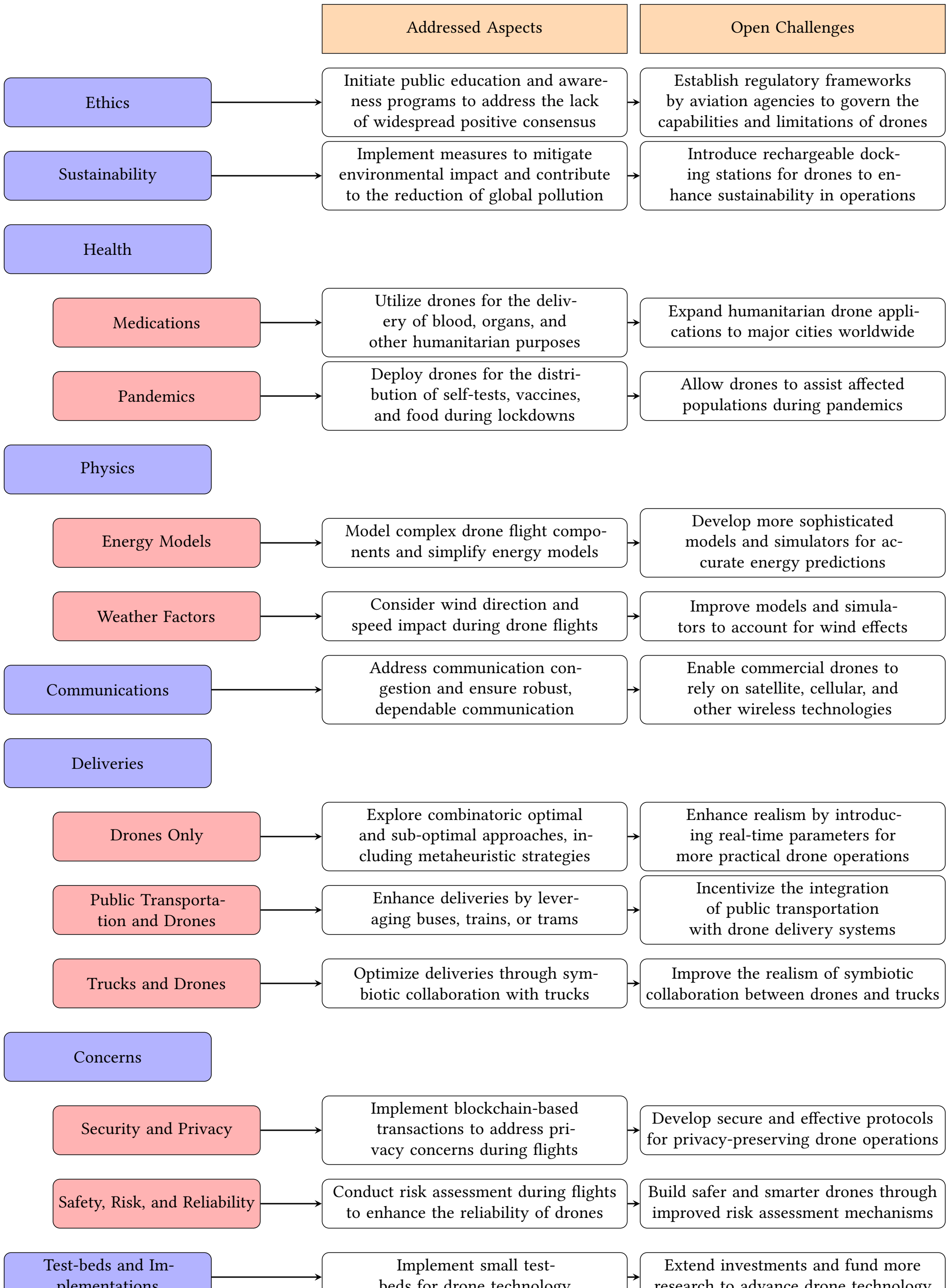

Fig. 1. Illustration of the proposed taxonomy, emphasizing categories, addressed aspects, and outstanding challenges.

Table 3. Ethics in Package Delivery: Studies and Focus.

Study	Focus	Key Findings and Implications
Yoo et al. [151]	US Consumers	Factors: speed, environmental friendliness, complexity, performance risk, and privacy risk. Rapid growth expected in the US, replacing in-person deliveries.
Frachtenberg et al. [49]	General	Widespread adoption hindered by technological and human limitations. Practical and widespread drone delivery anticipated in specific areas.
Khan et al. [74]	Pakistani Consumers	Privacy concerns significant. Retailers should address privacy concerns during service design and deployment.
Chen et al. [26]	Emerging Markets (Thailand)	Factors: personal innovativeness, opinion passions, privacy risk. Retailers in emerging markets need to understand factors for a competitive edge.
Aurambout et al. [6]	Europe	Economic feasibility of last-mile drone delivery. Up to 7% of EU citizens could benefit from last-mile drone delivery.
Osakwe et al. [110]	European Millennials	Factors: outcome expectancy, lifestyle compatibility, perceived self-efficacy, consumer attitude, and desire for drone usage. Lifestyle compatibility and desire are significant predictors.

A survey conducted in Europe, as described in [6], assesses the practicality and economic feasibility of employing drones for last-mile delivery. The study utilizes population and land-use data to determine the optimal placement of drone warehouses based on economic viability criteria. It is expected that up to 7% of EU citizens could benefit from last-mile drone delivery services, and this percentage could increase in more advanced scenarios. Moreover, countries such as the UK, Germany, Italy, and France highlight the highest potential for implementing efficient drone-based delivery systems. Another study assesses the intention of European millennial consumers to use drones for package delivery [110]. The study uses social cognitive theory and the model of goal-directed behavior to investigate factors such as outcome expectancy, lifestyle compatibility, perceived self-efficacy, consumer attitude, and the desire for drone usage. The authors found that these factors positively influence consumer attitude, which, in turn, increases the desire and intention to use drone delivery. Furthermore, the study highlights that lifestyle compatibility and desire are significant predictors of consumer intentions to use delivery drones.

4 SUSTAINABILITY

The use of drones offers a green alternative for accomplishing various tasks, including deliveries. As battery-powered flying vehicles, drones do not emit greenhouse gases, making them an environmentally friendly option. In comparison to traditional vehicles, drones have the potential to significantly reduce pollution and mitigate global warming. In the next, we present studies that have examined the sustainability aspects of drones in the context of package delivery. Table 4 summarizes the reviewed papers.

The article presented in [112] compares the environmental impacts of drone delivery versus motorcycle delivery, and evaluates the potential environmental contributions of electric motorcycles. The study found that the potential particulate emissions per unit of distance when delivering using drones are significantly lower than motorcycle delivery. Additionally, the impact reduction due to drone delivery is 13 times higher in rural areas compared to urban areas.

In [51], an estimation of CO_2 emissions and vehicle-miles traveled (VMT) levels has been studied for truck- and drone-based delivery systems. Results indicate significant differences in emission levels, which are affected by factors like energy consumption, travel distance, and the number of deliveries to be performed. However, when service zones are closer to the central depot, the utilization of drones is likely to result in a CO_2 benefit. Similarly, the paper [32] investigates the effects of employing UAVs for parcel deliveries on both CO_2 emissions and costs. The study introduces a mixed-integer green routing model designed to leverage the sustainability benefits of their usage. To efficiently solve the model, a genetic algorithm (GA) is developed, and an experiment is conducted to validate both the analytical model and the solution algorithm. Results indicate that optimal routing and delivery of packages using UAVs can lead to energy savings and a reduction in CO_2 emissions. The computational results strongly support the assertion that integrating UAVs into last-mile logistics is not only cost-effective but also environmentally friendly.

Li et al. [86] evaluate the environmental benefits of using UAVs for parcel delivery compared to traditional vehicle delivery, particularly in overcoming traffic restrictions. The authors propose a green routing model with vehicle-type and half-side traffic restrictions, and use a GA to solve the routing problem. They find that UAV delivery can save costs and reduce CO_2 emissions, even under traffic restrictions, and is more effective under the first kind of traffic restriction. The study supports the idea that UAVs can be a more environmentally friendly and cost-effective alternative to traditional delivery methods.

In [121], authors introduce an energy model and machine learning (ML) algorithm aimed at evaluating the energy consumption and CO_2 emissions associated with UAVs employed for deliveries. The model provides insights into the energy efficiency and environmental impact of small electric quadcopter drones transporting packages. Results show that drones use much less energy for each delivered package, and electric cargo bicycles are the only mode that has even lower CO_2 emissions for each package.

Table 4. Sustainability in Package Delivery: Studies and Focus.

Study	Focus	Key Findings and Implications
Park et al. [112]	Environmental Impacts	Comparison of drone vs. motorcycle delivery. Drones offer significant environmental benefits, especially in rural areas.
Goodchild et al. [51]	CO_2 Emissions	Estimation of CO_2 emissions and vehicle-miles traveled. Drones can provide CO_2 benefits in specific scenarios.
Chiang et al. [32]	CO_2 Emissions and Costs	Investigation of CO_2 emissions and costs for parcel deliveries. Integrating UAVs into last-mile logistics is cost-effective and environmentally friendly.
Li et al. [86]	Environmental Benefits	Evaluation of environmental benefits of UAVs for parcel delivery. UAVs present a more environmentally friendly and cost-effective alternative.
Rodrigues et al. [121]	Energy Consumption and CO_2 Emissions	Introduction of an energy model to evaluate energy consumption and CO_2 emissions of UAVs. Drones are energy-efficient with lower CO_2 emissions.
Troudi et al. [142]	Fleet Size Optimization	Model for determining drone fleet size for urban delivery operations. Aids in designing an optimal drone fleet for urban deliveries.
Baldisseri et al. [9]	Electric Trucks with Drones	Comparative life cycle assessment of a delivery approach with electric trucks equipped with drones. Electric trucks with drones offer sustainable delivery solutions with reduced emissions.

Troudi et al. [142] delve into the utilization of drones for parcel delivery and the specific challenge of determining the appropriate fleet size for urban delivery operations. The study introduces a model that accounts for factors such as drone autonomy, energy consumption, technical specifications, and sustainability considerations. Two optimization policies are proposed to facilitate route planning, focusing on reducing distances and striking a balance between distance and the number of drones. A case study that compares the two policies based on plan costs is evaluated. The goal is to develop a decision-making tool that aids in designing an optimal drone fleet for deliveries over a given time horizon while adhering to operational constraints.

Finally, the paper in [9] evaluates the sustainability of a delivery approach that incorporates electric trucks equipped with drones. A comparative life cycle assessment methodology is employed to compare this alternative with traditional logistics systems. Results demonstrate noteworthy reductions in emissions with the implementation of the truck-drone solution. Furthermore, the cost performance of this approach is primarily influenced by the level of drone automation.

5 HEALTH

One of the most critical applications of drones is the delivery of essential medical supplies, such as blood and organs. This becomes particularly important in situations where traditional modes of transportation, like ambulances, can be hindered by traffic congestion, and every minute lost can have severe consequences. In rural areas, especially in regions like Africa, drones can be effectively utilized to overcome such challenges. Additionally, drones can prove invaluable during pandemics, such as COVID-19 for example, as they can safely deliver self-tests and provide food to infected people during a global lockdown. In the following, we discuss papers that have examined the suitable use of delivery drones to enhance public health, specifically in the context of delivering medications and aiding in pandemic situations. Table 5 and 6 summarize the reviewed papers.

5.1 Medications

Since 2016, Zipline [1], an autonomous drone company, has been delivering blood products to hospitals in Rwanda using their drones called Zips (see Figure 2). The drones fly from a central distribution center to hospitals within a 75km radius, significantly reducing delivery times. Doctors can order blood via WhatsApp, and a drone uses GPS and Rwandan air traffic control to navigate to its destination. Once it arrives, the drone drops the blood pack in a padded container equipped with a parachute, and then returns to the distribution center for a quick battery swap. On the same context, the paper discussed in [107] examines the use of drones for delivering blood products. By analyzing data from 20 health facilities, the study reveals that this system significantly reduces delivery times compared to existing road-based methods. Moreover, drones helped in a notable decrease in blood unit expiration per month. The implementation of drone delivery exhibits the potential to enhance delivery times and minimize wastage of blood products within healthcare facilities. Furthermore, the study recommends future investigations to explore the cost-effectiveness of this approach and evaluate its suitability for transporting other pharmaceutical and healthcare supplies.

Fig. 2. The Zip drone from the Zipline company in Rwanda, Africa.

Scott et al. [128] discuss the potential impact of delivery drones on traditional transportation infrastructure, with a focus on healthcare delivery. The paper reviews leading companies in the field and decision models for operating a drone fleet, and proposes two new models to facilitate the design of a drone healthcare delivery network. It suggests that drone delivery has the potential to overcome accessibility issues in healthcare delivery and improve efficiency and cost-effectiveness.

The article in [88] discusses the potential use of drones for delivering medications and improving healthcare accessibility. It describes the current state of drone technology and the regulatory considerations that need to be considered by pharmacy stakeholders. The article highlights the potential benefits of using drones for medical supply delivery, including faster delivery times, reduced transportation costs, and improved access to medications in remote or disaster-stricken areas.

Table 5. Medications in Package Delivery: Studies and Focus.

Study	Focus	Key Findings and Implications
Ackerman et al. [1]	Blood products delivery in Rwanda	Zipline's drones improve healthcare accessibility, reduce delivery times.
Nisingizwe et al. [107]	Blood product delivery in Rwanda	Drone delivery minimizes wastage, shows potential cost-effectiveness.
Scott et al. [128]	Healthcare delivery	Drones overcome healthcare accessibility issues, enhance efficiency.
Lin et al. [88]	Medication delivery	Drones improve accessibility, reduce costs, and enhance medication access.
Hampson et al. [57]	Organ delivery for transplants	Drones aim for quick and safe organ transportation, increasing transplant success.
Scalea et al. [127]	Human organ delivery	Successful human kidney transport using a drone for transplantation.
Nyaaba et al. [108]	Medical supplies delivery in Africa	Drones offer faster response times, lower emissions, and increased accessibility.
Ling et al. [90]	Broad drone use in medical care	Overview of expanding drone use in healthcare, improving services in remote areas.
Sanfridsson et al. [124]	AED delivery in cardiac arrests	Bystanders perceive AED retrieval via drone as safe and helpful.
Rees et al. [119]	AED delivery using BVLoS drone	Successful AED delivery via BVLoS drone supports regulatory assurance for healthcare use.
Baumgarten et al. [10]	UAV-AED delivery in rural Germany	Simulation study shows feasibility and safety of drone AED delivery in rural areas.
Eichleay et al. [46]	UAVs addressing medical transport challenges	Discussion on UAV utility and introduction of a decision tool for healthcare systems.
Hii et al. [60]	Effects of drone transportation on insulin	Investigation shows no visible negative effects on insulin quality.
Ghelichi et al. [50]	Optimization of drone fleet logistics	Model introduced to optimize drone fleet logistics for medical item delivery.

Drones have been also tested for organ delivery in [57], which is crucial for successful transplants. Delay in organ transportation can affect organ functions. A surgeon at the University of Maryland Medical Center developed a drone delivery system to ensure organs reach their destination quickly and safely, increasing the chances of a successful transplant. Similarly, in the paper in [127] a team designed and built a drone to autonomously carry a human organ for transplantation. They successfully flew the drone 2.8 miles carrying a human kidney for transplant and transplanted it into a patient who showed positive post-operative results. This represents the initial successful transport of a human organ using unmanned aircraft. This achievement has the potential to enhance organ transplantation accessibility and address inefficiencies in the organ delivery system.

Nyaaba et al. [108] reviews the literature on the use of drones for delivering medical supplies, identifying blood, drugs, vaccines, and laboratory test samples as among the items that can be delivered. Challenges include regulation, cost, misuse, and psychological effects, while benefits include faster response times, lower CO_2 emissions, and increased accessibility. The authors suggest that to sustain drone technology in Africa, policies need to be developed, resources provided, communities sensitized, and personnel trained.

The use of aerial drones is expanding to various areas, including medical care, photography, shipping, disaster management, and law enforcement [90]. The broad use of drone technology can accelerate and reduce the cost of technological advances. The use of drones in medical care can improve health care, especially in remote areas, by reducing lab testing turnaround times, delivering life-saving medical supplies/devices just in time, and reducing prescription care costs in rural areas.

Sanfridsson et al. [124] investigate bystanders' experiences in simulated out-of-hospital cardiac arrest situations where a drone delivers an automated external defibrillator (AED). The study finds that bystanders perceive AED retrieval via drone as safe, feasible, and helpful. It suggests that drone delivery of AEDs can facilitate early treatment of cardiac arrest, calling for further research on real-life cases. Similarly, the study discussed in [119] focuses on delivering an AED using a drone beyond visual line-of-sight (BVLoS) in Wales. The drone is equipped with GPS technology, and extensive testing is conducted, including a BVLoS operating safety case and a three-week flight program. The study successfully completes multiple flights with parachute payload drops and achieves a final delivery within a specific time frame. Overall, the study provides valuable evidence to support the regulatory assurance for BVLoS drone use in healthcare, particularly for AED delivery. Additionally, Baumgarten et al. [10] conducted a study to assess the viability of utilizing UAVs for delivering AEDs directly to out-of-hospital cardiac arrest (OHCA) locations in rural Northeast Germany. The simulation study examined the combination of UAV-AED delivery with smartphone-based community first responder (CFR) dispatch. The findings indicate that integrating drone AED delivery into the chain of survival is both feasible and safe, although it still represents an experimental technology. The integration of CFR with UAV-AED delivery has the potential to enhance the accessibility of early public-access defibrillation, particularly in rural areas.

The article in [46] discusses the potential utility of UAVs in addressing medical transport challenges in health systems. It highlights the need to consider various factors, including regulations, stakeholder acceptance, financial resources, human resources, and operational procedures before implementing UAVs in health systems. The authors introduce a UAV delivery decision tool designed to assist decision-makers in the healthcare system. This tool enables them to identify transportation issues and assess the potential benefits and effects of UAVs on the overall health system.

Hii et al. [60] examine the effects of drone transportation on insulin quality. The investigation focuses on examining the effect of temperature and vibration on the integrity of insulin when it is transported via a drone. Results indicate that there is no visible evidence of insulin aggregation or any negative effects on insulin quality after drone transportation. Finally, Ghelichi et al. [50] introduce a model to optimize the logistics of a drone fleet for the delivery of medical items to remote locations. The model incorporates a unique timeslot formulation that schedules and sequences trips to perform deliveries across multiple locations.

5.2 Pandemics

In [33], authors study how perceived risk impacts image and intentions to use drone food delivery services (DFDS) and how COVID-19 affects this relationship. The study shows that different types of risks negatively affected the context before and after the pandemic. The authors suggest implementing a performance guarantee system and live streaming to improve the perception of DFDS. The study provides valuable insights into changes in consumer perceptions of contactless services during COVID-19. Yaprak et al. [148] explore the relationship between consumer perceptions, attitudes, and behavioral intentions towards drone delivery of online orders during pandemics. The authors use various theories as a theoretical background, and collected data through a questionnaire. It also provides insights into the potential for drone delivery systems as a solution for reducing anxiety during pandemics.

The article in [69] explores the influence of COVID-19 on global health and highlights the utilization of drones to automate manual tasks. It examines different solutions, such as using drones

Table 6. Pandemics in Package Delivery: Studies and Focus.

Study	Focus	Key Findings and Implications
Choe et al. [33]	Perceived risk in drone food delivery during pandemics	Various risks negatively affect perceptions of drone food delivery. Suggestions include a performance guarantee system and live streaming.
Yaprak et al. [148]	Consumer perceptions of drone delivery during pandemics	Relationship between perceptions, attitudes, and behavioral intentions towards drone delivery during pandemics. Insights into potential for drone delivery systems to reduce anxiety during pandemics.
Jain et al. [69]	Influence of COVID-19 on global health and drone utilization	Exploration of the influence of COVID-19 on global health and the use of drones for automated tasks, including deliveries. Utilization of drones to address challenges posed by the pandemic in global health.
Flemons et al. [48]	Feasibility of using drones for medical delivery during pandemics	Study on the feasibility and potential cost-effectiveness of using drones for medical delivery to remote communities during pandemics.
Mohsan et al. [100]	Utilizing drones to mitigate pandemic risks	Discussion on multi-purpose utilization of drones, including medical supply delivery, disinfectant spraying, communication broadcasting, surveillance, inspection, and screening to mitigate various risks during pandemics.
Valencia et al. [143]	Factors influencing drone delivery adoption during the COVID-19 pandemic	Investigation of factors associated with drone delivery adoption in Medellín, Colombia, during the COVID-19 pandemic. Identification of factors influencing the intention to use drone delivery during a pandemic.
Lin et al. [89]	Collaborative system for contactless delivery during pandemics	Presentation of a collaborative system for contactless delivery of emergency materials during pandemics, utilizing UAVs and trucks. Efficient contactless delivery system using drones and trucks during pandemics.

for deliveries to promote social distancing and for sanitization purposes. The feasibility of using drones to deliver medical supplies, equipment, and treatment to remote and rural Indigenous communities is studied in [48]. The paper assesses the development of drone fleets and custom payload systems, and conducts simulations for COVID-19 test kit delivery, personal protective equipment delivery, and remote ultrasound delivery. The results indicate that the use of drones for medical delivery is feasible, and offers a potentially cost-effective solution to address health care inequity in remote and rural communities.

The article in [100] discusses how various technologies such as UAVs, artificial intelligence (AI), blockchain, deep learning (DL), IoT, edge computing, and virtual reality (VR) can be used to mitigate the danger of pandemics. The primary emphasis lies in utilizing drones for multiple purposes, including the delivery of medical supplies, disinfectant spraying, communication broadcasting, surveillance operations, inspection tasks, and screening patients for potential infection. In [143], factors associated with the adoption of drone delivery in Medellín, Colombia, during the COVID-19 pandemic are investigated. A survey is conducted on participants, and the study identifies that factors like performance risk, compatibility, personal innovativeness, and relative advantage of environmental friendliness significantly influence the intention to use drone delivery.

Finally, Lin et al. [89] present a collaborative system for contactless delivery of emergency materials during the pandemics, utilizing UAVs and trucks. The system efficiently assigns delivery tasks to multiple trucks, while enabling parallel delivery operations by multiple drones on each truck. The paper focuses on studying the routing problem, and develops an optimal model and a hybrid algorithm to address it.

6 PHYSICS

Drones are battery-powered vehicles with inherent limitations. Their autonomy is restricted, requiring careful consideration during delivery missions. Various factors, including weather conditions and wind, can significantly influence their energy consumption. Moreover, the weight of the packages being carried negatively impacts the energy efficiency. Consequently, researchers have extensively studied the energy models of drones to analyze their effective use in package delivery.

For example, leveraging tailwinds can help extend the mission duration, possibly allowing to perform more deliveries. In the following, we present state-of-the-art papers that propose drone energy models, with particular emphasis on the influence of weather factors on drone missions. Table 7 and 8 summarize the reviewed papers.

6.1 Energy Models

Drones have a limited range due to their battery capacities, but new techniques can be used to optimize their energy consumption and increase their range. An energy model is developed in [106] to estimate the energy consumption based on factors such as payload, wind direction and speed. Strategies are evaluated to identify all reachable destinations, and adding a small amount of perturbation can increase the learning rate. One of the most important results is in [136], where authors explore the potential impact of using drones for package delivery on the energy consumption. Although drones consume less energy than trucks, the inclusion of urban warehouses and longer distances per package contribute to their overall life-cycle impacts. Nevertheless, the environmental footprint of drone-based delivery is generally lower than that of ground-based delivery in the majority of cases studied. Consequently, the research suggests a careful and well-planned adoption of drone-based delivery due to its potential to reduce CO_2 emissions and energy usage in the freight industry.

Table 7. Energy Models in Package Delivery: Studies and Focus.

Study	Focus	Key Findings and Implications
Nguyen et al. [106]	Energy model for drones	Developed an energy model for drones, optimizing consumption and improving range.
Stolaroff et al. [136]	Impact of drones on energy consumption	Explored potential energy consumption impact of drone package delivery, cautioned adoption due to potential reductions in CO_2 emissions and energy usage in freight.
Baek et al. [7]	Delivery scheduling algorithm	Presented a delivery scheduling algorithm considering drone battery level, enhancing efficiency and dependability.
Chen et al. [29]	Battery-aware model for flight time	Proposed a battery-aware model, achieving a 16% improvement in accuracy for estimating drone flight time.
Kirschstein et al. [77]	Energy consumption analysis	Analyzed energy consumption in drone-based delivery, comparing it to diesel and electric trucks in urban and rural settings.
Torabbeigi et al. [141]	Drone delivery scheduling	Developed a drone delivery scheduling model considering battery consumption, preventing unfeasible flight paths.
Zhang et al. [153]	Framework for drone energy consumption	Introduced a framework emphasizing the importance of energy consumption in drone delivery. Highlighted the need for appropriate energy models and further research.
Beigi et al. [11]	Overview of UAV energy consumption	Provided a comprehensive overview of UAV energy consumption research, categorizing factors influencing it and examining different energy models.

Baek et al. [7] present a delivery scheduling algorithm for drones delivery that considers the battery's energy level. The algorithm is designed to optimize delivery quality, throughput, and battery lifespan, recognizing that the amount of energy needed for a delivery task may not match the amount of energy available from the battery due to its state of charge. The approach is accurate and enables drones to transport more packages than conventional delivery models, utilizing the same battery capacity. This results in fewer unexpected drone landings, thereby enhancing the efficiency and dependability of the delivery process. Similarly, authors in [29] propose a battery-aware model to accurately estimate drone flight time. Traditional battery models do not account for the non-linear characteristics of batteries, causing inaccuracies. Indeed, the proposed model demonstrates a significant 16% improvement in accuracy for estimating flight time, which is crucial.

Kirschstein et al. [77] analyze the energy consumption of a drone-based parcel delivery system in comparison to diesel and electric trucks that serve the same customers from a shared depot. Results indicate that in urban areas, a stationary drone-based system consumes more energy compared to a truck-based system. However, in rural settings, the energy demand of a drone-based system is similar to that of an electric truck-based system. The drone delivery scheduling model presented by Torabbeigi et al. [141] incorporates the battery consumption rate as a function of payload. The approach involves strategic planning using a minimum set covering approach and operational planning utilizing a mixed-integer linear program (MILP). The model takes into account battery charge levels to ensure the safe return of the drone. Experimental data verifies that the battery consumption rate (BCR) exhibits a linear relationship with the payload. Neglecting the BCR can render 60% of the flight paths unfeasible.

Zhang et al. [153] introduce a framework that emphasizes the importance of energy consumption in drone delivery operations. The framework helps understand the relationships between key factors and performance measures. The authors conduct a review and categorization of different drone energy consumption models, revealing significant variations in energy consumption rates due to variations in model scope, drone design, and assumed operations. Results show the importance of selecting an appropriate drone energy consumption model and call for further empirical research to ensure accuracy in the design and usage of delivery drones. Finally, the article in [11] offers a comprehensive overview of the present research landscape concerning UAV energy consumption and the factors that impact it. The article categorizes the various factors that influence UAV energy consumption and conducts an examination of different energy models.

6.2 Weather Factors

The paper in [81] considers the effect of wind and UAV battery-power consumption on routing and scheduling. The UAV is allowed to fly at certain air-speeds that optimize airtime, distance flown, or power consumption. Experimental scenarios have been simulated to compare tour completion time metrics with varying wind velocities and delivery points.

Cheng et al. [31] propose a two-period drone scheduling model that adapts to uncertain wind conditions for robust delivery scheduling. The proposed approach aims to mitigate the risk of delivery lateness resulting from uncertain wind conditions by optimizing scheduling decisions in the morning and allowing for flexible adjustments in the afternoon based on updated weather information. By utilizing a cluster-wise ambiguity set derived from wind observation data, this method provides more robust solutions for delivery scheduling. Similarly, Thibbotuwawa et al. [138, 139] present two models for optimizing drone delivery in windy environments. The previous schedules drone deliveries to remote areas using robust optimization that accounts for wind uncertainties. The latter addresses fleet mission planning for large UAVs that considers changing weather conditions, energy constraints, and collision avoidance. Experiments test the impact of mission parameters on customer satisfaction. Both papers aim to provide efficient and effective drone delivery service to customers in challenging environments while optimizing the process.

The paper in [71] proposes a robust drone scheduling model for efficient parcel delivery which considers uncertainties of wind direction and speed using a sensitivity analysis. The model can save operational costs compared to the current practice, especially over longer distances. Validation experiments with real weather data support the proposed model's effectiveness in mitigating wind-related uncertainties.

Betti Sorbelli et al. [15] propose a framework for solving the mission-feasibility problem (MFP) of delivering goods using drones while considering payload constraints, time-dependent cost graphs, and wind effects on energy consumption. The framework includes three algorithms to i) minimize energy, ii) reconsider convenient trips online, and iii) select the best local choices. The algorithms are evaluated on synthetic and real-world data in terms of completed, delivered, and failed missions. The framework has been evaluated by Palazzetti [111] in a case-study showing the effectiveness

Table 8. Weather Factors in Package Delivery: Studies and Focus.

Study	Focus	Key Findings and Implications
Kundu et al. [81]	Wind and battery-power effect	Optimized drone routing and scheduling for enhanced airtime, distance, and power consumption considering wind and battery-power.
Cheng et al. [31]	Scheduling model for uncertain wind conditions	Developed a robust two-period drone scheduling model adapting to uncertain wind conditions, offering more resilient solutions.
Thibbotuwawa et al. [138, 139]	Models for windy environments	Presented models optimizing drone delivery in challenging windy environments, addressing wind uncertainties and fleet mission planning for large UAVs.
Jung et al. [71]	Scheduling model for wind uncertainties	Proposed a cost-effective drone scheduling model considering uncertainties in wind direction and speed, especially beneficial over longer distances.
Betti Sorbelli et al. [15]	Framework for mission-feasibility with wind	Introduced an efficient framework for solving the mission-feasibility problem, considering wind effects on energy consumption in drone missions.
Khanda et al. [75]	Minimizing energy consumption with wind	Developed an approach calculating time-varying routes for drones in multi-depot setups, optimizing delivery routes with reduced energy consumption.
Rigoni et al. [120]	Food delivery considering wind	Examined the impact of wind on UAV speeds during food delivery services, providing insights for enhancing food delivery operations in windy conditions.
Betti Sorbelli et al. [17]	Truck-drone tandem delivery system adapting to wind	Proposed minimum-energy trajectories for drones in a tandem delivery system, considering wind effects and improving the efficiency of delivery operations.
Shahzaad et al. [130]	Framework for drone-based delivery in dynamic weather	Introduced an efficient and adaptable framework for drone-based delivery in dynamic weather conditions, employing a skyline approach and heuristic-based adaptation.
Kirschstein et al. [78]	Impact of weather on energy savings potential	Explored the energy savings potential of drones in relation to customer density and environmental conditions, providing insights for optimized drone usage.
Zhang et al. [152]	Strategy for strong wind conditions	Introduced the SW-CCRP airdrop strategy, adapting the continuously computed release point (CCRP) strategy for accurate cargo delivery by UAVs in strong wind conditions.

of the approach. Similarly, Khanda et al. [75] aim to minimizing energy consumption in drone-based delivery systems. Their approach focuses on calculating time-varying routes for drones in a multi-depot multi-drone setup, considering the influence of wind. To optimize the delivery routes efficiently, a parallel algorithm that updates the routes over time, avoiding the need for complete recomputation, is proposed.

Rigoni et al. [120] examine the application of UAVs for food delivery services and generate a dataset using an open air traffic simulator called BlueSky [61]. Through the simulation, they transform a collection of food deliveries performed by cars into a set of simulated UAV deliveries. Results indicate that UAVs can achieve significantly higher speeds compared to cars in windless conditions, with tailwinds further increasing their speed while headwinds and crosswinds can have a decelerating effect. The paper concludes that air traffic simulators offer a valuable tool for conducting realistic simulations of UAV systems. Moreover, Betti Sorbelli et al. [17] present a truck-drone tandem delivery system where the drone trajectory is adapted to the wind. The authors propose the minimum-energy drone-trajectory problem (MDP) and two algorithms to solve it optimally under different routes of the truck. They also study the feasibility of sending drones with limited battery to deliver packages. The algorithms are evaluated on synthetic and real data, and the model is simulated by BlueSky. The authors claim that their approach can result in minimum-energy trajectories for the drone to serve customers.

Shahzaad et al. [130] introduce a novel framework for drone-based delivery in dynamic weather conditions. The framework employs a skyline approach to identify the optimal set of candidate drone services at the source node. Initially, the services are composed using a deterministic look-ahead algorithm. To adapt to runtime changes, a heuristic-based approach is proposed, which periodically updates the service composition. Through experimental evaluations, the authors demonstrate the efficiency of the approach. A study conducted by Kirschstein et al. [78] revealed that the energy savings potential of drones is affected by structural factors, such as customer density, as well as environmental conditions, including wind and traffic jam. The results suggest that drones have the potential to save energy in rural settings, but their impact is limited in urban areas with high customer density. Moreover, favorable conditions such as calm winds and heavy traffic can significantly enhance the energy-saving potential.

Finally, in [152] the continuously computed release point (CCRP) strategy is adapted for strong wind (SW) conditions, resulting in the SW-CCRP airdrop strategy. This new approach models cargo motion with differential equations and uses an adaptive mutant particle swarm optimization (PSO) algorithm to determine permissible parameter error ranges. Validation experiments show that the SW-CCRP strategy is effective in improving the accuracy of cargo delivery by UAVs.

7 COMMUNICATIONS

Drones face communication challenges during package delivery, particularly in urban environments, where reliable and robust strategies are essential for effective communication. This becomes even more crucial in the presence of unexpected events or traffic congestion, requiring the ability to reroute drones along alternative paths. Various wireless infrastructures, including Wi-Fi, LoRa, and cellular networks, can be utilized to address these communication needs. Moreover, communications are crucial in congested environments to prevent collisions among drones and facilitate efficient deliveries. In the following, we present the state-of-the-art studies in the realm of network communications for drone package delivery. Table 9 summarizes the reviewed papers.

Table 9. Communications in Package Delivery: Studies and Focus.

Study	Focus	Key Findings and Implications
Yang et al. [146]	RTMS for UAV delivery system	Introduced a real-time monitoring system (RTMS) for UAV delivery, enhancing monitoring and control capabilities from the ground station.
Cicek et al. [37]	C-DDP considering communication constraints	Addressed the communication-aware drone delivery problem (C-DDP), proposing a model to minimize flight distance while satisfying communication and time window constraints, enhancing delivery efficiency.
Al et al. [2]	UAVs for content delivery to vehicles	Explored UAVs for content delivery to vehicles in areas with poor communication infrastructure, proposing a caching method for efficient content delivery.
San et al. [123]	UAV delivery system with efficient communication	Introduced a UAV delivery system optimizing logistics through efficient communication, utilizing a concurrent scheduler approach with genetic algorithms for optimized delivery item assignments.
Rahmadhani et al. [114]	Feasibility of LoRaWAN in drone delivery systems	Evaluated the feasibility of LoRaWAN as a secondary communication mode for drone delivery systems, showcasing its potential for semi-real-time telemetry.
Colpaert et al. [38]	Multiple cellular modems in UAVs	Applied multiple cellular modems in UAVs to enhance communication reliability and coverage, achieving significant improvements.
Jo et al. [70]	Inter-drone communication for collision avoidance	Discussed inter-drone communication for collision avoidance, proposing an efficient routing protocol to improve network performance.
Zhou et al. [155]	Low-latency VR delivery system with UAV base station	Proposed a low-latency VR delivery system using a UAV base station, optimizing caching and employing a low-complexity iterative algorithm to minimize latency.
Yaqoob et al. [149]	Fog-assisted congestion avoidance in IoDs	Introduced a fog-assisted congestion avoidance approach for the Internet of Drones (IoDs), achieving large improvements in packet delivery ratio and message overhead cost.
She et al. [133]	Hybrid truck-drone delivery system	Proposed a hybrid truck-drone delivery system, formulating a continuous traffic equilibrium model and optimizing drone routing and truck-drone synchronization for efficient service design decisions.

The paper in [146] discusses a real-time monitoring system (RTMS) for a UAV delivery system that includes two systems: RTMS-GCS for ground control station, and RTMS-onboard for autonomous UAV flight. The system allows for monitoring of the delivery products' status and locations in real-time, in addition to controlling the UAVs' flight from the ground station.

Cicek et al. [37] discuss the communication-aware drone delivery problem (C-DDP), which includes communication quality requirements such as handover and outage constraints in delivery operations using drones. The authors propose a mixed-integer programming (MIP) model to minimize flight distance while satisfying communication and time window constraints, and a GA. The C-DDP can improve the efficiency of drone delivery operations by considering communication constraints. The work in [2], instead, explores the use of UAVs for content delivery to vehicles on road segments with poor communication infrastructure. The authors propose a method that involves caching the content library on the UAV, which changes as new vehicles arrive. The problem is formulated as a mixed-integer nonlinear programming (MINLP) and markov decision process (MDP), with proximal policy optimization used to solve it. Simulations show the superiority of this approach compared to other methods, in terms of operational utility and energy efficiency.

San et al. [123] introduce a UAV delivery system designed to enhance logistics by enabling faster deliveries. The paper focuses on various aspects of the system, including delivery order management, autonomous flight operations, real-time control for UAV flights, and delivery status tracking, facilitated by efficient communication mechanisms. The system employs a concurrent scheduler approach, incorporating a GA to optimize delivery item assignments. Additionally, the authors provide an extensive analysis of appropriate UAV components for delivery purposes and present field tests conducted using the described hardware components.

The challenges faced by drone-based delivery systems due to high power consumption and limited communication range are discussed in [114]. The paper evaluates the feasibility of using LoRaWAN, a low-power wide-area network technology, as a secondary communication mode for drone delivery systems. The study shows that LoRaWAN can be used for semi-real-time telemetry purposes, and can achieve a coverage of up to 8km with a tolerable percentage of packet loss. The study in [38] explores the application of multiple cellular modems in UAVs to enhance communication reliability and coverage during drone delivery operations. By equipping UAVs with multiple modems from different network providers, significant improvements are achieved. The coverage probability at an altitude of 100m is significantly enhanced compared to using a single network, resulting in a substantial increase in performance. Additionally, the size of outage zones is reduced, and the occurrence of harmful handovers is completely eliminated. The findings are based on simulations conducted using a physical-layer simulator and specific aerial channel models.

The paper in [70] discusses the use of inter-drone communication to avoid collisions and improve network performance. An efficient routing protocol is suggested using the Opnet simulator to design and simulate a drone intercommunication network using a mobile ad hoc network. Zhou et al. [155] proposes a low-latency VR delivery system that uses a UAV base station to deliver VR content from a cloud server to multiple ground VR users. The system caches popular VR input data at the base station to reduce backhaul latency, and uses a low-complexity iterative algorithm to minimize latency among all VR users. Results show that the proposed algorithm achieves lower latency compared to other schemes, with caching helpful in reducing latency.

The article in [149] introduces a fog-assisted congestion avoidance approach aimed at achieving smooth message dissemination (SMD) in the context of the Internet of Drones (IoDs). The proposed approach uses a layered model that considers different layers consisting of drones to select the most suitable next-hop node. The experimental outcomes demonstrate the effectiveness of SMD, with large improvements observed in terms of packet delivery ratio and message overhead cost when compared to alternative approaches. Finally, the authors in [133] propose a hybrid truck-drone delivery system in which a truck carries drones which perform the deliveries. A continuous traffic equilibrium model in the form of partial differential equations (PDEs) is formulated to describe optimal drone routing and truck-drone synchronization and communication strategies. An algorithm is devised to solve the PDEs and evaluate the operational cost of the system, providing the basis for optimizing several service design decisions. Simulations show the applicability of the proposed framework.

8 DELIVERIES

In the last decade, a significant number of papers have focused on the use of drones for last-mile package delivery. Therefore, this section encompasses the majority of the surveyed works. While drones have been employed to carry out deliveries independently, it is not always the most optimal approach for delivering goods to customers. Consequently, researchers have begun to explore symbiotic approaches involving other vehicles, including trucks, buses, and trains. In the following, we review the most important papers that examine the delivery of packages using drones exclusively, as well as those that investigate the integration of drones with public transportation systems or trucks. Table 10, 11, and 12 summarize the reviewed papers.

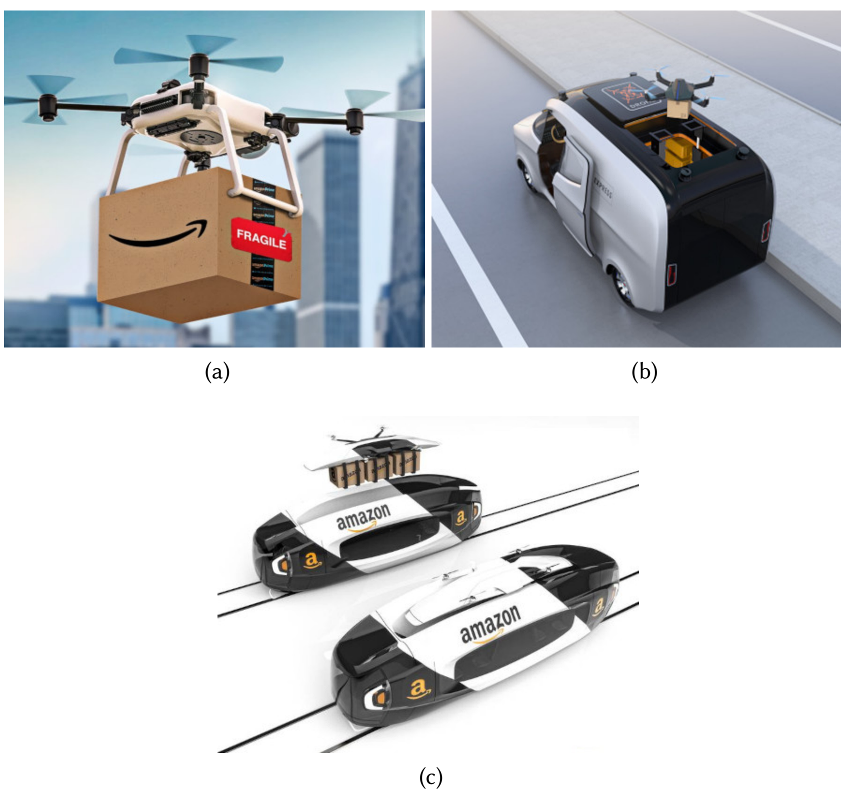

Fig. 3. Different use of drones in package delivery: drones only (a), relying on trucks (b), and relying on public transportation (c).

8.1 Drones Only

Drone delivery has the potential to improve efficiency and overcome last-mile delivery challenges. Cheng et al. [30] propose a branch-and-cut algorithm to address multi-trip operations, recharge planning, and energy consumption calculation. They model energy consumption as a nonlinear function of payload and distance, and incorporate logical and subgradient cuts to optimize routes.

The approach successfully solves large-scale problems and highlights a 9% difference in energy consumption between linear and nonlinear models.

The paper in [62] proposes a new location model for designing a network of recharging stations for commercial drone delivery services in urban areas. The model uses optimization methods to configure station locations and delivery routes for drones. The paper proposed an MIP-based algorithm and an efficient heuristic, and presents results for a large case study in Phoenix, AZ, demonstrating the model's effectiveness and efficiency. The work in [135] focuses on challenging such as limited flight time and cargo weight. So, an MILP approach is proposed to create optimal schedules, and a heuristic is devised to address computational challenges. The effectiveness of the algorithms have been tested using numerical examples focused on delivery in island areas.

Chen et at. [27] discuss the strategic and tactical decisions for e-commerce companies using drones for delivery. A framework based on MDP is developed to determine optimal policies for drone delivery, including decisions on offering drone delivery, delivery capacity, and pricing strategies. The algorithm identifies the fleet size to use for uncertain demand. The study also identifies structural characteristics affecting profit, suggesting retailers prioritize more profitable items and invest in more drones with shorter delivery times. Increasing the promised delivery time threshold and decreasing delivery delay costs can boost net profits.

The paper in [131] proposes a system for long-distance drone delivery, including battery exchange stations and maintenance checkpoints. A drone path model is constructed to minimize the path length and number of landing depots, and an improved ant colony optimization (ACO) algorithm is used to find the sub-optimal flight path. Results show feasibility and effectiveness in a case study in Shanghai. A multi-objective and three-stage stochastic optimization model for drone delivery scheduling, which considers unexpected events and multiple objectives, is proposed in [126]. The system uses the ϵ-constraint method to handle multi-objective optimization, and it is evaluated using a real dataset from Singapore delivery services.

In [44], novel VRPs for drone delivery are introduced to address challenges related to multiple trips to the depot and energy consumption. Two multi-trip VRPs are presented, one focused on minimizing costs within a specified delivery time limit, and the other aimed at minimizing overall delivery time while adhering to a budget constraint. The study derives and validates an energy consumption model for drones, and proposes a cost function that incorporates the energy consumption model and drone reuse. To solve practical scenarios, a simulated annealing (SA) heuristic is employed to find suboptimal solutions, with numerical results highlighting the significance of drone reuse and battery optimization.

The paper in [98] describes a navigation system for autonomous drone delivery that generates a path and controls the drone to follow it using GPS, inertial measurement unit (IMU), and barometer. To enhance landing precision, the system employs marker detection, ultra-wideband (UWB) devices, and an extended Kalman filter algorithm. Additionally, a vector field-based method is utilized to ensure the drone smoothly follows the desired path. Real experiments show that the proposed system is viable for autonomous drone delivery. Lee et al. [83] discuss the benefits of using modular drones for parcel delivery, which can increase fleet readiness and reduce fleet size. An optimization method is proposed for managing a fleet of modular drones, with simulation results showing that it can save time and energy compared to non-modular drones. The paper also highlights the instability of non-modular drones with increasing demand and the need for efficient operation management strategies.

Betti Sorbelli et al. [16, 20] examine a drone delivery scenario where one area permits unrestricted flight while the other requires drones to follow the open space above roads. They utilize a Euclidean-Manhattan-grid (EM-grid) model to determine the optimal distribution point (DP) for the drone, aiming to minimize the total distance traveled while accounting for multiple round trips to and

Table 10. Only Drones in Package Delivery: Studies and Focus.

Study	Focus	Key Findings and Implications
Cheng et al. [30]	Multi-trip drone operations	Developed a branch-and-cut algorithm for multi-trip drone operations, optimizing routes and energy consumption with a 9% energy consumption difference between linear and nonlinear models.
Hong et al. [62]	Recharging station network	Proposed a location model and MIP-based algorithm for efficient design of recharging station networks in urban areas for drone deliveries.
Song et al. [135]	Limited flight time and cargo weight	Utilized a MILP approach to create optimal schedules for drone deliveries, addressing challenges related to limited flight time and cargo weight.
Chen et al. [27]	Strategic and tactical decisions for e-commerce	Developed an MDP-based framework for e-commerce companies to make informed decisions regarding drone delivery, covering aspects like offering drone delivery, delivery capacity, and pricing strategies.
Shao et al. [131]	Long-distance drone delivery	Proposed a system for long-distance drone delivery with battery exchange stations and maintenance checkpoints, demonstrating feasibility and effectiveness in long-distance scenarios using an ACO algorithm for optimal flight paths.
Sawadsitang et al. [126]	Multi-objective drone delivery scheduling	Introduced a three-stage stochastic optimization model for drone delivery scheduling using the ϵ-constraint method, effectively handling unexpected events and multiple objectives.
Dorling et al. [44]	Multi-trip VRPs for drone delivery	Presented novel VRPs for drone delivery considering multiple trips to the depot and energy consumption, addressing challenges related to energy consumption and multiple trips in drone deliveries with an SA heuristic.
Miranda et al. [98]	Autonomous drone delivery navigation	Developed a navigation system for autonomous drone delivery utilizing GPS, IMU, and barometer, along with marker detection, UWB devices, and a vector field-based method for landing precision.
Lee et al. [83]	Modular drones for parcel delivery	Introduced an optimization method for managing a fleet of modular drones, highlighting increased efficiency and reduced fleet size compared to non-modular drones.
Betti Sorbelli et al. [16, 20]	Evaluation of drone delivery scenarios	Examined a drone delivery scenario with unrestricted and restricted flight areas, proposing an EM-grid model for optimal distribution points, providing an adaptable solution outperforming fixed DP approaches.
Kuru et al. [82]	UAV swarms in delivery systems	Conducted an analysis of UAV swarms in delivery systems, employing a dynamic multiple assignment technique for task assignment and 3D route planning, offering guidance for strategic decision-making.
Lee et al. [84]	Centralized framework for routing multiple drones	Presented a centralized framework for routing multiple drones in a drone-dense space, incorporating a drone energy consumption model and collision-free paths considering congestion and battery status, resulting in improved routing success rate and faster routing.
She et al. [132]	Finite element scheme for UAV traffic flow	Proposed a finite element scheme to solve the user equilibrium condition and investigate self-organized UAV traffic flow in low-altitude airspace, assessing operational cost and energy usage for insights into enhancing efficiency and sustainability in last-mile delivery.

from the DP. The authors develop time-efficient algorithms to solve this optimization problem. The results demonstrate that the proposed solution is highly adaptable and outperforms a fixed DP approach in terms of both time and distance covered by the drone.

The paper in [82] studies the use of UAV swarms in delivery systems, analyzing several delivery schemes to optimize the use of UAVs in dynamic environments while considering constraints and regulations. The authors develop a dynamic multiple assignment technique to assign tasks and plan 3D routes for UAV swarms in warehouses, and test several scenarios using simulators with several data sets. This can guide aviation authorities and companies producing UAVs, as well as logistics operators and municipalities in strategic decision-making for implementing UAV delivery systems.

The authors in [84] present a centralized framework for routing multiple drones in a drone-dense space. They use a drone energy consumption model to estimate battery state-of-charge, and generates collision-free paths considering congestion and drone battery status. The proposed method achieves a 6× higher routing success rate, and it is 10× faster than the state-of-the-art methods. It can be applied to delivery routing challenges involving drones with different battery capacities. Finally, the paper in [132] proposes a finite element scheme to solve the user equilibrium condition and investigate self-organized UAV traffic flow in low-altitude airspace. The authors assess the operational cost and energy usage in two distinct test scenarios: a ground-based distribution facility and an airborne fulfillment center. They consider different system configurations and analyze the results to gain insights for enhancing efficiency and sustainability in last-mile delivery.

8.2 Public Transportation and Drones

The paper in [66] introduces a novel drone delivery system that leverages a public transportation network to overcome the restricted delivery range associated with conventional drone-based systems. The authors propose a stochastic model and a label setting algorithm to establish a reliable path for the drone, considering the drone's limited battery capacity. The algorithm is extended to accommodate the feasibility of the path. Through a case study, the authors demonstrate the functionality and intricacy of the proposed system. The article in [73] introduces a new delivery concept called drone delivery using public transport (DDPT) to solve last-mile delivery problems in e-commerce. DDPT utilizes drones to deliver packages on existing public transport vehicles. The study compares DDPT with traditional truck delivery using agent-based simulation models and concludes that DDPT is more efficient and environmentally friendly.

Table 11. Public Transportation and Drones in Package Delivery: Studies and Focus

Study	Focus	Key Findings and Implications
Huang et al. [66]	Drone delivery via public transportation	Stochastic model and algorithm for reliable drone paths. Extended range using public transportation.
Khalid et al. [73]	Drone delivery on public transport (DDPT)	Efficient, eco-friendly last-mile delivery using drones on existing public transport.
Huang et al. [64, 65]	Parcel delivery with public train integration	Optimized system for cost-efficiency and reduced delivery time using public transportation.
Choudhury et al. [35]	Urban drone fleet hopping on public transit	Energy-efficient drones hopping on public transit for large fleet management.
Huang et al. [68]	Drones collaborating with public vehicles	Investigated direct drone delivery and collaboration schemes, optimizing scheduling decisions.
Moadab et al. [99]	Coordinated drone and public transport delivery	VRP-based model for efficient coordination, reducing drones and saving energy.
Huang et al. [67]	Drones transported by buses and trains	Explored optimal round trip paths using public transport, expanding drone delivery range.
Huang et al. [63]	Charging stations and public vehicles for drones	Deployed charging stations, minimized delivery time in remote areas, facilitating drone delivery.

Huang et al. [64, 65] present a novel parcel delivery system that integrates a public train with drones. The system aims to minimize delivery time by formulating an optimization problem and proposing two algorithms. Through simulations, it is demonstrated that this system offers cost-efficiency, reduces delivery time compared to existing schemes, and provides a larger delivery coverage area. Additionally, a simple strategy is proposed to handle uncertainties in the train's timetable, further enhancing the system's functionality.

An algorithmic framework is developed in [35] to manage a large fleet of drones for urban package delivery. Drones conserve energy by hopping between public transit vehicles, and the framework aims to minimize the maximum delivery time through a near-optimal task allocation algorithm. The framework incorporates efficient bounded-suboptimal multi-agent pathfinding techniques for task allocation execution. Experiments conducted in urban areas such as San Francisco and Washington DC demonstrate the framework's efficiency with a significant number of drones, packages, and transit networks, showcasing the drones' ability to travel well beyond their flight range with the aid of public transit.

A parcel delivery system that combines drones with public transportation vehicles is introduced in [68]. The paper proposes two delivery schemes: direct drone delivery and drone-vehicle collaboration. The authors present an exact algorithm and a sub-optimal algorithm. Simulations are conducted to evaluate the scheduling performance of these algorithms and analyze the effects of key system parameters. The algorithms take into account factors such as delivery time, energy consumption, and battery recharging in their scheduling decisions. Moadab et al. [99] propose a last-mile delivery system that coordinates drones with public transportation to deliver orders to customers. A VRP-based model is developed and tested in a real-world case. Results show that using public transportation can reduce the number of required drones and save energy. Efficiency in drone tour planning is influenced by the order in which customers and public transport stations are visited.

The work in [67] proposes using buses and trains to transport drones for package delivery beyond their battery range. The problem of finding the shortest round trip path in a time-dependent network with delivery deadline and energy budget constraints is investigated, and an exact solution algorithm is tested through simulations. Finally, the article in [63] discusses using charging stations and collaborating with public vehicles to enable drone delivery in remote areas. The focus is on deploying charging stations and minimizing delivery time for customer satisfaction. An optimal deployment problem is formulated to minimize average delivery time, and a sub-optimal algorithm is proposed to relocate charging stations in sequence while decreasing average flight distance.

8.3 Trucks and Drones

The paper in [101] proposes an optimal planning of delivery routes using an optimal and heuristic algorithms. The system combines truck and UAV operations, where one or more UAVs travel on a truck, serving as a mobile depot. The optimization model focuses on minimizing customer waiting time and determining the allocation of customers to trucks and UAVs. The truck and drone routing algorithm effectively solves real-world instances, as evidenced by notable reductions in customer waiting time observed in a case study conducted in São Paulo, Brazil.

In the paper [150], the focus is on the truck-based drone delivery routing problem with time windows. The authors propose an improved branch-and-price-and-cut algorithm to effectively address the complex problem. Extensive numerical studies are conducted to evaluate the algorithm's performance and assess the advantages of truck-based drone delivery compared to truck-only delivery. Moshref et al. [102] conduct a thorough comparison of three delivery models that involve synchronized truck-and-drone operations. These models entail launching drones from trucks to perform package deliveries and subsequently bringing them back to the trucks. The study provides formulations for the associated routing problems and establishes theoretical limits on the potential cost savings compared to using trucks alone. Simulations highlight the significant reduction in customer waiting times achieved through increased synchronization.

Gu et al. [53] introduce an operational scheme combining vehicles and UAVs for instant delivery. The study formulates a capacitated set covering location model to determine the optimal number of vehicle stops and their feasible locations. Additionally, a multilevel model is proposed to optimize decisions pertaining to the remaining processes, including the determination of vehicle stop locations, with the goal of minimizing the number of dispatched vehicles and total travel time. The paper further presents two advanced ACO algorithms by incorporating variable visibility and multilevel feedback pheromones. The article in [105] proposes a collaborative truck and drone delivery system that uses truck routes to deploy and retrieve drones for package delivery. Numerical experiments are conducted on a real-world dataset to assess the performance of the proposed system. The results show that the proposed system can improve delivery efficiency and reduce transportation costs.

Table 12. Trucks and Drones in Package Delivery: Studies and Focus.

Study	Focus	Key Findings and Implications
Moshref et al. [101]	Truck and UAV route planning	Mobile depot on a truck, optimizing for minimized customer waiting time. Real-world case study in São Paulo, Brazil. Reduced customer waiting time with effective truck and drone routing.
Yin et al. [150]	Truck-based drone routing	Improved algorithm for complex routing problems. Numerical studies showcase advantages of truck-based drone delivery. Effective solution to routing with time windows.
Moshref et al. [102]	Synchronized truck-and-drone models	Thorough comparison of delivery models with synchronized truck-and-drone operations. Simulations show reduced customer waiting times with increased synchronization.
Gu et al. [53]	Operational scheme for instant delivery	Capacitated set covering location model and advanced ACO algorithms. Minimized dispatched vehicles and total travel time. Efficient operational scheme for instant delivery with minimized travel time.
Najy et al. [105]	Collaborative truck and drone system	Utilization of truck routes for deploying and retrieving drones. Real-world experiments show improved efficiency and reduced costs. Enhanced efficiency and cost reduction with collaborative truck and drone delivery.
Dukkanci et al. [45]	Energy-minimizing drone delivery	Model addressing energy minimizing and range-constrained drone delivery. Second-order cone programming and perspective cuts for computational efficiency. Consideration of energy consumption for operational cost reduction.
Murray et al. [104]	Delivery system with truck and UAVs	Heuristic approach for solving MILP, addressing computational complexity. Quantification of potential time savings with multiple UAVs. Effective solution for practical-sized problems in a delivery system with trucks and UAVs.
Weng et al. [145]	Truck and drone path optimization	Hybrid metaheuristic optimization algorithm for cooperative path optimization in restricted traffic zones. Enhanced delivery time optimization in restricted traffic zones.
Dayarian et al. [41]	Same-day home delivery with drone resupply	Introduction of drone resupply in home delivery. Algorithm development and comparison for effective problem-solving. Advancement of same-day home delivery through regular drone resupply.
Betti Sorbelli et al. [13, 14]	Scheduling for truck and multiple drones	Introduction of SCDP for truck and multiple drones. Algorithms for scheduling considering battery capacity and non-overlapping intervals. Maximization of overall reward with battery and time constraints.
Das et al. [39]	Synchronized drones and delivery trucks	Multi-objective optimization for VRP with time windows. Collaborative pareto ACO algorithm for cost-effective solutions. Efficient solution to parcel delivery logistics through synchronized drones and trucks.
Sajid et al. [122]	Joint-optimization for UAV routing	Hybrid GA and SA algorithm for UAV-routing problem. MinMin algorithm for UAV-route scheduling. Efficient joint-optimization for UAV routing in delivery systems.
Moshref et al. [103]	Delivery model with multiple drones	Extension of traveling repairman problem to include multiple drones launched from a truck. Hybrid algorithm for customer waiting time reduction.
Kitjacharoenchai et al. [79]	Synchronized truck-drone operation	Two-level delivery model for minimizing arrival time of trucks and drones. MIP for small instances and efficient heuristics for larger ones. Effective approach for minimizing arrival time in synchronized truck-drone operations.
Li et al. [85]	Collaborative vehicle-UAV delivery	GA-based model for emergency logistics distribution. Reduction in total distribution cost compared to other delivery models. Efficient reduction of total distribution cost in collaborative vehicle-UAV delivery.
Deng et al. [42]	Vehicle-assisted UAV delivery	Exploration of vehicle-assisted UAV delivery with multi-UAV task allocation. Hybrid heuristic algorithm for optimizing paths. Effective solution for vehicle-assisted UAV delivery considering energy consumption.
Dienstknecht et al. [43]	Extension of TSP for truck and drone delivery	Novel approach extending TSP for truck and drone delivery with changing orders. Optimization applied to static and dynamic scenarios. Efficient solution to truck and drone delivery with extended TSP.

Dukkanci et al. [45] propose a model for addressing the energy minimizing and range constrained drone delivery problem. This model aims to minimize operational costs by explicitly considering the energy consumption of the drone, which is a function of its speed. To solve the problem, the authors employ second-order cone programming and perspective cuts. Computational results are provided using a realistic dataset, allowing for the analysis of the impact of different parameters on location, assignment, and speed decisions. Murray et al. [104] consider a delivery system that uses a truck and UAVs. A heuristic approach is proposed to solve an MILP due to the computational complexity of the problem. The approach solves a sequence of three subproblems, and numerical testing demonstrates its effectiveness for practical-sized problems within reasonable runtimes. Additionally, the study quantifies the potential time savings that can be achieved by utilizing multiple UAVs and examines the effects of different endurance models on UAV assignments.

In [145], authors introduce a path optimization problem for enhancing delivery time in restricted traffic zones. The problem involves optimizing the outer path of the truck and the inner path of the drone in a cooperative manner. To solve this problem, a hybrid metaheuristic optimization algorithm is proposed. Instead, Dayarian et al. [41] introduce the concept of drone resupply in same-day home delivery. A home delivery system is considered where delivery trucks are regularly resupplied by drones. The authors introduce the vehicle routing problem with drone resupply, and analyze it in detail. They develop and compare various algorithms to solve this problem effectively. Additionally, the study quantifies the potential advantages of drone resupply and provides valuable insights to further advance this concept.

Betti Sorbelli et al. [13, 14] propose the scheduling conflictual deliveries problem (SCDP) to explore the interaction between a truck and multiple drones in a package delivery scenario. The SCDP aims to find a scheduling solution for the drones that maximizes the overall reward while respecting the drone's battery capacity and ensuring non-overlapping delivery intervals for each drone. The paper presents an integer linear program (ILP), a pseudo-polynomial time optimal algorithm for the single drone case, and approximation algorithms for both single and multiple drones. The algorithms are evaluated and compared using various synthetic datasets.

The paper in [39] studies a novel mechanism that synchronizes drones and delivery trucks to solve the VRP with time windows and synchronized drones. A multi-objective optimization model is developed with a collaborative pareto ACO algorithm to minimize travel costs and maximize customer service level. Results show that the proposed mechanism is an efficient solution to parcel delivery logistics. Sajid et al. [122] present a joint-optimization framework for UAV-routing and UAV-route scheduling problems in UAV-assisted delivery systems. A hybrid GA and SA algorithm is proposed for the routing problem, while a MinMin algorithm is proposed for the scheduling problem. The effectiveness of the proposed algorithm is evaluated for different numbers of UAVs, and it outperforms baseline algorithms such as minimum completion time and opportunistic load balancing.

In [103], a novel approach is presented that extends the traveling repairman problem to a delivery model incorporating multiple drones launched from each stop location by a single truck to serve customers. The problem is formulated, and a hybrid algorithm combining tabu search and SA is developed to solve it. The findings indicate substantial reductions in customer waiting time compared to conventional delivery models. The paper described in [79] proposes a synchronized truck-drone operation for routing and scheduling. It considers two levels of delivery: primary truck routing and secondary drone routing. The model aims to minimize the total arrival time of trucks and drones at the depot after completing deliveries, accounting for their capacities. The problem is solved using MIP for small instances and efficient heuristics for larger ones, demonstrating the effectiveness of the approach.

In [85], a collaborative delivery path optimization model for vehicles and UAVs is introduced for emergency logistics distribution, which includes a GA to obtain the model solution. The model considers the effects of time window, customer demand, maximum load capacity, and duration of distribution benefits and converts the unsatisfactory degree of time window into a penalty cost. The results show that the proposed model reduces the total distribution cost compared to the vehicle-alone delivery model, the UAV-alone delivery model, and vehicle-UAV collaborative delivery model.

Deng et al. [42] explore a novel vehicle-assisted UAV delivery solution that enables multiple customers to be served by UAVs in a single take-off, while also considering energy consumption. The model incorporates multi-UAV task allocation and vehicle path planning to determine optimal paths for both UAVs and the vehicle. It takes into account the effect of payload variations on energy consumption. To address this problem, a hybrid heuristic algorithm combining an improved k-means algorithm and ACO is proposed. The results highlight the effectiveness of this approach. Finally, the paper in [43] introduce an extension of the TSP. The paper proposes a tour for the truck that encompasses a predefined set of customers, as well as a resupply schedule for the drone, with the objective of minimizing the overall delivery costs. The optimization approach is applied to both static scenarios and dynamic scenarios involving changing orders. Results indicate the effectiveness of the proposed extension.

9 CONCERNS

Drones are widely utilized for package delivery, but their close proximity to customers' places raises concerns regarding privacy violations. As a result, privacy and security have become crucial topics in drone delivery applications. Additionally, safety concerns arise as drones have the potential to crash and cause injuries to people on the ground. So, it is essential to consider and mitigate these risks while ensuring reliable and safe flights during package deliveries. In the next, we survey the most relevant papers addressing security and safety considerations when utilizing drones for delivery. Table 13 and 14 summarize the reviewed papers.

9.1 Security and Privacy

Gupta et al. [54] present VAHAK, an Ethereum Blockchain-based system that uses UAVs for secure outdoor healthcare medical supplies delivery. VAHAK addresses security, privacy, and reliability issues using Ethereum smart contracts and IPFS protocol. It is more efficient than traditional systems in terms of data storage cost, scalability, latency, and network bandwidth. The system has been tested and performs well. Similarly, Cheema et al. [25] propose a blockchain-based drone delivery system that utilizes Ethereum platform for implementation of blockchain and smart contract to register and authenticate participating entities such as products, warehouse, and drones. They also use ML-based intrusion detection system to make communication between the drone and command and control center more secure. The aim is to maintain social distancing while delivering critical applications such as medical supplies, and to prevent impersonation attacks and financial or physical losses.

Singh et al. [134] propose a blockchain-enabled framework for delivering goods via drones during pandemics like COVID-19. Smart contracts ensure secure payments and order processing, while a communication model facilitates the delivery and payment phases. The proposed scheme is evaluated based on gas price, transaction time, and mining time, proving its effectiveness. Furthermore, a security framework for delivery drones using white-box cryptography to protect cryptographic keys and critical data from white-box attacks, is in [129]. The proposed framework is cost-effective and suitable for resource-limited UAVs, providing security functions lacking in current delivery drone systems, which may be vulnerable to physical capture and cyber attacks.

The study in [125] introduces a framework to analyze and enhance the security of drone delivery systems. By formulating a network interdiction game and incorporating prospect theory, the paper shows that subjective decision making can lead to risky path selection strategies and delivery times that exceed the target. The authors in [40] discuss the use of IoT technology in commercial drones for online shopping. They highlight the vulnerabilities of drones and the risk of attacks on confidential information during monetary transactions. A solution is given to secure drone delivery using IoT technology to prevent malicious attacks by hackers and maintain privacy.

Table 13. Security and Privacy in Drone Delivery Systems: Studies and Focus.

Study	Focus	Key Findings and Implications
Gupta et al. [54]	Blockchain-based healthcare delivery	Ethereum Blockchain for secure healthcare delivery. Smart contracts and IPFS for security. More efficient than traditional systems.
Cheema et al. [25]	Blockchain in drone delivery	Ethereum platform for blockchain, smart contracts, and ML-based security. Ensures secure, authenticated drone delivery, preventing attacks.
Singh et al. [134]	Blockchain framework for pandemic drone delivery	Blockchain-enabled framework for secure drone delivery during pandemics. Smart contracts for efficient transactions.
Seo et al. [129]	Security framework for delivery drones	White-box cryptography for key and data protection. Cost-effective, suitable for UAVs. Addresses vulnerabilities and cyber threats.
Sanjab et al. [125]	Security analysis for drone delivery	Framework for security analysis and enhancement. Network interdiction game and prospect theory for better decision-making. Addresses path selection and delivery times.
Das et al. [40]	IoT in commercial drones for secure shopping	Discussion on IoT technology in commercial drones for secure online shopping. Proposes solutions to prevent attacks during transactions.
Alsamhi et al. [3]	Blockchain in multi-drone collaboration	Blockchain for secure multi-drone collaboration. Improves consensus, energy efficiency, and connectivity in swarm operations.

Finally, the paper in [3] proposes a blockchain-based approach to manage multi-drone collaboration during swarm operations. The IoD allows drones to collaborate safely in a restricted airspace for various applications. Drones pose a security risk to swarm coordination techniques, which can lead to unpredictable or disastrous results. The proposed approach aims to improve the security of the consensus achievement process, energy efficiency, and connectivity while exploring the environment in a swarm operation.

9.2 Safety, Risk, and Reliability

The variation of risk beliefs among different segments of the population poses a challenge to the adoption of drone delivery technology. A study in [156] uses latent class analysis to identify four distinct risk belief profiles of US residents towards drone delivery. Attitudes, perceived innovativeness, and expectancy predicted the profiles, emphasizing the importance of targeting the right communication strategies for adoption. Similarly, the paper in [95] examines Indian consumers' attitudes and intentions towards adopting drone food delivery by analyzing the effects of motivated consumer innovativeness (MCI), green image, and perceived risk. Results showed that functionally and cognitively MCI has a significant positive impact on attitude and intention, while perceived privacy risk has a significant negative influence. The study highlights the need for food delivery companies to consider these factors in developing successful drone delivery strategies.

Zhao et al. [154] introduce the robust TSP with a drone to optimize truck-drone delivery in contactless solutions, considering uncertainty and the risk of synchronization failure. A frontier heuristic is proposed to minimize expected makespan while minimizing synchronization risk, offering a considerable reduction in risk with only a small increase in makespan. The solution is effective for assignment decisions in a priori or a posteriori manner. The work in [140] proposes a two-stage programming approach to minimize expected loss of demand in a drone delivery network by considering the reliability of drones. The approach includes a pool solution of feasible paths and the most reliable scheduling to reduce the amount of lost demand. The results demonstrate the impact of reliability on drone scheduling. The study conducted by Magsino et al. [94] focuses on the implementation of a redundant flight recovery system (RFRS) for UAVs used in octocopter delivery or courier applications. The RFRS system ensures fault-tolerance in case of motor breakdown and enables the UAV to switch to a less energy-consuming mode after package delivery. The system utilizes both linear and nonlinear controllers to ensure flight and landing stability. Experiments provide evidence of the feasibility and effectiveness of the RFRS for octocopters.

Table 14. Safety, Risk, and Reliability in Drone Delivery: Studies and Focus.

Study	Focus	Key Findings and Implications
Zhu et al. [156]	Risk beliefs and drone adoption	Latent class analysis reveals four risk belief profiles. Attitudes and innovativeness predict profiles. Targeted communication crucial for adoption.
Mathew et al. [95]	Indian consumers' drone attitudes	MCI positively impacts attitude; privacy risk negatively influences. Factors essential for successful drone strategies.
Zhao et al. [154]	Robust TSP for truck-drone delivery	Frontier heuristic minimizes makespan and synchronization risk. Small makespan increase with considerable risk reduction. Effective for assignment decisions.
Torabbeigi et al. [140]	Two-stage programming for drone delivery	Minimizes expected demand loss by considering drone reliability. Demonstrates impact on scheduling and demand loss. Reliability crucial for minimizing demand loss in drone delivery networks.
Magsino et al. [94]	Redundant flight recovery system for UAVs	RFRS enhances UAV fault-tolerance and stability. Switches to energy-efficient mode after delivery. Feasibility and effectiveness demonstrated through experiments.
Zhu et al. [157]	Public perceptions of drone risks	Network analysis reveals interconnected risk beliefs. Tailoring messages to central beliefs enhances communication effectiveness. Variation in risk belief systems among individuals.

Finally, Zhu et al. [157] explore the interconnected nature of public perceptions regarding the risks associated with drone delivery within a cognitive system. They employ network analysis to examine 11 risk beliefs and uncover the structural connections among them. Additionally, the researchers investigate variations in the risk belief system among individuals with different attitudes toward drone delivery. The results demonstrate that risk-mitigating messages have been particularly effective when they are directed towards risk beliefs that occupy central positions within the network structure.

10 TEST-BEDS AND IMPLEMENTATIONS

While numerous papers have explored the use of drones in delivery, only a limited number of them have successfully implemented their ideas and solutions. In the following sections, we present the noteworthy attempts made by researchers in the field of drone delivery, showcasing their practical implementations and real-world applications. Table 15 summarizes the reviewed papers.

Table 15. Test-beds and Implementations in Drone Delivery: Studies and Focus.

Study	Focus	Key Findings and Implications
Ortiz et al. [109]	UAV content delivery in vehicular environments	Combines wireless access, RaptorQ-protected content diffusion, and UAVs. Effective solution for large-sized content delivery in vehicular environments.
Brunner et al. [22]	Autonomous last-mile delivery in urban areas	Uses off-the-shelf drones, GPS, and visual navigation for last-mile delivery. Prototype tested in simulated and real-world environments.
Chen et al. [28]	IoT-based drone delivery in mixed environments	Integrates GPS, inertial measurement unit, and visual information for collision-free drone delivery. High success rates demonstrated in simulation and in-field experiments.
Kannan et al. [72]	Autonomous household drone delivery system	Utilizes deep learning and semantic image segmentation for precise location estimation. Faster speeds compared to existing strategies in simulated and real-world scenarios.

Ortiz et al. [109] present a solution for content delivery in vehicular environments by combining rapidly deployable wireless access infrastructures with RaptorQ-protected content diffusion and UAVs. The solution aims to address issues of efficiently delivering large-sized content to multiple moving receivers and lack of fixed infrastructures outside main urban areas. The proposed solution has been tested using actual vehicles and UAVs and proved to be effective and efficient.

Brunner et al. [22] introduce an autonomous last-mile delivery system in urban areas using off-the-shelf drones. The system utilizes GPS for approximate delivery location and visual navigation to find the exact drop-off location indicated by a visual marker. The authors built a prototype system and tested it in simulated and real-world environments, opening the source code for future research.

Chen et al. [28] propose a new IoT-based drone delivery system that enables drones to autonomously fly in mixed indoor-outdoor environments for mail delivery. The system integrates GPS, an IMU, visual information, and an autonomous drone control system to avoid problems related to drone collisions. Simulation and in-field experiment results indicate that the proposed system can attain a high user-defined flight success rate without any collisions and can be feasibly used in real-world environments.

Finally, Kannan et al. [72] introduce a system that enables drones to navigate and deliver packages at different locations within a household, eliminating the requirement for external markers. The proposed system utilizes deep learning and semantic image segmentation-based descending location estimation to identify a secure delivery spot around the house. The system's performance was evaluated in simulated environments as well as real-world scenarios with toy examples. The results show that the system achieves faster speeds compared to existing strategies based on frontier exploration.

11 DISCUSSION

In this section, we will delineate the lessons learned from this study, emphasize the remaining and emerging challenges that need to be addressed, and provide insights or guidance on how to overcome them.

11.1 Lessons Learned

It is evident that there is no widespread positive consensus among the public regarding the application and expansion of drone usage, especially in the context of drone-based delivery systems. This sentiment is reflected in numerous surveys conducted worldwide, which have produced diverse outcomes. A notable trend is that younger individuals tend to be more receptive to this new technology. This may be attributed to their familiarity with and acceptance of emerging trends and technologies. On the contrary, older individuals are generally less inclined to welcome the presence of drones overhead, possibly due to a lack of familiarity or comfort with these technological advancements. Understanding these age-related differences in perception is crucial for the successful integration and acceptance of drone-based technologies. Public education and awareness initiatives may play a vital role in bridging the gap and fostering a more positive reception among individuals of all age groups.

Indeed, the integration of UAVs into various industries represents a transformative step towards the future. Just as automotive manufacturers are transitioning towards hybrid and fully electric vehicles to reduce carbon emissions, the use of UAVs presents a promising avenue for mitigating environmental impact. Numerous studies consistently highlight the eco-friendly nature of drones, given their lack of harmful gas emissions, and they also showcase the potential to enhance the efficiency of delivery operations. Despite the existing reservations among the public about adopting drones in delivery services, it is vital to recognize the positive impact they can have on pollution reduction. As online trades continue to grow exponentially, the environmental benefits of drone-based deliveries become increasingly significant. Acknowledging and addressing public concerns, along with highlighting the potential environmental advantages, can contribute to fostering wider acceptance and facilitating the integration of drones into the future landscape of transportation and logistics.

The use of UAVs in the delivery of blood and organs, as exemplified by the Zipline system in Rwanda, Africa, serves as a globally accepted and implemented application with promising outcomes. Several factors contribute to the success and potential of this initiative. Firstly, the lack of suitable or any regular ground transportation systems in rural areas makes aerial service a necessity. UAVs play a crucial role in bridging the transportation gap and reaching underserved regions where access is limited. Secondly, UAVs present a cost-effective alternative to helicopters, particularly advantageous for economically disadvantaged populations. The affordability of drone technology makes it a viable and accessible option for a broader range of communities, ensuring that life-saving deliveries can be made more efficiently. Lastly, the positive reception of drones as carriers for critical cargo such as blood and organs is notable. The emphasis on utilizing drones for humanitarian purposes helps mitigate concerns and fosters greater acceptance within the community. This positive perception underscores the potential for UAVs to not only address logistical challenges but also to positively impact public sentiment when employed for noble and life-saving missions.

UAVs indeed pose significant challenges due to their complexity and susceptibility to various factors, many of which are unpredictable, such as weather conditions. While drones can fly directly from a starting point to a destination to deliver items, they must be highly aware of their surroundings. Moreover, considerations like returning to the depot and accounting for unexpected battery drainage are critical aspects that can impact their flights. One of the primary reasons for public hesitation towards drones is the perceived risk of losing control, potentially causing harm to people. To better understand and mitigate these challenges, numerous studies have been conducted, aiming to characterize the energy models of drones based on known variables like shape, size, and payloads, as well as unknown variables such as wind speed and direction, pressure, and more. While these models contribute to the development of more realistic UAV-based autonomous transportation systems, it is important to note that the physics behind them can sometimes be oversimplified. Researchers are continuously working to improve the accuracy of these models to enhance the safety and efficiency of drone operations. Interestingly, some studies explore leveraging wind effects to optimize drone deliveries, not only as a safety measure but also to expand business opportunities. By incorporating weather aspects into the planning of drone operations, researchers aim not only to safeguard the drones but also to enhance the overall capabilities and feasibility of autonomous delivery systems.

Communication plays a crucial role in drone operations, and various wireless technologies, including cellular, satellite, and proprietary ones, are available. Each technology comes with its own set of advantages and disadvantages, heavily dependent on the specific operational scenario. One of the most extensively researched aspects in this domain is communication congestion. Optimizing message exchanges between drones and the depot during operational deliveries is essential not only to increase the number of deliveries but also to handle unforeseen events, such as collisions with objects or other flying vehicles. However, a notable challenge in these studies is that many have been limited to simulations or small test beds. The reliability of communication is paramount, especially considering potential malfunctions that could have disastrous consequences. Ensuring robust and dependable communication is crucial to the safe and effective functioning of drone delivery systems, particularly when dealing with real-world scenarios and potential emergencies. Continued research and advancements in communication technologies are essential to address these challenges and pave the way for the widespread adoption of drone-based autonomous transportation systems.

The research landscape on drone-based or drone-assisted delivery systems is extensive, with a predominant focus on scenarios where deliveries are executed solely by drones or in collaboration between drones and trucks. In these models, researchers commonly assume that drones can navigate along straight lines, while trucks adhere to established roads. Numerous optimization sub-problems have been proposed, often mirroring classical problems like the TSP, VRP, and/or orienteering problem (OP). However, a noteworthy observation is that only a limited number of researchers have explored the symbiotic relationship between UAVs and public transport vehicles, such as buses, trams, or trains. This perspective emphasizes the recognition that our roads are already inundated with private trucks and cars conducting countless deliveries. There is a growing realization of the potential to leverage public transport vehicles, not only to enhance the efficiency of deliveries but also to alleviate traffic congestion on roads. Exploring collaborations between UAVs and public transport opens up new avenues for optimizing delivery systems in urban environments and addressing the challenges associated with increasing demand for transportation services.

Researchers indeed recognize the significance of security and safety in drone-based delivery systems. Security considerations often involve privacy concerns and ensuring secure transactions between customers and UAVs. To address these issues, several researchers have proposed blockchain-based drone delivery systems. These systems aim to implement secure mechanisms that ensure traceability and robustness, fostering secure interactions throughout the delivery process. Privacy is a crucial aspect, as individuals may have reservations about having drones in close proximity. Consequently, numerous studies are dedicated to investigating and addressing privacy concerns associated with drone operations. Understanding and mitigating these concerns are essential for fostering public acceptance and trust in drone-based delivery systems. Safety is another critical dimension, encompassing the risk and reliability of UAV systems. Researchers have responded to this by proposing fault-tolerance systems to enhance the safety of drone operations. Developing robust systems capable of handling faults or malfunctions is vital to ensure the overall safety and reliability of drone-based delivery services. Continued research in these areas is essential to create secure, private, and safe drone delivery systems that meet the expectations and concerns of both regulators and the public.

The implementation of real UAV-based delivery systems remains a complex challenge, and only a few researchers have attempted to realize such systems in controlled environments. Besides the Zipline system and a handful of others, major companies like Amazon, Google, and DHL are at the forefront of pushing towards the adoption of this technology. Numerous hurdles, including ethical, communication, security, and safety concerns, hinder the widespread deployment of UAV delivery systems. Additionally, regulatory frameworks, or the lack thereof, pose a significant barrier. Specifically, BVLoS capabilities are essential for autonomous delivery systems, and current regulations often restrict testing to confined environments. Despite these challenges, researchers are actively exploring intelligent methodologies, particularly those based on ML, to address various scenarios. ML algorithms can help counteract challenges such as weak or absent GPS signals by enabling drones to reroute and adapt intelligently to changing conditions. As technology advances and regulations evolve, the prospect of real-world implementation of UAV-based delivery systems may become more feasible.

11.2 Open Challenges and Future Directions

The advancement of drone-based delivery systems faces several open challenges across different sub-domains, with a common critical issue being BVLoS operations. The regulatory environment, governed by international agencies like the European Union Aviation Safety Agency (EASA) in Europe or the Federal Aviation Administration (FAA) in the US, plays a pivotal role in shaping the practicality of drone operations. Currently, drones are often confined to visual line-of-sight (VLoS) operations due to regulatory constraints. Implementing UAV-based delivery systems within the operator's sight limits their effectiveness and potential. The airspace regulations are not fully established, presenting hurdles to the practical application of cutting-edge research in this field. BVLoS flights are restricted to specific circumstances, and concerns about disturbances to the population arise, especially when drones fly at low altitudes. Laws and regulations need to evolve to address these aspects, fostering the ethical and practical implementation of drone delivery. Encouragingly, both EASA and FAA are progressively working towards the regulation of standardized BVLoS scenarios. This step-by-step approach aims to create a regulatory framework that accommodates BVLoS flights in various scenarios, paving the way for the potential realization of fully autonomous UAV-based transportation systems in the future.

The sustainability of drones is intrinsically linked to their electric nature, which inherently positions them as green vehicles. However, the overall sustainability picture involves considerations not only about the environmental impact of drones but also the source of electricity that powers them. To enhance the sustainability of drone operations, integrating renewable energy sources like solar panels directly onto drones or using docking stations strategically placed in smart cities becomes a promising approach. This not only aligns with green energy principles but also contributes to safety by providing opportunities for drones to recharge and prevent unexpected battery drainage. Implementing such infrastructure in smart cities could create a sustainable ecosystem for drone operations. The collaboration among different types of vehicles, such as trucks, presents an interesting prospect. Drones could potentially recharge their batteries directly on these ground vehicles, fostering a cooperative and sustainable approach to energy use in the transportation system. This synergy not only contributes to the sustainability of drone operations but also aligns with broader efforts to reduce the overall environmental impact of transportation systems.

Evaluating and enhancing drone energy consumption models is indeed crucial for optimizing their flight time and overall lifespan. The theoretical models developed need validation through both simulations and real-world testing to ensure their accuracy and effectiveness. The development of drone simulators that integrate energy models, battery drainage, and other relevant factors is imperative for advancing research and unlocking new applications. As of now, there is a notable gap in the availability of comprehensive simulators tailored for drone energy consumption studies. Creating sophisticated simulators would enable researchers and engineers to conduct virtual experiments, refine algorithms, and assess the performance of energy-related optimizations. These simulations could serve as valuable tools for testing various scenarios and configurations without the constraints and costs associated with real-world experimentation. In summary, the development of advanced drone simulators specifically designed for evaluating energy consumption models is an essential step towards improving the efficiency and capabilities of drone technologies.

Ensuring reliable and continuous connectivity is indeed crucial for the successful operation of drones, especially in scenarios involving BVLoS drone deliveries. While utilizing the existing cellular infrastructure is a potential solution, obtaining the necessary authorizations for practical implementation can pose challenges. The advent of new technologies, such as 5G and the potential future introduction of 6G, along with satellite infrastructure like low earth orbit (LEO) constellations (e.g., Starlink), holds great promise for addressing connectivity issues. These advanced technologies offer the potential to guarantee continuous communication for drones, even in remote or challenging environments. Implementing such advanced communication systems can enable long-distance deliveries and establish a robust communication network for drones, facilitating BVLoS scenarios. As these technologies continue to evolve, their integration into drone operations could significantly enhance the reliability and efficiency of communication, opening up new possibilities for the future of drone-based delivery systems.

Privacy is also a significant concern in drone delivery operations, particularly when drones interact with private properties during landings. Addressing privacy protection measures is an ongoing challenge that demands careful consideration and regulatory frameworks to safeguard individuals' privacy. Security issues, including the potential threat of jammers and spoofers, pose additional challenges that need to be effectively addressed. Preventing unauthorized interference is crucial to ensure the safe and secure operation of drone-based delivery systems. Furthermore, conducting thorough safety and risk assessments is essential to build public trust and confidence.

Catastrophic events or accidents involving drones could have a profound impact on public perception and acceptance. Demonstrating a commitment to safety through rigorous assessments and adherence to safety protocols is vital for the successful integration of drone deliveries into everyday operations. Overall, a comprehensive approach that considers privacy, security, and safety measures is essential to overcome the challenges and foster widespread acceptance of drone-based delivery systems in society.

12 CONCLUSION

This survey paper has provided a comprehensive overview of drone delivery, emphasizing its opportunities, challenges, and future perspectives. Drones have the potential to revolutionize last-mile delivery, reaching remote locations and enabling time-critical shipments like organs and blood samples. The environmental sustainability of drone delivery, due to reduced emissions, is a significant advantage. On the other hand, limited flight autonomy and establishing a reliable communication infrastructure remain challenges. Collaborative approaches integrating drones with other vehicles enhance efficiency and address issues such as battery life and regulatory compliance. Privacy, security, and safety concerns require careful consideration for responsible implementation.

However, there are still several challenges that need to be addressed to facilitate daily drone-based deliveries. One of the key requirements is the authorization of BVLoS drone operations and the subsequent evaluation and mitigation of risks for people on the ground. Without careful attention to these aspects, the utilization of drones for delivery purposes will remain an elusive goal.

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