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A Bane or Boon of Technologies: Risks and Benefits of Drone Delivery on Last-Mile Operations

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Abstract—**Drones for logistics operations have emerged as a popular topic in logistics, offering numerous benefits and risks to the society and environment. While drones can have a significant impact on the surroundings, the environment and external factors can also influence drone delivery operations, resulting in a complex interplay. This paper combines a comprehensive literature review and co-citation analysis, supplemented by practices, to explore the two-way interaction between drones and the environment. The benefits and risks of this interaction are also examined. A trend analysis is further conducted to generate insights regarding the stages of development in the literature. Combining findings from the reviewed literature and practices, we propose the novel 3R framework to guide future drone delivery adoption in practical operations. This framework highlights the importance of investigating drone delivery models and their respective risks that should be mitigated. Finally, a future research agenda is proposed to inspire further explorations in this rapidly evolving field of last-mile operations.**

Index Terms—**Co-citation analysis, last-mile operations, literature review, risk analysis, societal and environmental impacts, unmanned aerial vehicles.**

Managerial Relevance Statement

In the recent decade, the fast development of drone technology has reshaped the last-mile delivery operations due to its superior reachability and sustainability. Several giant companies have successfully integrated the drone technology into their last-mile operations, like Amazon and UPS, in a variety of industries. Our study has identified the benefits of drone last-mile deliveries, including pollution control (less carbon emissions), societal and psychological impacts (as consumers trust that companies using drones are acting sustainably), and economic development (as drones can promote economic democratization and improve accessibility to essential products or services in rural and underdeveloped areas). These findings can assist in the decision making for engineering managers who plan to introduce this new technology in their business modes, by figuring out whether this new technology suits their organizational goals. Despite the merits and increasing popularity, drones face a list of operations challenges that may hinder their efficient applications in the real world and dampen their practical values. By exploring the interplay between drones and the last-mile logistics environment, we also identify the potential risks for the drone application in last-mile deliveries, such as regulatory restrictions, adverse weather conditions, service agility, disruption to the labor market, inherent limitations (like payload, flight range, battery capacity), and social trust building (safety and privacy concerns of the public), which should be carefully evaluated and considered by companies that aim to introduce this new technology. By further analyzing the four main drone last-mile operational models based on the real practice of four world-leading companies (Amazon, FedEx, UPS, and Walmart), we provide important insights into the practical challenges and opportunities of drone delivery implementation, which can be referenced by other small or medium sized companies in both developed and developing economies. Based on our findings derived from both the literature review and practice analysis, we further propose a 3R framework to offer important managerial and practical insights for decision makers to compare their needs with the impacts associated with each drone operational model, identify the best alignment, and prioritize specific impacts. It is believed that by following the three steps (i.e., reveal, reduce, and reward) as instructed by the 3R framework, engineering managers in the last-mile logistics industry can improve their decision making in the transformation from traditional operations into the drone-facilitated next-generation operations.

I. INTRODUCTION

THE rapid progression of technology has revolutionized our daily life, simplifying tasks across numerous industries [1], [2], including logistics and distribution [3]. Last-mile delivery, the final leg in the delivery process, has become a focal point in the field of logistics due to its unique challenges, such as high labor costs, time sensitivity, urban restrictions, and the demand for personalized services [4]. With increasing consumer demand for faster and greener deliveries, last-mile operations face the urgent need to reduce their carbon footprint while ensuring cost-effectiveness [5], [6], [7], [8].

A study by Accenture indicates that last-mile delivery accounts for over 50% of the total cost of shipping and about 40% of total supply chain costs, with a projected 32% increase in carbon emissions from urban delivery traffic by 2030 without interventions.[1] As consumers become more conscious of supply chain sustainability, 60% of them hesitate to buy from organizations they perceive as non-sustainable.[2] Therefore, technological tools and interventions to address the environmental impact of last-mile delivery activities have become paramount. A prominent solution in both industrial and academic domains involves the deployment of unmanned aerial vehicles (UAVs), commonly referred to as drones, to optimize last-mile delivery operations [9], [10], [11],[12].

Drones address various last-mile delivery challenges such as traffic congestion, reduced lead times, heightened delivery demands, and environmental concerns [13]. By reducing the reliance on human labor [14] and overcoming urban restrictions, drone technology has the potential to transform last-mile delivery operations, making them more cost-effective and responsive to customer needs [9]. Companies worldwide, spanning various sectors, have embraced drone delivery for last-mile operations and gained the benefits of its efficiency[15],[16].

Several prominent companies have successfully integrated drone technology into their last-mile operations. For instance, Amazon's Prime Air service aims to reduce delivery time and increase customer satisfaction [17]. UPS has partnered with Matternet to launch a drone delivery service catering to the healthcare industry [18]. Domino's Pizza has experimented with drone delivery for faster and more efficient food delivery services [19]. Novant Health, a healthcare provider, has employed drones to deliver medical supplies and essential equipment during emergencies, highlighting the versatility and potential of drones in addressing critical last-mile challenges [20].

Despite promising growth, drones face real-world constraints that can limit their performance and efficiency in last-mile operations [21]. These challenges stem from the drones' inherent characteristics or the environment in which they operate. For example, drones rely on battery power with varying capacities [22] and have flight range limitations. Additionally, drones are susceptible to adverse weather conditions, such as snow, hail, storms, or strong winds, potentially resulting in damages, failures [23] and even collisions [24]. These factors necessitate further investigations to determine the safety [25], agility, and resilience of drones in handling diverse last-mile delivery tasks.

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[1] Accenture (2021). The Sustainable Last Mile: Faster. Greener. Cheaper. Available at: https://www.accenture.com/content/dam/accenture/final/a-com-migration/r3-3/pdf/pdf-148/accenture-sustainable-mile-pov.pdf

[2] Capgemini Research Institute (2020). How sustainability is fundamentally changing consumer preferences. Available at: https://www.capgemini.com/wp-content/uploads/2020/07/20-06_9880_Sustainability-in-CPR_Final_Web-1.pdf

A. Motivation

There have been growing interests in drone technologies due to their potential to revolutionize various sectors [26]. As emphasized by [27], the incorporation of robustness and resilience into supply chains is crucial for navigating the complex interplay between technology and environmental factors. While the existing literature has addressed specific aspects of drone technologies, such as operational models [28] and comparative advantages [29], the mutual relationship between drones and the last-mile logistics environment is under-explored. This mutual relationship, as shown in Fig. 1, demonstrates how drone operations and the environment influence one another. For instance, using drones can impact the environment through energy consumption and noise pollution, while environmental factors such as weather conditions, topography, and regulatory frameworks can pose challenges to drone operations. By exploring this dynamic "two-way" relationship, we can identify potential risks and operational challenges such as regulatory restrictions or incentives, adverse weather conditions, service agility, unemployment rate, and social trust building [30].

Moreover, there are numerous controversies around the use of drones in different countries. Drone operations are increasingly regulated worldwide, highlighting the significance of this issue. Regulatory bodies like the Federal Aviation Administration (FAA) in the United States,[3] the European Aviation Safety Agency (EASA),[4] the UK Civil Aviation Authority (CAA),[5] and the Civil Aviation Safety Authority (CASA) in Australia,[6] have developed frameworks addressing commercial drone deployment, laying out guidelines and restrictions on flight paths, proximity to people and vehicles, operator certifications, and more. These regulations underscore the importance of understanding and managing the two-way interaction between drones and our environment. This study aims to explore this under-explored area, adding to the growing body of the literature on technological innovations in last-mile operations. The focus is on examining the interplay between drone technologies and our society and environment, emphasizing the potential risks and challenges associated with adopting drones in last-mile operations.

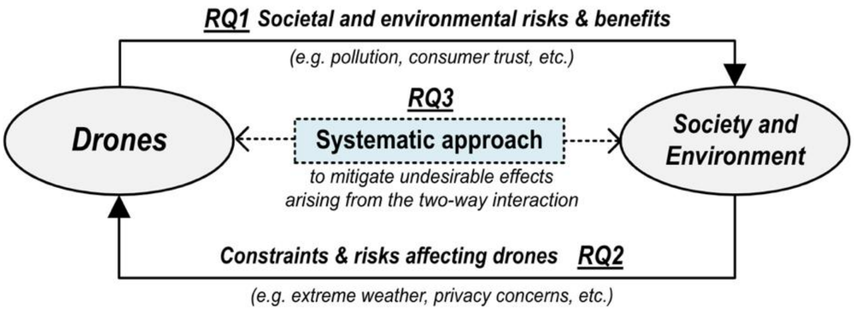

Fig. 1. Two-way interaction between drones, and our society and environment.
(P.S.: RQ1, RQ2 and RQ3 refer to the research questions proposed in Section I.B).

B. Research Questions and Contribution Statement

Motivated by the real-world importance of drones, especially in last-mile logistics and the gaps in the literature, this study aims to answer the following research questions:

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[3] FAA has set rules for commercial drone use, including a requirement that drones must be flown within the operator's line of sight, and a prohibition on flights over people and moving vehicles. More information can be found at: https://www.faa.gov/uas/commercial_operators/

[4] EASA introduced regulations in 2020 to create a harmonized framework for drone operations across member states. The regulations categorize drone operations into three risk-based categories: 'open', 'specific', and 'certified' and set forth requirements for each category. More information can be found at: https://www.easa.europa.eu/domains/civil-drones-rpas

[5] CAA introduced a new regulatory framework for drones in 2021, taking into account the EU's regulations, which include specifications on drone operator registration, pilot competency, and operation in different airspace classes. More information can be found at: https://www.caa.co.uk/drones/

[6] CASA requires commercial drone operators to hold a Remote Operator's Certificate and has set forth rules on operating drones in various environments, including near people and at night. More information can be found at: https://www.casa.gov.au/drones

1) RQ1: How do the advances in drone technologies affect last-mile operations and the corresponding environmental and societal impacts?
2) RQ2: What are the environmental constraints and challenges that influence the performance and efficiency of drone deliveries in last-mile operations (as revealed by the existing literature and real-world examples)?
3) RQ3: Can we establish a systematic framework to optimize drone operations in last-mile settings while accounting for the environmental and societal implications and the associated risks?

Contributions: Addressing the above three RQs, this study makes several important theoretical and practical contributions towards the understanding of drone technologies in last-mile operations: First, we examine how recent advances in drone delivery reshape the last-mile delivery environment, shedding light on the societal and environmental implications of this rapidly evolving technology. This investigation through a systematic literature review with scientific co-citation analysis provides insights into how drone technologies revolutionize the last-mile sector while considering its potential consequences. Second, this study uncovers real-world constraints caused by environmental factors, exploring drone delivery's vulnerability to these constraints. We explain how these constraints evolve into risks through risk analysis and discuss potential long-term effects. These findings are further verified by examining some real practices across various sectors. Third, a framework is proposed to guide effective drone delivery implementation in last-mile settings. This framework considers the unique characteristics and challenges of last-mile operations and provides a way to improve drone delivery operations while considering the constraints and risks identified in the study. Finally, a future research agenda, which includes five research avenues for drone operations, is established.

As a remark, a few prior review studies in transportation and operations management journals have examined drone delivery implementation and operations (see Fig. A1 in *Online Appendix A*). However, their perspectives are fragmented and different from us. For instance, [28] and [31] focus on analytical and optimization models. [32] reviews how socioeconomic factors affect drone operations. [33] and [34] study how environmental factors may affect drone logistics in a one-way examination. Other reviews such as [35], [36], [37] only focus on relatively narrow aspects.

More recently, review studies on drone technology continue to focus on specific yet varied aspects, such as examining facility location problems for drone delivery systems that utilize other vehicles for transport [32], [38], surveying optimization techniques for last-mile delivery with a focus on AI, IoT, and the role of drones in hybrid delivery networks [33],[39] and assessing the common drones limitations while identifying leading drone technology providers and drone types [34], [40]. In contrast to these reviews, this paper distinguishes itself by providing a holistic investigation into the two-way interaction between drone delivery operations and their societal and environmental context, specifically within last-mile logistics. Our integrated methodology combines a comprehensive literature review, a scientific co-citation trend analysis, and an examination of real-world practices to systematically identify and analyze the benefits and risks stemming from this drone-environment interplay. Furthermore, this research proposes the novel 3R (Reveal, Reduce, Reward) framework, offering actionable guidance for drone delivery adoption, and culminates in a detailed future research agenda, thereby providing transportation practitioners and policymakers with a uniquely encompassing and practical understanding of this evolving field.

C. Paper's Structure

The rest of this paper is organized as follows. Section II presents the methods and selection of materials in this study. Section III reviews the impact of drone deliveries on the society and environment, and the real-world constraints and risks associated with drone deliveries. Section IV reports a trend analysis of the related literature on drone-based operations. Section V examines some real practices. Section VI establishes the novel 3R framework for adopting drone deliveries. Section VII presents future research directions. Section VIII concludes this study.

II. MATERIALS AND METHODS

An integrated approach combining literature review and practice analysis for identifying research gaps and developing practical guidance has been employed in various studies [41]. The main rationale behind this approach is to develop the research framework based on a scientific literature review with supplements of real practices from public sources. This approach is particularly relevant for investigating timely issues by consolidating existing findings.

As depicted in Fig. 2, after defining the research scope and focus, the study proceeds with a systematic literature review that examines both aspects of the interaction between drone delivery and its environment. Additionally, current practices of drone technologies implemented by global corporations in the last-mile supply chain sector are examined. Finally, a framework and a research agenda to guide future studies are developed.

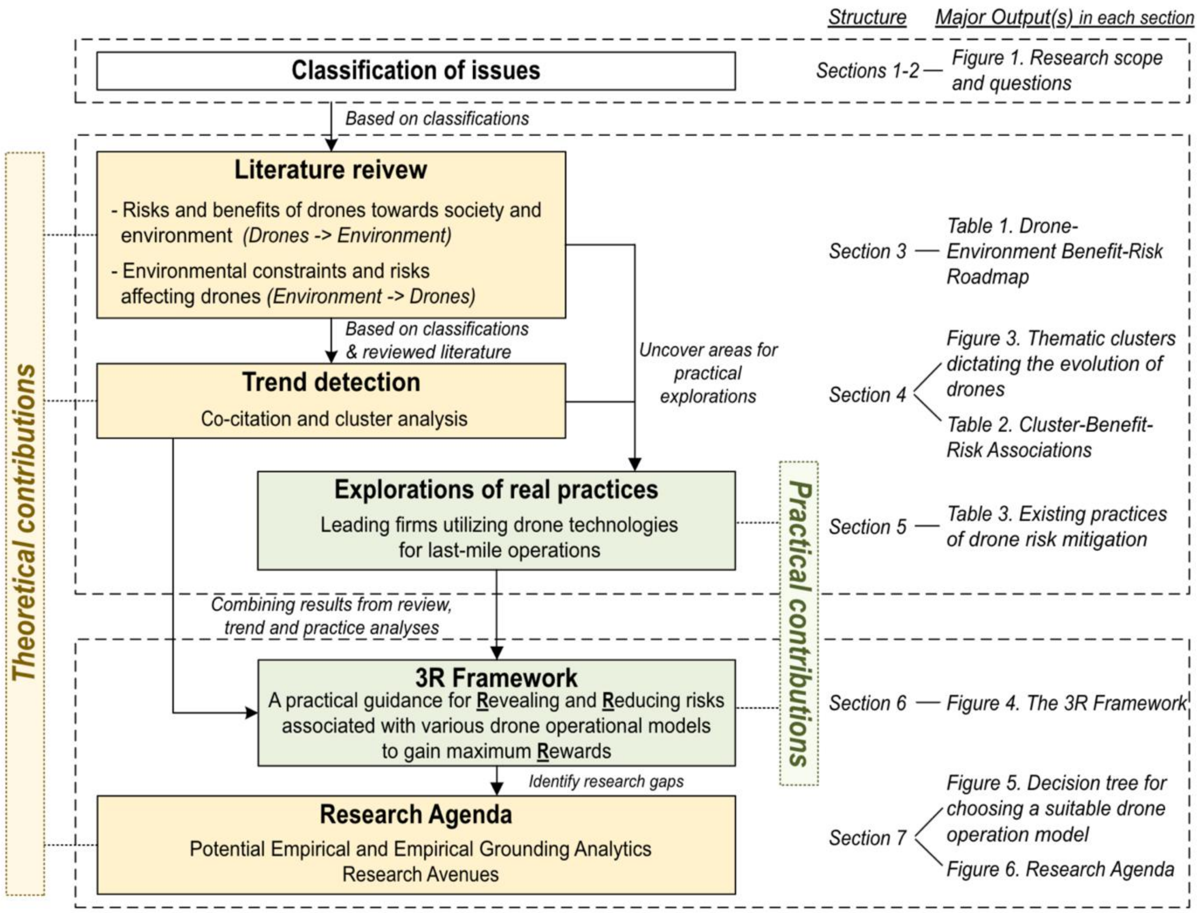

Fig. 2. Overview of the research method and contributions of this study.

A. Literature Review and Trend Analysis

Our systematic literature review comprises four steps [42], as depicted in Fig. B1 in *Online Appendix B*. First, a bibliographic record search is conducted on Web of Science, one of the most authoritative databases for journal papers. Three distinct groups of keywords are employed in the search process. Table B1 displays the full list of keywords utilized for gathering materials. The first group relates to drone delivery, including terms such as "drone delivery", and "unmanned aerial vehicle". The second group consists of keywords representing last-mile operations, and the third group revolves around real-world constraints likely associated with the subject. These keywords are identified by reviewing highly relevant journal articles discussing drone delivery models, environments, and constraints, such as [28], [31], and [43]. The keywords extracted from these journals are then further explored in this study. Both groups of keywords are combined using the "AND" command to ensure the presence of keywords from each group in every paper. The initial step yields 555 papers, which are then filtered using a set of inclusion and exclusion criteria, as shown in Table B2, resulting in a final set of 131 papers for analysis. The 131 papers are manually verified for their relevance and contribution to this study.

Co-citation network approach for rigorous scientific analysis: To scientifically reveal the intellectual structure of drone development in last-mile operations, the co-citation analysis approach is adopted. Note that studying citation metrics longitudinally offers significant insights into the evolution and status of a discipline over time and has been applied in numerous fields including transportation and operations research [44], [45], [46], [47]. In addition, a graphical illustration via the co-citation network can uncover: "*what the most influential citations are for each of the factors, how they are related, how strong their relationships are, and how far removed from, or central to, the factor groups they are*". Thus, rather than following the traditional literature analysis approach, in this paper, we generate a co-citation network based on the final set of 131 papers. The parameters used for the network generation are further discussed in *Section IV.A*. This approach can reveal insights that may not be readily apparent through other methods [42] in a scientifically solid manner.

B. Explorations of Real Practices and Framework Development

To deepen the understanding of real-world constraints, existing practices of various global companies utilizing drones for delivery are examined. This analysis focuses on prominent companies including Amazon, FedEx, UPS, and Walmart. Both literature review findings and practice investigations reveal real-world constraints and their effects on different drone delivery models. In response, a framework is proposed. This framework will help researchers and practitioners better understand the effects of real-world constraints on drone delivery models and contribute to improving the models themselves.

III. LITERATURE REVIEW

This section offers a comprehensive review of the selected papers focusing on the risks and benefits of drone deliveries. We examine the two-way interaction between drone deliveries and the environment, emphasizing the impact of drone delivery models on the environment and vice versa. This analysis is critical for understanding how drones can be integrated into last-mile delivery operations sustainably and effectively.

A. The Impacts of Drone Delivery on Our Society and Environment

The environmental impact of drone deliveries is a critical consideration in the adoption of this technology. From analyzing the 131 papers, we find that pollution control and societal and psychological impacts are the two main areas of focus. These areas are pivotal as they encompass both the direct environmental benefits of reduced emissions and the broader societal acceptance and psychological responses to drone delivery [48]. The discussion synthesizes the contributions of various studies, highlighting their practical relevance to businesses and policymakers.

1) **Pollution Control:** Drones offer an environmentally friendly alternative to traditional delivery methods by using electric power, which significantly reduces carbon dioxide emissions compared to trucks [49]. This makes drones a promising solution for businesses aiming to lower their carbon footprint while meeting sustainability goals.[7] Furthermore, drones operate in the air, allowing them to take shortcuts unattainable by conventional delivery methods [54]. They have a substantial environmental impact since replacing conventional delivery methods with drone delivery decreases global warming potential. [55] support this by stating that careful deployment of drone logistics has a high potential for minimizing greenhouse gas emissions and energy use in

[7] Previous studies have quantified the environmental benefits of drones. For example, as the transportation sector accounts for up to 15% of global carbon dioxide emissions [26], adopting electrically charged drones can significantly contribute to environmental protection [50]. [51] compare truck deliveries and drone deliveries, revealing that drone delivery generates significantly lower CO_2 emissions. These findings have practical implications for businesses looking to reduce their carbon footprint and policymakers seeking to promote sustainable transportation options. [52] stresses the importance of ecological-environmental sustainability in business recovery following the COVID-19 pandemic. Reduced carbon dioxide emissions directly correlate with decreased fuel consumption, making non-fuel-powered delivery methods beneficial for the environment [53].

logistics simultaneously. In an ideal setting, unmanned aerial vehicles consume much less energy, enhancing their environmental benefits and sustainability [32].

2) **Societal and Psychological Impacts:** Drones not only significantly impact the quest for sustainability but also influence consumers and society. As sustainability becomes a global responsibility and global warming a critical issue, many companies have incorporated sustainability into their operations [56]. Consequently, consumers demonstrate environmental responsibility through their consumption habits, opting for eco-friendly products and services [57]. This has psychological ties to drone delivery as the greener option for logistics and distribution. Drone delivery potentially offers consumers peace of mind and trust that the company using drones is acting sustainably [58], benefiting the company's reputation and brand.

   Besides psychological benefits, drones operate outside land-based paths, making it easier to reach areas that are difficult for trucks and other conventional vehicles to access, thereby promoting economic democratization and improving accessibility to essential products or services in rural and underdeveloped areas [29], [59]. [60] provide evidence that drones can efficiently deliver medications to patients in rural Virginia, USA, reducing waiting times. [61] argue that drone delivery is a viable option for medical emergencies due to its ability to quickly reach areas with complicated terrains.

   However, drone delivery poses potential threats to job stability for delivery workers [62]. The widespread adoption of drone delivery may lead to job losses and hinder public acceptance of this technology [63]. A study conducted in Germany reveals that public opinion is a major challenge for drone delivery technology.[8] Most German respondents are not ready to embrace drone technology for deliveries, with 55% opposing delivery via drones. The study also found significant fears about potential accidents causing injuries, with 75% expressing concerns.

3) **Insights on the Environmental, Societal and Psychological Impacts of Drone Delivery:** Drones offer noticeable environmental benefits, positioning them as a sustainable alternative to traditional delivery methods. However, the existing literature overlooks the comprehensive lifecycle impacts, including drone manufacturing, maintenance, and disposal. Additionally, due to the distinct characteristics of each drone operational model, such as Pure Play Drone-Based, Unsynchronized Multi-Modal, Synchronized Multi-Modal, and Resupply Multi-Modal, which will be introduced in Section V, the environmental impacts of each model require further investigation. Future research should address these gaps to develop drone delivery systems that are sustainable and integrative to our environment.

   On the societal and psychological front, drone deliveries can enhance consumer trust and brand reputation by aligning with eco-friendly practices and improving accessibility in remote areas. However, concerns about job displacement and public acceptance persist. There is substantial public apprehension regarding safety and privacy, but in-depth research on strategies to mitigate these concerns and foster public trust is lacking. This motivates us to develop the 3R framework to facilitate firms in identifying suitable drone operational models and mitigate associated risks. Tables C1 and C2 in Online Appendix C respectively summarize existing studies examining the environmental impacts, and societal and psychological impacts of drones.

B. Real-world Constraints and Risks Hindering Drone Delivery Development

After uncovering the environmental impacts of drone deliveries, we then examine the various real-world challenges and constraints that hinder the widespread integration of drones into last-mile operations. The mainstream literature on the interplay between environmental factors and drone technology mainly focuses on external elements, such as severe weather conditions and privacy issues, and the inherent technical limitations of the drones themselves. Revealing and addressing these constraints aligns with the call for innovative business models that manage environmental impacts while tackling the operational challenges in supply chains [64]. Therefore, the review of these constraints holds profound significance for both businesses and policymakers.

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[8] Dronelife (2020). Public Opinion of Drone Delivery? New Study Finds Most Germans Say No Thanks. Available at: https://dronelife.com/2020/07/09/public-opinnion-of-drone-delivery/

1) **External Constraints: Drone Sensitivity Towards Extreme Weather and Privacy Concerns:** Drones, being smaller and airborne compared to land vehicles, are more susceptible to risks arising from extreme weather conditions like heavy rain, strong winds, snow, and hail. This sensitivity to weather poses significant logistical challenges, as it directly affects the reliability and predictability of drone delivery services [65], [66]. Unlike traditional ground-based delivery vehicles that can operate in various weather conditions, drones can be severely impacted by adverse weather, leading to potential delays [67], damage to the drones and the products being delivered, and safety concerns if drones fail in mid-flight [68]. For instance, a drone delayed or damaged by a storm may fail to deliver critical medical supplies on time, resulting in serious health consequences. [69] emphasize that heavy precipitation poses a significant threat to drone delivery's potential, particularly in emergencies where traditional delivery methods may be hindered by traffic jams, road closures, or congested areas. Furthermore, extreme weather can affect the drone's navigation and control systems, making them less reliable [33]. This raises concerns about the feasibility of drone deliveries in time-sensitive situations and may impede adoption in regions with frequently adverse weather.

   Privacy concerns are another external constraint affecting drone delivery. Since drones fly over residential areas instead of following predetermined routes, they may be perceived as trespassing or invading privacy, leading to legal disputes [70]. In densely populated neighborhoods or apartment buildings, drone deliveries may inadvertently compromise the privacy of residents not directly involved in the transaction [71], [72]. Additionally, drones with cameras may inadvertently capture private information or images, further exacerbating privacy concerns [73]. [74] point out that privacy concerns have become significant in drone delivery implementation in the United States, Canada, and the European Union. As technology advances and drones become more sophisticated, [75] argue that new regulations and privacy measures are necessary to address these concerns and ensure proper use of commercial drones. Without such measures, public acceptance and adoption of drones in last-mile delivery may be hindered, turning external constraints into serious risks for overall development and investment in drone delivery technology [34]. Existing studies relevant to real-life external constraints of drone delivery are summarized in Table C3.

2) **Internal Constraints: Drone Flight range and Battery Limit:** While drone delivery offers numerous benefits in terms of costs and environmental impacts, fully transitioning from conventional delivery methods to drone-only delivery faces challenges due to the drones' inherent limitations. Drones face inherent limitations in flight range due to battery capacity, which restricts their ability to complete long-distance deliveries without recharging or support from other vehicles.[9] [34] emphasize that drone technical performance has a substantial impact on public acceptance of drone delivery adoption.

   Since drones operate autonomously without a pilot, there is a risk of damaging or losing the package if the drone runs out of charge during delivery. This contrasts with traditional delivery methods, where drivers can secure the parcel until the vehicle is operational again [79]. This raises questions about the reusability of drones on a single charge and how their usage can be optimized. To cover longer distances and expand coverage from each depot, drones would require multiple recharges [80]. Consequently, implementing proper scheduling strategies, such as optimizing depot placement, charging station locations, or developing hybrid delivery models that combine drone and truck deliveries, would benefit drone logistics [81], [82].

   The literature reviewed shows that strategies are being developed to enhance battery life, optimize flight paths, and improve charging efficiency for drones. However, overcoming internal constraints remains crucial for drone delivery operations to be widely accepted by businesses and society. Without proper operational strategies or breakthrough innovations in drone technology, these internal constraints pose a risk to drone performance, which will, in turn, affect the

[9] [76] find that the average flight range for a fully loaded commercial drone is 3-33km, highlighting power shortage as a significant barrier to drone delivery for longer journeys [77]. This limitation in travel distance is attributed to the drone's battery capacity, allowing only a certain amount of flight range and payload [78].

acceptance of drone delivery operations within companies. Table C4 summarizes existing studies investigating drone's battery life and flight range.

3) **Insights on Real-world Constraints and Risks:** The literature reviewed on the constraints and risks associated with drone deliveries highlights several significant challenges that need to be addressed for successful integrations into last-mile operations. External constraints such as extreme weather and privacy concerns, and internal constraints like flight range and battery limits, present considerable hurdles. We find that the current literature falls short of assessing the performance of each type of drone operational model in relation to internal constraints (battery, range, etc.) and external factors (weather, privacy). To mitigate these constraints and risks, future transportation research should recognize different drone operational models, evaluate and compare their agility and resilience against various external and internal scenarios.

Outcome of this review: Based on our review of the two-way interaction between drone deliveries and the environment, we develop a *Drone-Environment Benefit-Risk Roadmap*, as depicted in Table I, highlighting the positive and negative impacts associated with drone delivery adoption. This roadmap classifies the impacts of drones on the environment and vice versa as either benefits or risks, which influence societal acceptance and adoption of drone delivery. Each positive impact from either side of the interaction is considered a benefit or strength, as it boosts the likelihood of drone delivery being widely accepted. On the other hand, each negative impact from either side of the interaction is considered as a risk, jeopardizing drone delivery adoption and potentially hindering its acceptance by society or businesses. This Drone-Environment Benefit-Risk roadmap will be used in the subsequent trend analysis and real practice analysis to map how literature trends and real practices have or have not addressed these impacts.

TABLE I
DRONE-ENVIRONMENT BENEFIT-RISK ROADMAP

Side of interaction	**Impacts**		**Benefit / Risk**	**Potential long-term effect**
Drones shaping our society and environment (**D**)	DI_1	Pollution control: CO_2 emission reduction	**Benefit**	A decrease in global warming potential Minimizing greenhouse gas emissions
	DI_2	Psychological sense of environmental responsibility	**Benefit**	Better branding and trust building with customers
	DI_3	Economic democracy	**Benefit**	Better economic flow, even globalization
	DI_4	Intimidation of potential job loss	**Risk**	A bigger socioeconomic gap, potential social unrest
Environmental impact on drone delivery (**E**)	EI_1	Weather restrictions: *rain, lightning, strong wind, snow, etc.*	**Risk**	Mid-delivery malfunction and damage
	EI_2	Privacy and security issues	**Risk**	Trespassing charges; Negative public perception
	EI_3	Flight range limit	**Risk**	Inefficiencies in delivery operations; Limited service areas
	EI_4	Battery / Power limit	**Risk**	Mid-delivery malfunction and breakage; Reduced operational efficiency

IV. Trends In Drone Delivery Development

After exploring the literature from two perspectives in Section III, we proceed to drill deeper by conducting a co-citation network-based trend analysis.

A. Generating the Co-citation Network

A trend analysis is conducted through generating a document co-citation network (DCN) from the same set of literature investigated. This approach enables us to identify key trends in drone delivery models and their environments, offering a deeper comprehension of how these literature trends connect to the benefits and risks outlined in the previous section. The network unveils thematic clusters within the scope of this study showcasing the most debated topics over time, which helps contextualize our findings and reveal their priority or importance [42].

Additionally, our trend analysis reveals the evolution of drone development stages, mapping them to the diffusion of innovation theory. This understanding helps us recognize the growth trajectory of drone technologies and their shifts over time. Moreover, it guides our examination of real practices in Section VI, focusing on the aspects most relevant to the current state of drone technologies.

The trend analysis is carried out considering several key parameters, including cluster labeling methods, paper selection criteria, phases of drone delivery evolution, and cluster formation metrics. These parameters ensure the robustness and reliability of our analysis. The detailed parameter settings are provided in *Online Appendix D*. Applying these parameters, a DCN with seven clusters is generated, as visualized in Fig. 3. The color of a cluster indicates its popularity at a certain year over the past decade. A summary of the clusters generated by this analysis is detailed in Table D1.

Drawing from these insights, the following sub-sections discuss the seven most prevalent trends in drone delivery ($T_1 – T_7$) and its two-way relationship with its delivery environment, which are further subdivided into three distinct "stages of drone innovations". It is worth mentioning that these trends, denoted as clusters in Fig. 3, are highly reliable and valid, as each cluster obtained an impressive silhouette index (SI) higher than 0.9.[10] In other words, the seven thematic clusters generated from the DCN are highly separated from each other within the network, indicating a strong validity of these prevalent trends.

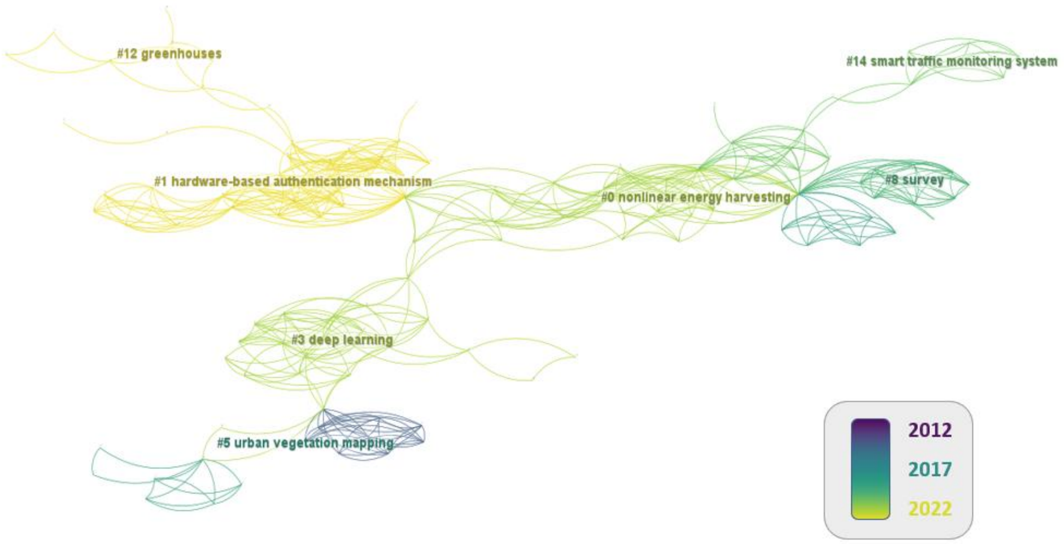

Fig. 3. Seven thematic clusters dictating the evolution of drones.

B. Stages of drone innovations

The visualized trend, which demonstrates an overall growing interest in the subject matter, is presented in Fig. D1. Our trend analysis focuses on three timeframes, which correspond to the stages of innovation as defined by the Diffusion of Innovations Theory [85]: the Innovator stage (2015-2018) when drone development was nascent and captured by a small percentage of the population; the Early Adopter stage (2019-2021) when drone adoption began to increase as influential early users, particularly the firms investigated in the next section, embraced the technology; and the Transition stage (2022-current), marked by a shift from Early Adopters to the Early Majority as the technology gains wider acceptance. Segmenting drone development into several stages allows us to trace the technology's trajectory in the literature. These stages represent the adoption pattern among different groups over time and provide key insights into the evolution of drone usage, its acceptance, and trends associated with each phase.

[10] The silhouette index indicates the degree of certainty of a cluster and its characteristics [83]. A cluster's SI varies from -1 to 1, where a higher value indicates greater separation from other clusters. A clustering network with an average SI in the range of 0.7 to 1 is classified as having a strong structure, which means the cluster well-separates from other clusters [84].

1) Innovator Stage (2015 – 2018): During the Innovator stage, drone development was nascent and captured by a small percentage of the population, resulting in a relatively small number of publications and citations. This stage is characterized by early exploration and experimentation with drone technology, with researchers focusing on the potential applications and capabilities of drones in various contexts. From the DCN in Fig. 3, we discover a cluster during this stage:

a) T_1: Urban vegetation mapping (17 papers; SI=0.998) – The emergence of non-military drone applications began with urban vegetation mapping, which involves identifying urban landscapes to support ecosystem and agricultural planning. Initially combining satellite and drone data, drones soon demonstrated significant potential for detailed vegetation mapping at lower altitudes and at a reduced cost [86]. While commercial drone deliveries were not yet popular during this stage, drones exhibited the ability to navigate complex landscapes accurately, which is a key advantage of drone delivery. Even at this early stage, drones contributed to environmental improvements by providing valuable data for ecosystem development.

2) Early Adopter Stage (2019 – 2021): The Early Adopter stage is characterized by a more substantial increase in publications and citations, reflecting the growing interest and adoption of drone delivery technology by influential users. This stage represents a period of increased experimentation and exploration, with researchers investigating the technical and operational aspects of drone delivery systems. From the DCN in Fig. 3, two clusters are discovered during this stage:

a) T2: Smart traffic monitoring system (7 papers; SI=0.969) – In this stage, drone delivery evolved further by the incorporation of traffic surveillance. Drones played a crucial role in improving societal safety by reducing accidents and ensuring compliance with traffic regulations [87]. Although commercial drone deliveries were not yet a primary focus, the use of drones for traffic monitoring had a positive impact on the environment and society, encouraging advancements in drone technology for delivery purposes. This period also highlighted drones' capability to capture detailed event information.

b) T3: Surveys on drone delivery modeling (10 papers; SI=0.947) – Technically, this stage saw an increased focus on surveys assessing drone communication capabilities and network infrastructure. As drone technology gained popularity for surveillance and delivery, researchers began investigating existing drone communication networks [88].

3) Transition Stage (2022 – Current): Our investigation of real-world practices in Section VI reveals that only dominant firms have invested in and initiated trial drone delivery projects. This observation suggests that the Early Adopter stage persists, characterized by aggressive moves from leading industry players, while gradually transitioning towards the Early Majority stage. In this dynamic period, we observe a surge in the number of clusters, indicating a growing breadth of drone research encompassing a diverse array of topics and areas:

a) T4: Non-linear energy harvesting (36 papers; SI=0.94) – The largest cluster in this study, with 36 papers, explores drone delivery's relationship with energy. In addition to energy efficiency and eco-friendliness, advancements in 2021 allowed drones to wirelessly transmit energy to ground devices within a certain radius [89]. Researchers introduced energy transfer in drones to enable hybrid drone delivery and operation models where drones cooperate with ground devices. Studies in this area focus on designing trajectories considering non-linear energy consumption and drone flight limits.

b) T5: Deep learning (20 papers; SI=0.969) – In 2021, deep learning emerged as a technical trend in drone delivery. Applying deep learning to drones enhances their environmental scanning accuracy and overall performance [90]. Future research on robust drone cameras and sensors could leverage deep learning to help drones navigate adverse weather conditions, such as rain, wind, and lightning. Deep neural networks are also widely used for drone communication [91].

c) T6: Authentication mechanisms (30 papers; SI=0.971) – Since 2022, authentication mechanisms for the Internet of Drones have become the most popular trend and the second-largest cluster, with 30 papers. Security and privacy concerns pose significant challenges to drone delivery adoption, and researchers must consider drone limitations, such as energy constraints and memory capacity, when designing efficient authentication mechanisms [92].

d) T7: Greenhouses (8 papers; SI=1.000) – Environmental benefits of drone delivery are undoubtedly an important topic. Since 2022, researchers have been exploring the use of drones in precision agriculture and greenhouses to further enhance their environmental benefits, address climate change, and improve production efficiency [93]. Drones have proven to be valuable data collectors and efficient automated workers in various applications. However, limitations such as battery life, weather conditions, and payload capacity still need to be considered in these studies.

C. Remarks

1) More "risks" than "benefits"? To further extract insights from the trends identified above, a cluster-impact mapping is performed, as summarized in Table II. It illustrates the correlation between each cluster (Fig. 3) and the impacts (benefits and risks) identified in the literature review section (Table I). The mapping reveals that the risks of drone delivery receive slightly more attention than benefits, with 4 out of 7 clusters relating to risks identified in the literature review. Interesting insights into the associations between clusters and the benefits and risks of drone delivery development are highlighted in Table II.
2) Implications for the existing drone operational models: From our practice analysis discussed in Section V, we identify four mainstream types of drone operational models: Pure Play Drone-Based (PD), Unsynchronized Multi-Modal (UM), Synchronized Multi-Modal (SM), and Resupply Multi-Modal (RM). The identified trends have a direct influence on the design and adoption of these drone operational models. For instance, advancements in non-linear energy harvesting (Cluster T4) and deep learning (Cluster T5) have significant implications for improving drone efficiency and resilience. Energy harvesting technologies can enhance battery life and extend flight ranges, making PD models more viable for longer-distance deliveries. Similarly, deep learning algorithms can improve drones' ability to navigate complex urban environments, enabling SM and RM models to operate more effectively in densely populated areas. However, these advancements also highlight trade-offs between operational efficiency and technological complexity. For example, while integrating deep learning into drone systems can improve navigation accuracy, it may increase costs and require substantial computational resources. Firms must weigh these trade-offs when selecting or adapting operational models to align with their strategic goals.
3) Implications for drone regulatory frameworks: The trends underscore the need for adaptive regulatory frameworks that can accommodate technological advancements while addressing societal concerns. For instance, the growing focus on privacy and security in authentication mechanisms highlights the importance of developing regulations that balance innovation with public safety. Regulatory bodies must establish clear guidelines for data protection, especially as drones equipped with advanced sensors and cameras become more prevalent. Furthermore, advancements in energy efficiency and environmental benefits (Clusters T4 and T7) have implications for sustainability-focused regulations. Policymakers could incentivize firms to adopt greener drone technologies by offering subsidies or tax benefits for energy-efficient operations. At the same time, regulations must address potential risks associated with increased drone usage, such as noise pollution and airspace congestion.
4) Gaps identified from trend analysis: It is noteworthy that two particular impacts, DI2 – the psychological sense of environmental responsibility and EI4 – Battery/Power limit, do not have corresponding clusters in the OM literature. This observation suggests that although some individual papers have examined these topics, there is a lack of a concentrated body of research focusing on these specific aspects. For instance, the absence of a cluster related to DI2 – the psychological sense of environmental responsibility, implies that more research is needed to understand how drone delivery might affect people's perception of their environmental responsibilities. As drone technology advances and becomes more prevalent in society, it is essential to investigate how drones might influence individuals' attitudes and behavior toward the environment. This knowledge could help maximize the potential environmental benefits of drone delivery and ensure that it contributes positively to sustainable development.

Similarly, the lack of a cluster associated with EI4, i.e., Battery/Power limit indicates that this crucial aspect of drone delivery has not received enough attention in the literature. Battery life and power management are critical factors in determining the feasibility, efficiency, and overall performance of drone delivery systems. As drone technology continues to evolve, it is vital for researchers to explore innovative solutions for extending flight range, optimizing power consumption, and enhancing overall energy efficiency. Addressing these issues could lead to significant improvements in drone delivery systems, ensuring their agility and potential for widespread adoption.

The identified gaps serve as the foundation for developing the research agenda. Specifically, the lack of research on DI2 highlights the need for more work on societal and environmental implications of drones, while the gap in EI4 suggests the necessity for analytical work on load and power performance. These insights will inform the comprehensive research agenda established in Section 7 aimed at mitigating the risks associated with drone implementation.

Table II
CLUSTER-BENEFIT-RISK ASSOCIATIONS

Side of the interaction	**Drones shaping our environment (D)**						**Environment's impact on drone delivery (E)**			
Impact	***DI_1*** *Pollution control*		***DI_2*** *Psychological sense of environmental responsibility*	***DI_3*** *Economic democracy*	***DI_4*** *Intimidation of potential job loss*	***EI_1*** *Weather restrictions*	***EI_2*** *Privacy and security issues*	***EI_3*** *Flight range limit*	***EI_4*** *Battery / Power limit*
Benefits (B) or Risk (R)	**B**	**B**	**B**	**B**	**R**	**R**	**R**	**R**	**R**
Associated cluster(s)	***T_4***	***T_7***	***No cluster is found****	***T_1***	***T_2***	***T_5***	***T_6***	***T_3***	***No cluster is found****
Correlation	Extended benefits that relate to energy saving and emission reduction	Exploring advanced ways drones can shape a greener environment	*N/A*	Discussions of how drones reach previously unreachable areas	Drones taking over the human role of traffic security and surveillance	Tackling the extreme weather constraints	Workarounds to privacy and security	Although indirect, surveys about the drone communication network infrastructure investigate how far a drone can fly from where it is controlled	*N/A*

** See Section IV.C - Remarks*

V. REAL PRACTICES

We now investigate the connections between real-world "risks and constraints" and drone delivery models via examining real practices. Note that our exploration of the real-world applications of drone delivery builds directly upon the insights gained from our previous sections. The literature review conducted reveals the impact of drone delivery on the environment, the environment's impact on drone delivery, and the benefits and risks associated with each impact. Trend analysis complements our literature review findings by highlighting the most researched topics within the study scope, indicating high priority or importance. Nevertheless, while these former sections provide theoretical and conceptual insights, they underscore the necessity for concrete real-world relevance. This need is particularly vital in the context of drone last-mile operations, an inherently practical domain. Therefore, our real practice analysis in this section serves to collate empirical evidence from actual operational experiences.

Four global companies are selected from *The World's Most Valuable Brands 2020* list evaluated by Forbes [85]: Amazon, FedEx, UPS, and Walmart. These companies are pioneers in implementing drone delivery and have been investigated through their respective official websites and various verified supporting articles from trusted sources (official news, annual reports, etc.). The main findings from Amazon, FedEx, UPS, and Walmart are summarized in Table III. This table highlights the identified risks and strengths of various drone delivery strategies for each company. When examining industrial practices of drone technologies in last-mile operations, we refer to the four existing drone operational models defined by [28], which have a broad applicability representing the entire spectrum of possible drone deployment strategies currently adopted in practice by the industry:

1) Pure Play Drone-Based (PD) Model: Drones deliver directly to recipients from the depot, fulfillment center, or store.
2) Unsynchronized Multi-Modal (UM) Model: Other delivery vehicles, such as trucks, handle last-mile deliveries for recipients outside the drone's delivery range.
3) Synchronized Multi-Modal (SM) Model: Drones complete the last-mile delivery after being launched from a secondary vehicle or moving hub.
4) Resupply Multi-Modal (RM) Model: Supporting vehicles resupply drones during last-mile deliveries.

It is observed that companies operating with the PD model (Amazon and Walmart) face common risks, such as flight range and load limit. In contrast, UPS, which adopts SM model, experiences fewer concerns regarding flight range due to the collaboration between drones and delivery trucks. Table III also shows that privacy and security risks seem to be the lowest, as all four companies clearly state that they operate within the FAA regulations. The main concerns for last-mile delivery include the drone's capability in making deliveries of longer distances and its load limit without the support of another vehicle like trucks, as well as the operation of smaller last-mile delivery drones in extreme weather. In summary, the practice analysis provides important insights into the practical challenges and opportunities of drone delivery implementation.[11]

Table III
EXISTING PRACTICES OF DRONE RISK MITIGATION ADOPTED BY THE LEADING COMPANIES

Company	**Last-mile drone operating model**	**Risks**					
		DI_4	***EI_1***	***EI_2***	***EI_3***	***EI_4***	Other risks unexplored in the literature
		Potential job loss	*Weather restrictions*	*Privacy, Security issues*	*Flight range limit*	*Battery limit*	
Amazon	PD	▲	▲		√	√	Load limit
FedEx	Unrevealed	▲	√				
UPS	SM		√				
Walmart	PD	▲	▲		√	√	Load limit

▲ ***Middle to low-risk priority****: These risks are primarily speculative, meaning that they are inferred from existing knowledge and past experiences rather than being directly observed or confirmed in current practices. These risks might not demand immediate attention but should be monitored and evaluated as drone delivery operations evolve.*

√ ***High-risk priority****: These risks have been directly observed and documented in the operational practices of companies using drone delivery systems. Addressing these high-priority risks is crucial for ensuring the successful integration and sustainability of drone delivery models.*

VI. The 3R Framework For Drone Delivery Adoption

In recent years, several theoretical frameworks have been applied to evaluate the adoption of drone delivery systems in last-mile logistics. Among them, the Technology Acceptance Model (TAM) has been widely used to understand consumer and organizational acceptance of drone technologies. Studies, such as [95] and [96], have extended TAM by incorporating constructs like environmental friendliness and innovativeness, revealing its relevance in assessing attitudes toward drone delivery adoption. Similarly, the Innovation Resistance Theory (IRT) provides another lens by examining barriers to adoption, including functional challenges (e.g., complexity, cost) and psychological resistance (e.g., risk perception, emotional concerns) [1]. However, both TAM and IRT primarily focus on psychological and behavioral aspects without offering actionable guidance for operational or managerial decision-making.

Based on our examination of the existing literature and real firm practices on drone technologies in last-mile operations, we introduce the 3R framework to guide the adoption of drone delivery. Unlike any existing theoretical frameworks examining drone technology adoption, which focus primarily on psychological or behavioral aspects, the 3R framework provides actionable steps for firms to evaluate operational models, mitigate risks, and quantify

[11] To save space and enhance readability, the detailed discussion of each company's practices is relegated to *Online Appendix E.* Additionally, this practice analysis covers how drones are transforming sectors like agriculture and healthcare.

the benefits of drone adoption. By integrating risk management with benefit realization into a unified framework, practically, firms can balance short-term operational needs with long-term sustainability goals; and theoretically, this framework bridges theoretical insights with practical applications, making it particularly relevant for practitioners navigating the complexities of drone delivery implementation.

As illustrated in Fig. 4, the framework encompasses three elements: "Reveal", "Reduce", and "Reward". We infer that only by carefully revealing and evaluating each possible drone operational model, identifying respective risks to mitigate, and assessing and quantifying expected benefits prior to implementation, can a firm ultimately capitalize on the benefits of drone technologies upon deployment.

We refer to [97] who propose three major classifications of the current last-mile operations that are already established and successfully applied in daily operations: Human-driven delivery vans, Cargo bikes, and self-service. Their survey identifies drones as a near-future concept to be incorporated into these existing classifications of last-mile operations. Our framework extends and generalizes this near-future incorporation by evaluating the risks associated with each model and assessing compatibility with business requirements to achieve maximum rewards. This framework offers important managerial and practical insights for firms to compare their needs with the impacts associated with each operational model, identify the best alignment, and prioritize specific impacts to facilitate the decision-making process. The three steps involved in this framework are shown in Fig. 4.

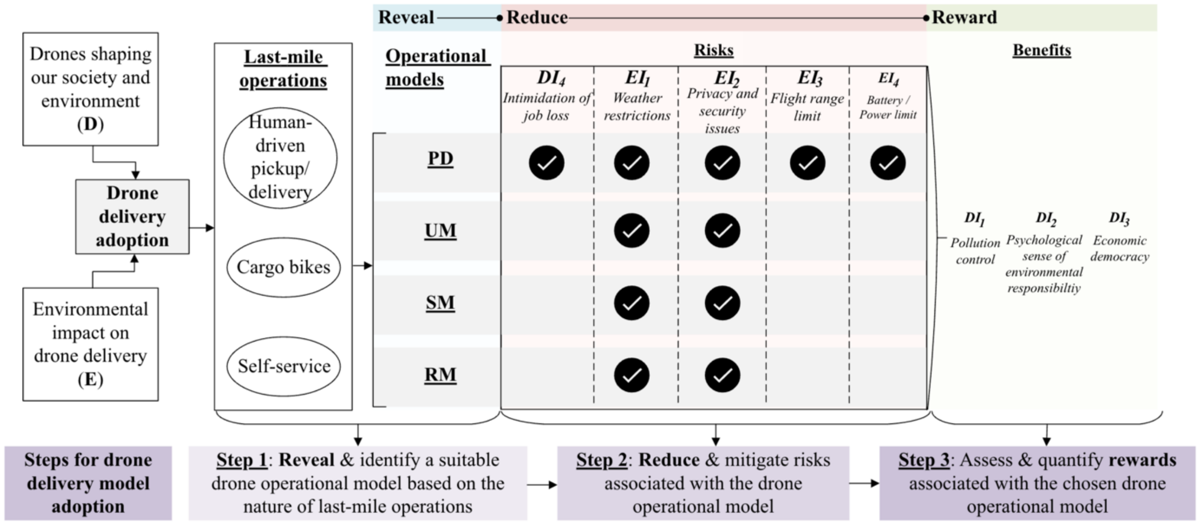

Fig. 4. The 3R Framework.
(Note: PD – Drones deliver directly to recipients; UM – Other vehicles handle last-mile deliveries for recipients outside drone's range; SM – Drones complete the delivery after transported by a secondary vehicle; RM – Supporting vehicles resupply drones during last-mile deliveries.)

A. Step 1. Reveal: Identify and select a suitable drone operational model

The initial step in integrating drone technology into last-mile operations involves revealing the most suitable drone operating model (PD, UM, SM, and RM) that aligns with the firm's existing operations. Current last-mile operations fall under three major classifications [97]:

1) Human-driven delivery vans: Delivery vans operated by humans. These vans serve as a medium to carry parcels from central storage units to customers' doorsteps. Due to its

flexibility in accommodating packages of different sizes and covering varied routes, this approach has become a universally accepted delivery method.

2) Cargo bikes: A green alternative, especially in heavily populated urban areas. These bikes, equipped with special compartments for holding parcels, provide a solution for package delivery that's not only resistant to traffic congestion but also reduces carbon emissions.

3) Self-service: The use of automated lockers or parcel stations where customers can pick up their packages at their convenience. By eliminating the need for doorstep delivery, this model significantly reduces instances of unsuccessful deliveries while providing customers with greater flexibility.

Given these classifications, firms can identify the drone operational model that can be best integrated into their existing setup. For instance, firms using the Human-driven delivery vans model may find the UM, SM, or RM models more suitable as these models rely on a larger vehicle for part of the delivery process. Conversely, those using Cargo bikes or self-service models may consider the PD model, as it aligns with the direct-to-recipient and flexible nature of these operations. A decision tree is presented in Fig. 5 to depict the process of identifying the right drone operation model based on the current last-mile delivery model in use and the operational factors. While the decision tree provides a structured way of approaching the selection, the final decision should be based on a holistic consideration of all factors and circumstances, such as package size, delivery distance, and regulatory constraints.

For SMEs, they require a focused approach to model selection due to resource limitations. Unlike large corporations that can experiment with multiple models, SMEs may benefit from simpler models such as the PD or UM models. These models require fewer infrastructural investments and suit better for firms operating in localized markets or rural areas with less regulatory complexity. For instance, SMEs could partner with third-party logistics providers or technology vendors to access drone delivery capabilities without incurring significant capital costs.

In addition to the type of drone operational models, firms must also evaluate the types of drones available, as their designs and capabilities significantly impact operational efficiency. In last-mile delivery operations, drones can be categorized into three main types based on their design and operational capabilities: rotary-wing drones, fixed-wing drones, and hybrid drones. A comparison between these drone types is summarized in Table IV.

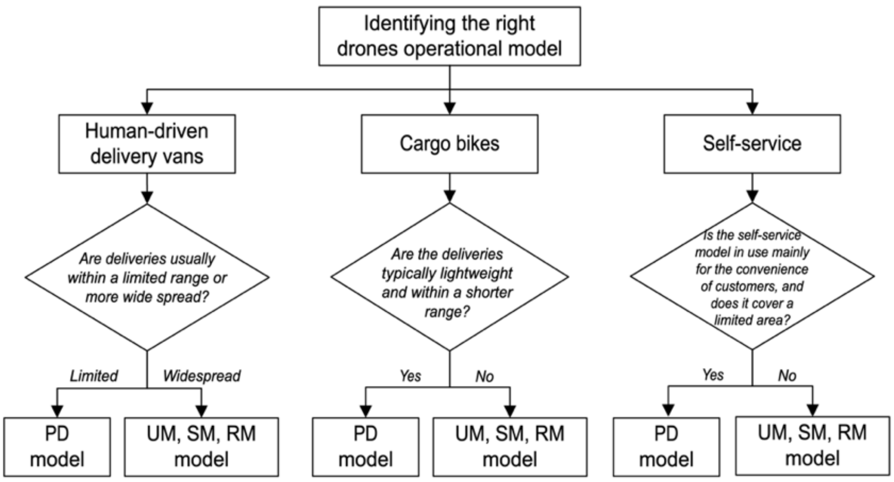

Fig. 5. Decision tree for choosing a suitable drone operational model.

Table IV
COMPARISON OF DRONE TYPES FOR LAST-MILE DELIVERY OPERATIONS

Drone type	Design features	Advantages	Limitations	Applications
Rotary-wing drones	Vertical Take-Off and Landing (VTOL); multi-rotor design (e.g., quadcopters)	Highly maneuverable; ideal for urban areas; can hover and land in tight spaces	Short flight range; limited payload capacity [12]	Urban deliveries (e.g., Amazon Prime Air) [11], lightweight parcels
Fixed-wing drones	Airplane-like design; requires runway or catapult for take-off [98]	Long flight range; energy-efficient; high-speed operation	Requires larger landing/take-off areas; limited maneuverability in confined spaces	Rural and remote deliveries (e.g., Zipline for medical supplies) [14]
Hybrid drones	Combines rotary-wing and fixed-wing features; VTOL with extended range	Versatile for urban and rural areas; balances range and payload capacity; flexible design[12]	Higher operational complexity; potentially higher costs	Mixed-use scenarios (e.g., UPS Wingcopter partnership for multipurpose deliveries[12])

B. Step 2. Reduce: Mitigate risks associated with the drone operational model

Each drone delivery operational model has its own unique risks. In a broader context, the UM, SM, and RM models face similar risks since they all represent different variations of the "truck and drone collaboration" model. However, when selecting a model, we should consider the existing operational model prior to drone delivery implementation and choose one that will facilitate a smoother transition, as all three hybrid models are technically distinct. For SMEs, managing these risks is particularly critical given their limited financial and technical resources.

Regardless of the chosen drone delivery operational model, extreme weather and privacy/security risks are present in every scenario. Until a new breakthrough emerges in drone delivery advancements or regulations, these risks will remain barriers to drone delivery acceptance and adoption.

The PD model encounters three risks not prominently present in other drone delivery models. The first is the flight range and battery limitations, as drones operate independently without support from secondary vehicles, reaching recipients far from the depot or warehouse. Businesses have two options: (1) Open more depots to serve all existing customers with the PD operational model, serve only customers within range and leave the rest to existing delivery options (adopting the UM operational model), or (2) adopt another operational model such as SM or RM. Another unique risk is public concern that drone delivery adoption will eliminate human involvement in commercial deliveries, threatening job security for these workers. While this risk may be present in other operational models, drones do not completely remove the human role since secondary delivery vehicles, which are human-operated, are still incorporated into the delivery process.

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[12] UPS partners with Wingcopter to develop new multipurpose drone delivery fleet. More information can be found at: https://techcrunch.com/2020/03/24/ups-partners-with-wingcopter-to-develop-new-multipurpose-drone-delivery-fleet/

Finally, one drawback of adopting non-PD drone delivery models (UM, SM, and RM) is that the benefits of drone delivery may not be as directly or strongly experienced, especially regarding environmental benefits, since secondary vehicles continue to support drone delivery operations [99].

In this crucial step of risk mitigation, one effective strategy, especially for SMEs, is incremental deployment. Instead of fully transitioning to drone-based operations, firms can begin by integrating drones into low-risk applications such as deliveries in suburban or rural areas where regulatory hurdles are less pronounced. This phased approach allows firms to test the technology while minimizing potential disruptions to their existing operations. Furthermore, to facilitate firms in assessing and mitigating associated risks for actual deployment, we present three Key Risk Indicators (KRIs) in Table V, which can be used in measuring and quantifying risks associated with the drone operational model(s). We suggest firms incorporate these KRIs as part of their risk assessment framework to evaluate risks and prioritize mitigation efforts.

Table V
KEY RISK INDICATORS FOR RISK MEASUREMENT

KRIs	**Description**	**Measurement**
Battery performance metrics	Firms can measure this risk by calculating the percentage of delivery zones within the drone's operational range. A coverage ratio (e.g., percentage of customers served within a 10 km radius) can provide a quantifiable metric to assess whether additional depots or hybrid delivery models (e.g., SM or RM) are needed.	Average flight time per charge, or energy consumption per kilometer/mile.
Weather resilience metrics	Firms can track the number of delivery days lost due to weather-related disruptions over a defined period (e.g., one year). This metric helps assess whether investing in weather-resistant drones or alternative delivery methods is necessary.	Maximum wind speed or precipitation levels under which drones can operate safely.
Privacy violation reports	Firms can measure public acceptance by conducting surveys or focus groups before implementation. Metrics such as the percentage of respondents expressing concerns over privacy or safety can guide targeted communication strategies to build trust.	Number of complaints received from residents regarding drone operations.

C. Step 3. Reward: Realize and quantify expected benefits

The final step in the 3R Framework involves realizing and quantifying the rewards associated with the adoption of the chosen drone delivery system. This process requires assessing the specific benefits that align with the company's strategic objectives and the overall value addition to the delivery environment. To effectively grasp the extent of these benefits, they must be measurable and quantifiable. Notably, drone delivery contributes significantly to pollution reduction, corporate environmental responsibility, economic democracy, and improved delivery services. Examples of how firms can gain, measure, and quantify these benefits are presented below:

1) Pollution reduction: Drone deliveries can drastically reduce carbon emissions compared to traditional delivery means, particularly in short-range deliveries within urban areas. Therefore, firms can measure their carbon footprint reduction by benchmarking the emissions before and after the integration of drones into existing operations. This metric can be expressed as "grams of CO_2 saved per package delivered".
2) Corporate environmental responsibility: The adoption of drone delivery showcases a firm's commitment to care for our environment, a key facet of Corporate Social Responsibility (CSR). Firms can measure this benefit by assessing the change in their Environmental, Social, and Governance (ESG) scores or other CSR ratings after implementing drone deliveries. For example, Amazon's Prime Air drone delivery service showcases their efforts to reduce carbon emissions, a positive move reflected in their sustainability reports.
3) Economic democracy: Drone delivery can provide cost savings and economic efficiency, which can be passed on to customers by offering lower prices or reinvesting into the business. These cost savings arise from reduced fuel consumption and fewer human labor hours. Therefore, firms can evaluate cost savings by comparing fuel expenses, labor costs, and maintenance costs before and after drone adoption. Metrics such as "cost per delivery" or "percentage reduction in last-mile delivery costs" provide concrete evidence of financial benefits. For example, Zipline, a California-based drone delivery service, has used drones to deliver medical supplies in remote areas of Rwanda, saving lives and significantly reducing delivery costs.[13]
4) Improved delivery services and market expansion: Drone technology can facilitate rapid deliveries, often within an hour, which greatly enhances customer satisfaction. The efficiency gain can be measured by the reduction in delivery time compared to traditional methods. Metrics such as "percentage reduction in average delivery time" or "number of same-day deliveries completed" provide clear indicators of improved efficiency. Furthermore, as drones enable access to remote areas previously underserved by traditional logistics methods, firms can measure this benefit using metrics like "percentage increase in geographic coverage" or "number of new customers served".

To ensure these benefits are realized effectively, firms should implement regular performance reviews using dashboards that track these KPIs over time. For example, a dashboard can be used to display daily carbon emissions saved, average delivery times achieved, and customer satisfaction scores. SMEs could focus on simpler KPIs like cost per delivery and geographic coverage expansion to justify their investment in drones.

Firms should also explore creative ways to monetize these benefits. For example, firms, especially the SMEs, could charge premium fees for eco-friendly delivery options or partner with local businesses to share drone infrastructure costs. Smaller firms may also consider

[13] Time (2017). The American Drones Saving Lives in Rwanda. Available at: https://time.com/rwanda-drones-zipline/

leasing drones or subscribing to drone-as-a-service platforms to eliminate the need for large upfront investments.

Finally, it is worth noting that the interplay between risks and benefits requires a holistic approach that considers both short-term operational needs and long-term sustainability goals. We propose two ways of balancing risks and benefits: (1) *Dynamic prioritization*: Firms can leverage scenario analysis to explore how different operational models (e.g., PD model vs SM model) perform under varying conditions. This allows firms to apply dynamic prioritization based on various conditions or requirements. For instance, in urban areas with high delivery density, prioritizing operational efficiency through optimized flight paths may yield greater rewards. On the other hand, in rural areas with limited infrastructure, focusing on environmental benefits by minimizing emissions during long-range deliveries may be more impactful. (2) *Stakeholder engagement*: Firms can collaborate with stakeholders, including customers, regulators, and community groups, to align priorities and build consensus on acceptable trade-offs.

VII. A Research Agenda For Mitigating Drone Implementation Risks

The key research gaps and future research directions in drone technologies for last-mile operations are presented below. Drawing from the findings of our comprehensive review of the existing literature, trend analysis, investigations of real-world practices, and the proposed 3R Framework, we articulate a research agenda to mitigate drone implementation risks in last-mile operations. The research agenda, shown in Fig. 6, comprises five avenues for potential empirical or empirically grounding research in drone last-mile operations, each of which addresses identified research gaps and provides practical insights for industry stakeholders.

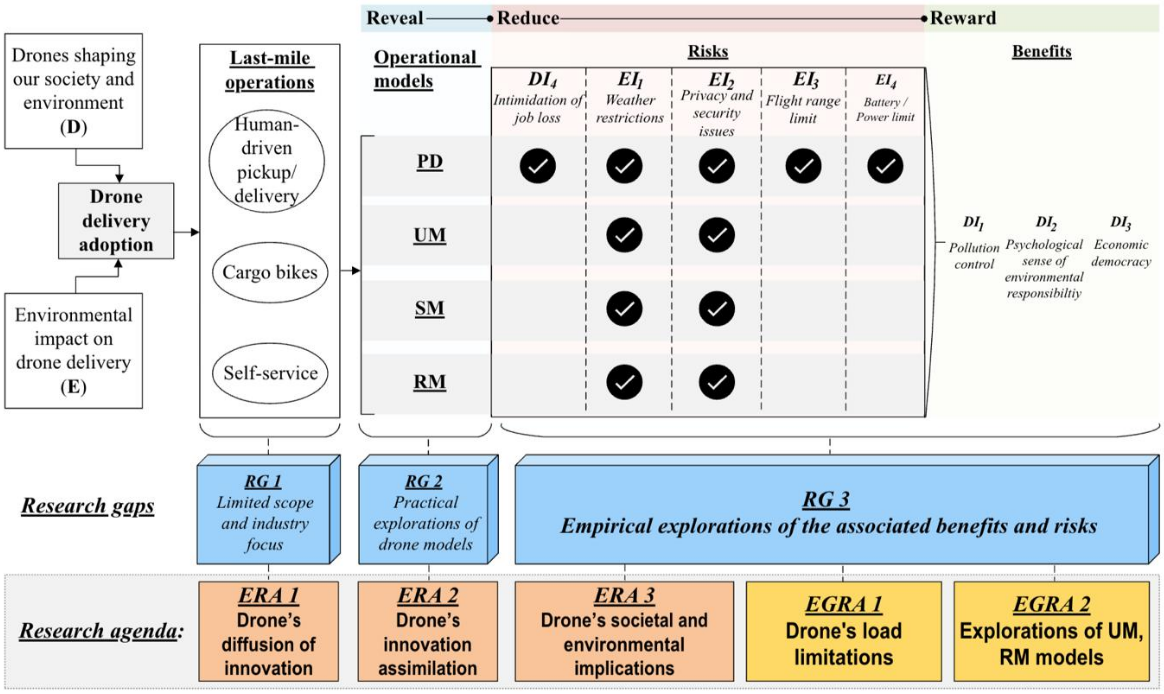

Fig. 6. Research agenda.

A. Research Gaps

Table VI provides an overview of the research gaps between the existing literature and this study's contributions, categorizing them into key issues, outputs, industries, and methods. These research gaps, combined with the findings from previous sections, reveal areas of the study that remain underexplored and point out the future research agenda in a clear direction. The main research gaps (RG) identified include:

1) RG 1 – limited scope and industry focus: Most existing studies on drone delivery focus on healthcare and emergency deliveries [100], leaving a gap in understanding the application of drone delivery in commercial sectors. For instance, DHL has emphasized the need for scalable drone solutions across various commercial sectors, highlighting the importance of expanding research to understand drone applications beyond healthcare. [14] Furthermore, our practice analysis reveals that drone technology adoption predominantly occurs in larger firms within developed countries [101]. Our observations support the implication suggested by [102] that future research on supply chain transformation and technology management should explore the associated challenges in both developed and developing regions, as well as in firms of varying sizes. This would address the existing research gap concerning technology transformations in small firms within developing countries, as noted by [103].
2) RG 2 – practical explorations of all drone operational models: While existing literature discusses various drone delivery operational models (PD, UM, SM, and RM), it mainly focuses on the technical side, such as algorithms and the definition of each model [104]. This study proposes the 3R framework, which takes into account the analyzed risks and their weightage to each business. However, there is still a need for more in-depth risk analysis and practical exploration of UM and RM operational models [105], [106]. This facilitates a more comprehensive understanding of the determinants and implications of innovation assimilation, a key source of competitive advantage [107], [108] involved in last-mile supply chain operations.
3) RG 3 – empirical explorations of drone delivery-associated benefits and risks: Supply chains are particularly influenced by the growth and development of technologies [109]. A comprehensive exploration of drones' benefits and risks is crucial to understanding the potential positive and negative impacts of drone technology in practice. Most existing literature focuses on the environmental benefits of drone delivery, while little attention is given to the constraints and risks that drone delivery systems may face. Topics such as social utility and unemployment are only lightly touched upon, as drone delivery is still a relatively fresh technology in last-mile delivery. DHL's trend report also points out that privacy, noise, and safety remain top concerns in residential areas, necessitating operational compromises in drone route planning[14]. Further empirical studies are needed to explore various dimensions of drone delivery constraints and risks existing in last-mile operations.

Table VI
SUMMARY OF THE EXISTING LITERATURE, THE CONTRIBUTIONS OF THIS STUDY, AND THE RESEARCH GAPS IN BETWEEN

[14] The logistics trend radar. DHL Trend Research. Available at: https://www.dhl.com/content/dam/dhl/global/csi/documents/pdf/csi-logistics-trend-radar-6-dhl.pdf

Elements	Existing literature	This study's contribution	Research gaps
Key issues	Research is restricted to what environmental benefits are to be reaped from drone delivery. Little to no attention is paid on drone delivery constraints and risks.	Highlights the two-way interaction between drone delivery and its environment and discusses both the good and the bad that comes as its consequences/risks.	Some topics in the literature review section are only lightly touched as drone delivery is still a relatively fresh technology in last-mile delivery.
Outputs	Focusing on the technical side of drone delivery, like algorithms and the definition of each drone delivery operational model.	The 3R framework. It is crucial to be able to consider all analysed risks and its weightage to each business.	Lack of risk analysis and practical exploration of other operational models, specifically UM and RM.
Industries	Focusing mostly on healthcare and emergency deliveries.	Focusing on commercial deliveries.	Only a few industries have been explored.
Methods	Dominated by literature reviews and surveys, little to no empirical studies.	A balanced blend of literature review, trend analysis, and real practices to better support the research findings.	More companies are still yet to implement drone delivery.

B. Research Agenda

Based on the research gaps discussed in Table VI and the underexplored areas identified above, we develop Table VII, revealing critical areas of the study that remain underexplored, pointing out the future research agenda in a clear direction. Table VI identifies four types of results: (i) Areas explored only in literature; (ii) Areas explored only in practices, (iii) Areas explored in both literature and practices; and (iv) Empty cells. The design of the research agenda is inspired by the identifications of the empty cells in Table VI, and findings from our review, trend and practice analysis. Consequently, five research avenues are proposed to address underexplored areas and support the 3R Framework.

Table VII
BENEFITS AND RISKS OF EACH DRONE OPERATIONAL MODEL WITH OUR ENVIRONMENT

Models	**Drones shaping our environment (D)**				**Environment's impact on drone delivery (E)**				
	Benefits			***Risks***					
	DI_1	***DI_2***	***DI_3***	***DI_4***	***EI_1***	***EI_2***	***EI_3***	***EI_4***	***EI_5***
	Pollution control	*Psychological sense of environmental responsibility*	*Economic democracy*	*Intimidation of potential job loss*	*Weather restrictions*	*Privacy and security issues*	*Flight range limit*	*Battery limit*	*Load limits*
PD	O	O	O	O	O	O	O	O	√

UM	▲		▲		▲	▲	▲	▲	
SM	O		O		O	O	√	√	√
RM	▲		▲		▲	▲	▲	▲	
Areas explored in: ▲ *existing literature* √ *practice* O *both literature and practice*									

The first three are Empirical Research Avenues (ERA) that support the existing body of theories, including, but not limited to, the technology acceptance model, diffusion of innovation theory, innovation assimilation theory, institutional theory, triple bottom line framework, resource-based view theory, dynamic capabilities theory and stakeholder theory:

1) ERA 1 – drone's diffusion of innovation across diverse contexts: The dominance of literature reviews and surveys in existing research has left a gap for empirical studies in the context of drone delivery in last-mile operations across various settings. Future research should incorporate empirical studies that explore the real-world application and performance of drone technologies in diverse industries, varying firm sizes, and both developed and developing regions. These studies could focus on case studies, experimental setups, and pilot projects, offering managerial insights into the factors influencing technology acceptance [110] and diffusion of drone operational models.
2) ERA 2 – drone's innovation assimilation: The overall process of invention, adoption, and deployment of new technology, often referred to as innovation assimilation (IA) [111], is rooted in a broad spectrum of inter-organizational connections [112] extending beyond the boundaries of single firms [113]. Drawing from the institutional theoretical perspective, external institutional pressures drive firms to engage in innovation assimilation [108]. Given that drone technology is in the early stages of adoption for last-mile operations, further research could offer a more comprehensive and thorough comprehension of organizational preparedness for drone innovation assimilation, as well as the influence of drone innovation assimilation on a firm's supply chain prominence in relation to financial and operational outcomes such as cost, quality, and adaptability.
3) ERA 3 – drone's societal and environmental implications: Consumers are increasingly concerned about how firms address societal and environmental impacts in their supply chain practices [114]. As DHL's trend report has noted, the consequences of drone technology adoption in last-mile logistics remain underexplored[14]. To this end, future studies can build on the Triple Bottom Line, Resource-Based View, Dynamic Capabilities, and Stakeholder theories. Detailed discussions of these theories and their implications can be found in *Online Appendix F*.

The final two research avenues are identified from the underexplored areas discovered in I V focusing on empirically grounding analytics (EGA) research. This analytical approach led by empirical findings is particularly valuable in operations and supply chain management, as it effectively combines data-rich practical settings with decision models that expose key variables, ultimately contributing to a deeper theoretical comprehension of the underlying operational system processes and improved managerial decision-making [115]. With this in mind, we present two Empirical Grounding Research Avenues (EGRA) related to drone technology in last-mile operations:

1) EGRA 1 – load and power limitations of drones: Analyzing load and power limitations in drone last-mile delivery requires data-driven insights and analytical/optimization models. Researchers can collect empirical data on the load capacities and battery performance of drones used by companies like Amazon and Walmart. Integrating these data with models can help identify factors influencing last-mile delivery efficiencies. This can contribute to an improved understanding of the relationships between drone design, operational constraints, and customer demands, leading to better decision-making in drone deployment.
2) EGRA 2 – UM and RM operational models in the last-mile sector: Researchers should investigate the practical applications and performance of UM and RM models in real-world last-mile delivery operations. This involves collecting empirical data from companies using these models and evaluating their strengths and weaknesses compared to PD and SM models. Combining these data with analytical models can uncover reasons for the industry preference for PD and SM models and highlight the potential benefits of UM and RM models. This EGA approach bridges the gap between theory and practice, providing valuable insights for both academia and industry.

VIII. CONCLUSION

Drone delivery, particularly in last-mile applications, has garnered significant interests in both academia and industry due to its potential for contactless and eco-friendly deliveries [116]. This study examines the two-way relationship between drones and the last-mile environment by evaluating the existing literature, performing trend analysis, and analyzing real practices from Amazon, FedEx, UPS, and Walmart. The investigation uncovers three main benefits of drone delivery: pollution control, a psychological sense of environmental responsibility, and economic democracy. Conversely, five risks are identified: potential job loss, extreme weather, privacy and security concerns, flight range limitations, and battery/power constraints. This study reveals that the double-edged nature of drone delivery is reflected in the different risks faced by various operational models.

The Reveal-Reduce-Reward Framework is proposed as a practical guideline to navigate the dual nature of drone technologies by choosing the most suitable operational model. This framework assists practitioners in making informed decisions about which model best aligns with their unique operational requirements by considering three steps: Identify, Mitigate, and Gain. This structured approach aids in maximizing the benefits while minimizing the risks associated with drone delivery.

This study contributes to the growing body of knowledge on drone last-mile operations by examining its double-edged nature in terms of both the benefits and risks, and the interplay between drone delivery systems and the last-mile environment. From a managerial perspective, it generates several actionable insights for managers seeking to adopt drone technologies in last-mile logistics. First, selecting an appropriate drone operational model is critical for aligning drone delivery with organizational goals. The 3R framework provides a structured approach to assess operational needs and identify models that best suit specific business contexts. Second, risk mitigation emerges as a central challenge in drone adoption. Managers must address external constraints such as regulatory compliance and public acceptance while also tackling internal limitations like battery life and payload capacity. Third, leveraging sustainability as a competitive advantage is increasingly important in today's environmentally conscious market. Drone delivery's potential to reduce carbon emissions can be integrated into corporate sustainability initiatives to enhance brand reputation and attract eco-conscious consumers.

From a theoretical perspective, this study provides a comprehensive research agenda with practical implications, identifying avenues for both empirical and empirically grounding analytics research. By encouraging future research to explore these areas further, this agenda highlights the significance of continued investigation in optimizing drone delivery systems. This will ultimately help the industry make more informed decisions, achieve broader adoption, and enhance the positive impacts while mitigating the negative consequences of this double-edged sword.

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