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Embracing drones and the Internet of drones systems in manufacturing – An exploration of obstacles

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ABSTRACT

The manufacturing sector attributes the growing prominence of Drones and the Internet of Drones (IoD) systems to their multifaceted utility in delivery, process monitoring, infrastructure inspection, inventory management, predictive maintenance, and safety inspections. Despite their potential benefits, adopting these technologies faces significant obstacles that need systematic identification and resolution. The current literature inadequately addresses the barriers impeding the adoption of Drones and IoD systems in manufacturing, indicating a research gap. This study bridges this gap by providing comprehensive insights and facilitating the organisational transition towards embracing Drone and IoD technologies. This research identifies 20 critical barriers to deploying Drones and IoD in manufacturing. These barriers are validated through a global quantitative survey of 120 Drone experts and analyzed via Exploratory Factor Analysis (EFA). EFA categorises these challenges into six distinct dimensions. Utilizing the Analytical Hierarchy Process (AHP), these dimensions and individual barriers are ranked, incorporating feedback from five Drone specialists. The study highlights 'Safety and Human Resource Barriers' and 'Payload Capacity and Battery Barriers' as the most predominant obstacles. Key concerns include limited battery life, explosion risks, and potential damage to assets and individuals. This research significantly advances the existing literature by presenting a practical methodology for categorising and prioritising Drone and IoD adoption barriers. Employing EFA and AHP offers a globally relevant framework for stakeholders to strategically address these challenges, advancing the integration of drones and IoD systems in the manufacturing domain.

1. Introduction

The manufacturing landscape is transforming with the integration of advanced technologies, signalling the progression from traditional practices to Industry 4.0 and beyond [1,2]. Technologies like IoT, advanced analytics, RFID, automated storage systems, and robotics address specific challenges, improving supply chain management, inventory optimization, and workers' safety [3]. Among these technologies, Unmanned Aerial Vehicles (UAVs), commonly known as drones, and their networked systems under the framework of the Internet of Drones (IoD) stand out as particularly revolutionary [4]. Various sectors, including manufacturing, are increasingly repurposing drones for commercial use to enhance operational efficiency, worker safety, and inventory management [4,5].

Initially developed for military use, drones have significantly broadened their applications, demonstrating substantial impact across various sectors [6]. In agriculture, drones have revolutionized precision farming, enhancing crop yields by up to 30 % and reducing water and chemical use by approximately 50 %, optimizing resource management [7,8]. The logistics industry has also seen transformative changes, with

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companies like Amazon reducing delivery times and costs by up to 50 % through drone integration [9,10]. Drones contribute significantly to environmental conservation and disaster management by enabling efficient real-time data collection in affected areas [11,12].

The commercial drone market has experienced robust growth, valued at approximately $19.89 billion in 2022, with projections of a 13.9 % compound annual growth rate through 2030 ([13]*Share & Trends Report 2030*, n.d.). Expanded applications in sectors like construction drive this growth, as drones reduce surveying times by 85 %, enhancing project efficiency and safety [14]. Technological advancements and adaptive regulatory frameworks globally, such as those by the Federal Aviation Administration (FAA), have supported this surge, with over 500,000 drones registered for commercial use in the USA by 2021 [15].

In rural areas, drones are crucial for delivering essential medical supplies in regions like sub-Saharan Africa, showcasing their effectiveness locally and nationally ([16] | *UNICEF Supply Division*, n.d.). Urban centres in Europe also benefit, with drone delivery services projected to be economically viable for about 30 % of the population, expected to reduce delivery times, operational costs, and CO2 emissions [17]. Additionally, legislative adaptations in countries like Norway facilitate the integration of drones into their transportation systems, illustrating a proactive approach to embracing autonomous vehicle technologies [18]. This global adoption underscores the diverse capabilities of drones, marking them as integral to the future of industrial and service sectors worldwide.

Recent research comprehensively examines the complex barriers to adopting Drones and the Internet of Drones (IoD) systems across various sectors, including agriculture, construction, healthcare, transportation, and logistics, underscoring significant technological, operational, regulatory, and societal challenges [8,19–21]. The literature highlights the importance of integrating both technological innovations and socio-economic strategies to facilitate the adoption of drone technologies in industrial environments. This integration is crucial for aligning with broader efficiency and productivity goals while adapting to specific operational and market conditions [19,21,22].

Strategic frameworks are necessary to address the vast array of barriers to drone adoption, calling for robust policies that support the scalability of these technologies across diverse industrial landscapes [23]. Region-specific studies from India and Europe provide insights into local regulatory and socio-economic factors influencing drone integration, enriching our understanding of the implementation of advanced manufacturing technologies [8,23]. These investigations highlight the global nature of the shift towards innovative manufacturing technologies and illustrate the need for an integrated, multifaceted approach in adopting drones and IoD systems for manufacturing processes.

The surge in drone usage for industrial applications marks a transformative approach to enhancing operational efficiency and reducing the environmental footprint of manufacturing systems [24]. While existing research primarily focuses on generic barriers to drone adoption, such as regulatory obstacles [25] and technological challenges [26], it often neglects specific challenges in the manufacturing sector's integration of advanced aerial technologies. Although studies like Zhong et al. [27] and Kas and Johnson [28] address issues like drone path planning and safety hazards, comprehensive exploration of systemic and regulatory hurdles is lacking. Additionally, while valuable insights are offered within European industrial contexts [29] and perspectives from the European Steel Industry [30], the broader complexities of transitioning to drone-integrated manufacturing paradigms remain underexplored.

Addressing this research gap, our research endeavours to meticulously discern, authenticate, and prioritize impediments confronting global EV deployment for LMD.

Within the context of the current study, the research aims to address the following research questions.

RQ1 What are the primary barriers to adopting drones and the Internet of drone systems in the manufacturing industry?
RQ2 What is the relative significance of each barrier that hinders the adoption of drones and the Internet of Drone systems in manufacturing operations?
RQ3 What implications do barriers to adopting drones and the Internet of Drone systems pose for advancing technology adoption in the manufacturing industry?

This study enhances the discourse on drone adoption within the manufacturing sector by addressing critical research questions that explore the multifaceted barriers impeding the integration of drones and Internet of Drones (IoD) systems into advanced industrial operations. Unlike previous research that predominantly focuses on technological aspects [31], our investigation delves into the socio-technical, financial, and operational challenges, providing a granular analysis of the systemic and regulatory hurdles that affect drone deployment in manufacturing environments. This research is grounded in a global perspective, gathering insights from various regions to understand the universal barriers and opportunities for drone integration in manufacturing, leading to actionable strategies developed through extensive stakeholder consultations.

Our comprehensive framework integrates technological, operational, socio-technical, and policy-related challenges, offering a cohesive understanding of these impediments and their implications for advanced manufacturing systems. By contrasting our holistic approach with segmented analyses found in existing literature, such as the efficiency assessments by Zhong et al. [27] and safety evaluations by Kas and Johnson [28], this study highlights its innovative contributions to the field. It calls for further research and policy development to facilitate a transition towards more integrated and sustainable manufacturing operations, thus addressing a critical gap in existing scholarly work.

The paper is structured as follows: Section 2 offers a literature review focusing on Drones and IoD benefits for manufacturing and its implementation challenges. Section 3 describes the adopted research methodology. Section 4 presents the findings from the barriers analysis. Section 5 delves into an in-depth discussion of the results, while the paper culminates in the conclusions presented in Section 6.

2. Literature review

2.1. Drones and the Internet of drones (IoD)

The emergence of Unmanned Aerial Vehicles (UAVs), commonly referred to as Drones, signifies a noteworthy technological advancement in aerial capabilities [6]. Operated remotely or autonomously and equipped with cameras and sensors, Drones serve various purposes such as aerial photography, surveying, logistics, and disaster management. Their utility extends to accessing challenging areas in both commercial and research domains [11,32].

Initially designed for military reconnaissance, Drones have expanded across diverse domains, categorized by operational zone (outdoor or indoor) and mission type (military or civil) [33]. In military contexts, Drones undertake critical operations such as missile launches, bomb deployment, battlefield surveillance, communications disruption, and medical supply delivery in combat zones. Civil applications include high-altitude Wi-Fi provision, aviation, delivery, videography, disaster response, environmental monitoring, construction, space exploration, inspection, maritime activities, meteorology, agriculture, and recreational use (M. [32,34–36]).

Technological advancements have significantly expanded the capabilities of drones, making them versatile tools for diverse applications. Drones, equipped with high-resolution cameras, sophisticated sensors, and advanced flight controls, perform various tasks, including agricultural monitoring, environmental assessment, emergency response, and infrastructure inspection [4,37]. UAV applications in mining range from mineral exploration to reclamation, highlighting their role in geological analyses and environmental monitoring [38]. Additionally, drones have become vital in forestry management, providing cost-effective, high-intensity data collection and operational flexibility, making them a formidable alternative to traditional remote sensing platforms [39].

Integrating artificial intelligence and the Internet of Things (IoT) has significantly enhanced drone capabilities, allowing for autonomous operations and real-time data processing (Yazdinejad et al., 2021). UAVs play a transformative role by improving services in cellular communications, IoT networks, and disaster management through controlled mobility and adjustable altitudes [40]. Furthermore, advances in trajectory planning, strategic charging stations [41], and IoD simulator technology [42] optimize drone delivery systems and ensure their effective integration in shared airspace environments.

The Internet of Drones (IoD) is an evolving network framework crucial for managing multiple Drones in shared airspace [43]. IoD dynamic network architecture enables improved communications and coordination between drones, offering significant advancements in applications ranging from critical mission services to environmental monitoring. It facilitates communication, navigation, and monitoring, enhancing efficiency and safety, which is particularly influential in manufacturing and collaborative operations [37,44]. The IoD has demonstrated substantial adaptability across diverse applications, enhancing network reliability, connectivity, and performance, crucial for its integration into sectors like agriculture, search and rescue, and surveillance [45].

In manufacturing, Drones encompass hardware, software, and support processes, integrating individual and collaborative functionalities [4]. The evolution from individual to collaborative functionalities in UAV technology underscores significant advancements in wireless communication and network protocols, reflecting a technological leap in UAV capabilities [37].

2.2. Transformative potential of drones and IoD in manufacturing

Drones have significantly transformed logistics and supply chain management, notably in imaging, monitoring, and inspection tasks [26,31]. UAVs have been instrumental in reducing delivery times and operational costs in last-mile delivery, offering a cost-effective alternative to traditional methods [46]. Major companies like Amazon and FedEx have incorporated drones extensively, with Amazon now utilizing drones for over 83 % of its light orders, dramatically enhancing operational efficiency [43].

In the manufacturing sector, Drones and the Internet of Drones (IoD) are increasingly enhancing operational efficiency [47]. Drones, equipped with sensors, cameras, and data tools, are crucial for accessing difficult areas, monitoring processes, inspecting infrastructure, and managing inventory [48]. Mourtzis et al. [31] discuss UAVs' efficacy in indoor settings, utilizing Augmented Reality for path planning, which enhances decision-making and operational efficiency. Additionally, their role in predictive maintenance is vital, providing data that minimizes downtime and extends equipment life [12].

Drones significantly enhance manufacturing asset tracking and inventory management, utilizing RFID technology to optimize processes in large complexes [21,49]. They facilitate substantial improvements in inventory management, intra-logistics, inspections, and surveillance within smart warehouses, offering socio-economic benefits and a competitive edge [50]. Additionally, drones are crucial for inspecting complex structures, implementing thermal imaging for equipment monitoring, and enhancing safety in hazardous environments and search and rescue operations [4,51,52].

Drones play a critical role in energy management by monitoring usage to support efficient strategies and enhancing safety through compliance and hazard identification [35,53]. They automate inventory management in large warehouses, reducing labour and errors [50], and advanced scheduling solutions optimize logistics and operational efficiency, crucial for scaling production [54]. In response to industrial accidents or natural disasters, drones rapidly assess and aid recovery, minimizing disruptions [11]. Along with Industry 4.0 principles, drones promote sustainable practices and reduce carbon emissions in last-mile delivery, offering a sustainable alternative to traditional transport methods [46].

Integrating machine learning with the Internet of Drones (IoD) enhances data collection and predictive modelling, improving decision-making in manufacturing [35]. IoD ensures the efficient and safe coordination of drone fleets [44] and optimizes manufacturing by enhancing performance parameters such as reliability and connectivity [45]. IoD Simulators allow manufacturers to explore advanced applications and improve operational planning [42]. Additionally, drones provide real-time insights into logistics within supply chain management, increasing efficiency and responsiveness [32,55].

2.3. Barriers to the adoption of drones and IoD systems in manufacturing

Integrating drones into manufacturing presents significant technical and operational challenges despite their potential. These include limited battery life of 2–25 min and difficulties in transporting heavy loads, complicating their use in continuous operations [6,8,10,40]. Indoor navigation is problematic for drones primarily designed for outdoor use, particularly in hazardous factory settings that require ATEX-certified drones [51,56]. Additionally, technical issues such as complex trajectory planning and the necessity for robust security measures pose significant barriers [41]. A fundamental challenge that Zhong et al. [27] identified is ensuring accurate localization and flight paths in indoor environments, where traditional sensor-based methods often fail, highlighting the need for innovative solutions like image-based flight control systems.

The integration of Drones and the Internet of Drones (IoD) into manufacturing introduces substantial operational changes and incurs significant costs, further complicated by concerns over data privacy and susceptibility to cyberattacks [34,57–59]. The risk of data leakage heightens if someone commands drones [60]. Operational challenges include intricate drone scheduling and flight path optimization, which are critical to enhancing efficiency [54]. Multi-UAV systems in cyber-physical applications confront design challenges such as energy-efficient navigation and integrating machine learning for image analysis, which limit their adoption in manufacturing and related sectors [59]. Additionally, internal physical obstacles and worker fatigue complicate drone operations, while the essential development of advanced collision avoidance systems remains a significant barrier to reliable and safe UAV integration in manufacturing settings [6,31,61].

Challenges such as communication losses and data errors occur when multiple drones operate simultaneously, necessitating investment in advanced technologies like 5G and intelligent routing systems for reliable data transfer ([37]; Yazdinejad et al., 2021). Effective airspace management architecture is crucial for managing drone traffic and avoiding conflicts ([43]; S. [62]). Moreover, integrating the Internet of Drones (IoD) and drones for indoor navigation in confined manufacturing spaces raises concerns about data protection [31]. The reliability of drones poses challenges, with failure rates around 25 %, highlighting the need for rigorous maintenance [21,63]. Additionally, the absence of robust IoD simulators underscores significant issues in network management and performance evaluation, which are essential for optimizing drone deployment and operational efficiency in manufacturing [42].

Safety concerns in obstacle-dense industrial spaces, especially near human workers, highlight the need for skilled pilots and comprehensive training to minimize human error [10,64,65]. Jeelani and Gheisari [22] highlight the critical safety challenges associated with integrating UAVs into the construction industry, noting the lack of comprehensive research on the impact of UAVs on worker health and safety. The accountability issue in Drone-related accidents remains unresolved, emphasizing the necessity for research to ascertain Drones' safety and reliability in industrial applications [6].

The substantial initial financial investment for Drone technology, including procurement, setup, and maintenance, poses challenges for small and medium-sized enterprises [35,36,59]. Furthermore, a robust network infrastructure is essential for effective IoD operation, representing a significant investment [40,53]. Scaling Drone operations for larger manufacturing tasks is economically challenging, particularly for smaller manufacturers [37,40,47].

The regulatory landscape for drones is evolving, marked by strict airspace regulations and privacy concerns that vary regionally, complicating compliance for manufacturers [66,67]. Lee et al. [25] highlight the disparity between well-developed safety regulations focusing on technical specifications and the less developed privacy regulations that fail to address UAV-specific challenges, presenting a significant barrier to broader UAV adoption. In many developing countries, the absence of explicit rules for commercial drone usage poses challenges for organizations aiming to legitimize drone applications [10]. Sociocultural factors such as perceptions of drones as substitutes for human roles and concerns over personal information security also hinder drone integration [51,68,69]. Additionally, the development of Advanced Air Mobility highlights the need for a multi-level governance model and a comprehensive policy framework for integrating environmentally friendly drones, reflecting broader challenges in adopting Drones and Internet of Drones (IoD) systems in manufacturing [23]. Concerns about reduced human interaction and unauthorized data collection also raise privacy issues, affecting worker acceptance of drones [70].

3. Research methodology

This study meticulously reviewed contemporary literature to decipher the complexities inhibiting the assimilation of Drones and IoD systems in the manufacturing industry. The review was executed across multiple reputed databases, such as Emerald, Elsevier, Springer, Wiley, Sage, Taylor & Francis (T&F), Inderscience, Google Scholar, IEEE, EBSCO, Scopus, and ISI Web of Science, leveraging a comprehensive set of keywords and phrases. The systematic literature review strategy encapsulated terms like "Unmanned Aerial Vehicles", "UAVs", "Drones", "Internet of Drones", "IoD", "Barriers", "Obstacles", "Challenges", "Impediments," "Application of Drones in Manufacturing", "Drone Technology", "Drone Applications", "Barriers to Drone Adoption in Manufacturing", "Challenges in Implementing IoD in Manufacturing" and "Integration of Internet of Drones in Production". Boolean operators, precisely "AND", "OR", and "NOT", were judiciously deployed, fine-tuning the search outputs to enhance precision and relevance. Additional phrases, notably "Regulatory Compliance of Drones", "Technological Limitations of Drones", "Battery Life Limitations of Drones", and "Drone Security", "Drone Security", and "Noise pollution using Drones", further enriched the search paradigm. The collated literature underwent rigorous evaluation, initiating with a preliminary abstract analysis and culminating in an in-depth perusal of pertinent full-text articles. This thorough methodology, underpinned by academic exactitude, facilitated a holistic comprehension of barriers, blending scholarly and pragmatic vantage points.

After this literary exploration, we designed a structured questionnaire and meticulously validated it with industry and scholarly authorities to confirm its robustness. Utilizing convenience sampling, we collected data, optimizing accessible demographics and data sources. The instrument underwent beta testing to ensure clarity and consistency before broad-scale deployment. Table 1 presents the barriers discerned from the literature.

As shown in Fig. 1, the research methodology followed a tripartite structure to investigate the Drone and IoD adoption barriers in manufacturing. An extensive literature review initially yielded 20 potential barriers, see Table 1. The subsequent phase involved an empirical

Table 1
Summary of barriers to Drones and IoD systems adoption in manufacturing.

S/N	Barriers	Explanation of Barriers	Sources
1	Limited battery capacity	The barrier hinders extended operational periods for drones as their batteries can only store a limited amount of energy, often limiting flight times to 20–25 min. This constraint necessitates frequent recharging, thereby reducing the active usage time of Drones and adversely affecting the efficiency of manufacturing operations.	[4,10,71]
2	High cost of Drone systems	The high cost of Drone systems encompasses not only the initial acquisition and implementation expenses of Drones in manufacturing but also the significant costs associated with supporting communication systems, ensuring reliable data transfer, providing high-speed internet, and conducting comprehensive training programs.	[6,37]
3	Challenges with government regulations	The barrier refers to the complexities and uncertainties manufacturers face due to the lack of standardized and clear governmental guidelines governing Drone usage, especially in developing countries. These barriers include navigating varying regional laws and compliance issues,	[6,10]
4	Socially unacceptable	The barrier reflects societal resistance to Drones in manufacturing, stemming from concerns about job security, privacy invasion, and the intrusive nature of Drones.	[10,51,72]
5	Noise	The barrier refers to the significant auditory disruption caused by Drones during operation, which can impact the work environment. This noise can affect communication and overall ambience in manufacturing settings.	[4,37]
6	Data leakage	The barrier addresses the risk of unintentionally exposing or accessing sensitive information through Drones and IoD in manufacturing. This concern highlights vulnerabilities in data security, potentially leading to cyber threats and loss of confidential information.	[57,60]
7	Lack of skilled pilots and operators	The barrier highlights the difficulty of finding adequately trained personnel to operate drones and IoD systems in manufacturing. The shortage of skilled professionals can impede the effective implementation and operation.	[6,10]

(continued on next page)

Table 1 (*continued*)

S/N	Barriers	Explanation of Barriers	Sources
8	Insurance uncertainty in the event of a crash	The barrier refers to the ambiguity and complexities surrounding insurance coverage and claims for Drones in manufacturing, particularly after accidents. This uncertainty creates challenges in risk management and liability determination.	[73]
9	An inability to carry a large amount of weight	This barrier pertains to the limited payload capacity of current Drone models, which restricts their ability to transport heavier or bulkier items in manufacturing settings. This limitation hampers the scalability and applicability of Drones for more extensive and varied industrial tasks.	([5]; Choi & Schonfeld, 2021; [10])
10	A time-consuming process for integrating Drones	The barrier relates to the extensive duration and complexity of seamlessly incorporating Drones into existing manufacturing systems. The challenges include developing compatible workflow navigation algorithms and ensuring proper synchronisation with current operations.	([6,73]; Li et al., 2020)
11	Limited flying area	The barrier highlights the spatial constraints posed by machinery, structural elements, and safety installations, limiting the operational scope of Drones in manufacturing- settings.	[4,31]
12	Insufficient navigation accuracy	The barrier refers to the challenges Drones face in navigating complex manufacturing environments. The challenge includes difficulties in manoeuvring around obstacles and maintaining consistent flight paths, which are crucial for effective and safe Drone operations.	[4,51]
13	Poor data transfer	The barrier arises from the high mobility of Drones, which can lead to challenges in data upload and download processes. These mobility-related issues can result in interrupted or incomplete data transmission, affecting the efficiency of Drone operations.	[4,37,74]
14	Poor communication between Drones	The barrier highlights the challenges in multi-drone scenarios, where inter-drone communication may face hindrances. Other machinery and robots could also interfere with the transmission of Drones, leading to potential data inaccuracies or complete data loss, which in turn impacts the effectiveness of coordinated Drone operations.	[6,31,37]
15	The risk of damaging assets and people	The barrier underscores the potential for Drones to interfere with manufacturing assets and personnel, posing a risk of damage and harm. This barrier necessitates robust airspace management and safety measures to mitigate collision risks.	[26,31]
16	The complexity of integrating the Drones and Internet of Drones	The barrier highlights the intricate nature of assimilating these technologies within multifaceted manufacturing operations. This complexity poses challenges in coordinating and synchronizing the various components of Drone systems and the Internet of Drones, requiring meticulous planning and technical expertise for successful integration.	[6,31,74]
17	Long battery charging time	The barrier underscores the extended periods required for recharging Drone batteries after depletion, often exceeding an hour. This prolonged charging time leads to operational delays and affects the time efficiency of Drone utilization in continuous industrial operations.	[6,10,21]
18	Lack of ATEX-certified Drones	The barrier highlights the absence of Drones for safe operation in hazardous environments containing flammable substances, where ATEX compliance is essential. This limitation restricts their usability in critical industrial settings and calls for developing specialized drones to meet safety requirements.	[75]
19	Risk of explosion	The barrier underscores the potential danger of Drone operations in manufacturing environments containing flammable materials, such as oil, petrol, and wood, which can lead to detonation hazards. Mitigating this risk is crucial for ensuring the safety of both personnel and assets in such settings.	[6,73]
20	High failure rate	The barrier highlights the significant impact of suboptimal maintenance practices on Drone reliability, with failures occurring in approximately 25 % of cases. Addressing this challenge is essential to ensure Drones' consistent and safe operation within manufacturing environments.	[63]

inquiry through a quantitative survey, collating insights from 120 global manufacturing industry professionals. This data underwent an EFA to validate and categorize the barriers. The culminating stage adopted the AHP technique for a hierarchical barrier ranking. The following sections

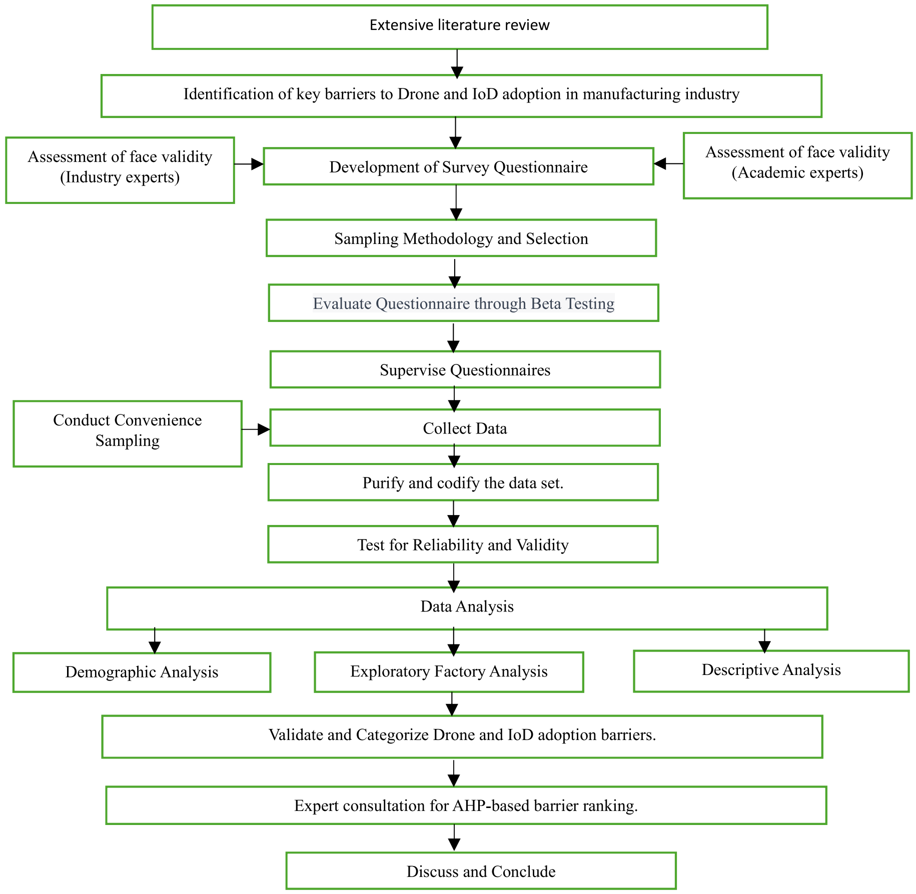

Fig. 1. Research methodology stages.

detail this methodology, accentuating its potential for replication in subsequent similar investigations.

3.1. Data collection and analysis

A survey questionnaire harvested expert perspectives, subsequently facilitating the validation of the barriers and categorisation into coherent clusters via an EFA. We then used the AHP technique to rank the barriers, drawing upon feedback from an expert panel. The survey was disseminated through email and LinkedIn, capitalizing on a diverse network of scholars and practitioners. This approach followed the suggested 5:1 ratio of respondents to variables for EFA, as Reio and Shuck [76] outlined, which indicated that we needed to obtain a minimum of 100 responses. Post-collection data underwent stringent cleaning, coding, and validation. This approach is consistent with the methodologies outlined in previous literature [77].

3.2. Survey instrument design

To align with the principles established by Nardi [78], we formulated a structured questionnaire to guarantee valid and reliable data collection. The questionnaire comprised two segments: demographics and a detailed exploration of the 20 barriers, see Table 1, related to Drone and IoD adoption in manufacturing. The first segment of the questionnaire aimed to gather demographic details, focusing specifically on the respondents' industry background and expertise. In the second segment of the questionnaire, the primary research section asked participants to assess 20 impediments associated with drone and IoD integration in manufacturing, using a Likert scale anchored at 1 (Not Important) and culminating at 5 (Extremely Important). Table 2 outlines both sections.

Table 2
Description of survey questions.

Question Category	Questions	Significance
Demographic	What type of manufacturing industry does your organisation belong to? Please specify the size of your organisation Which region is your organisation located in? Has your organisation ever used Drones or the IoD in the manufacturing process?	The questions provided a deeper understanding of the participants' industrial backgrounds, allowing for a more thorough examination of the data.
Importance Rating of Barriers on a 5-point Likert scale	Please rate the following barriers and their significance in adopting Drones and IoD in manufacturing. (1- Not important; 2- Moderately Important; 3- Important; 4- Very Important; 5- Extremely Important)	These questions gave insights into professionals' views on the primary obstacles to adopting Drones and IoD in the manufacturing industry. The validation and analysis of this data helped to answer RQ2 and RQ3.

4. Analysis and results

4.1. Demographic analysis

In examining respondent demographics, this study evaluated four salient criteria: industry type, organisational size, geographical location, and organisational experience in using Drones and IoD systems in the manufacturing processes. This selection was grounded in expert recommendations for survey face validity and paralleled methodologies documented in prior research [79]. Table 3 presents the demographic distribution of 120 valid survey responses, categorized by industry, size, region, and drone usage experience, crucial for this study's findings.

4.2. Data cleansing and coding

Rigorous data cleaning and coding procedures were employed to maintain data integrity during the analyses. Out of the initially received 138 responses, 120 were considered suitable for further examination after a stringent review for data completeness and accuracy. The number of participants exceeded the projected sample size of 100, as specified in Section 3.1. Notably, the attained sample size is comparable to, and even exceeds, those observed in other studies that have employed EFA [80]. We denoted demographic questions as 'DMa', referring to Table 3, and tagged questions concerning barriers as 'Ba', as shown in Table 4.

4.3. Assessment of reliability and validity

To uphold the reliability of the data, we instantaneously captured responses via a survey platform and safeguarded them on a drive secured by password protection. The collected data, identified by variable codes B1 through B20, were subjected to a reliability assessment using Cronbach's Alpha. This present cross-sectional study confirmed the reliability of its survey with a Cronbach's Alpha of 0.77, surpassing the accepted threshold of 0.7, which underscores satisfactory internal consistency among the survey items [81]. The data, coded from B1 through B20, underwent a rigorous reliability assessment to ensure the robustness of the findings related to the barriers to adopting drones and Internet of Drones (IoD) systems. Table 4 presents the Alpha values for each surveyed barrier, alongside their mean and standard deviation, demonstrating that all items exceed the 0.7 benchmark for internal consistency. Moreover, mean values exceeding 2.5 highlights the significance of these barriers, validating their examination in the Exploratory Factor Analysis (EFA). This validation ensures the survey's adequacy in capturing critical insights into drone and IoD integration challenges within the manufacturing sector.

Table 3
Demographic analysis of survey data.

Variables	Received Responses	Frequency	Per cent
DM1: Industry	Aerospace and Defence Manufacturing	51	42.5
	Agricultural Manufacturing	12	10
	Automotive	9	7.5
	Construction	9	7.5
	Energy and utilities manufacturing	9	7.5
	Chemical and pharmaceutical manufacturing	7	5.8
	Electronics	5	4.2
	Food and beverage manufacturing	5	4.2
	Heavy machinery and equipment manufacturing	4	3.3
	Others	9	7.5
	Total	**120**	**100**
DM2: Organisation Size	Large (more than 250 employees)	23	19.2
	Medium (50–250 employees)	39	32.5
	Small (less than 50 employees)	58	48.3
	Total	**120**	**100**
DM3: Region	Asia Pacific	41	34.2
	Europe	36	30
	South America	19	15.8
	Middle East	11	9.2
	North America	8	6.7
	Africa	5	4.2
	Total	**120**	**100**
DM4: Experience in Drones and IoD	Yes, currently	82	68.3
	Yes, in the past	17	14.2
	Never used, but intending to use	21	17.5
	Total	**120**	**100**

Table 4
Reliability test outcome of survey data.

Variable	Adoption Barriers	Cronbach's Alpha if Item Deleted	Mean	SD
B1	Limited battery capacity	0.768	3.97	0.987
B2	High cost of Drone systems	0.766	3.61	1.056
B3	Challenges with government regulations	0.765	4.09	1.053
B4	Socially unacceptable	0.76	2.88	1.089
B5	Noise	0.758	2.39	1.132
B6	Data leakage	0.757	3.97	1.144
B7	Lack of skilled pilots and operators	0.753	3.73	1.053
B8	Insurance uncertainty in the event of a crash	0.755	2.91	1.202
B9	An inability to carry a large amount of weight	0.772	3.78	1.063
B10	A time-consuming process for integrating Drones	0.769	3.22	1.006
B11	Limited flying area	0.765	3.41	0.992
B12	Insufficient navigation accuracy	0.759	3.25	1.055
B13	Poor data transfer	0.755	2.83	1.042
B14	Poor communication between Drones	0.754	2.92	1.12
B15	The risk of damaging assets and people	0.758	4.32	1.021
B16	The complexity of integrating the Drones and Internet of Drones	0.757	3.45	0.839
B17	Long battery charging time	0.767	3.03	1.334
B18	Lack of ATEX-certified Drones	0.764	2.69	1.419
B19	Risk of explosion	0.757	3.78	1.24
B20	High failure rate	0.754	3.32	1.069

The survey's validity was corroborated through correlation with relevant scholarly literature, ensuring content validity. A panel of six experts, comprised of individuals from both academic and industrial sectors, conducted a pilot test to establish face validity. This panel included three academic experts with over fifteen years of experience and three drone experts with at least a decade of experience. Their feedback prompted minor adjustments, ultimately confirming the survey's suitability. Discriminant validity was further verified by applying Pearson's Correlation Coefficient. Table 5 displays Pearson Correlation coefficients from an analysis that examines interrelationships among barriers to adopting drones and Internet of Drones (IoD) systems labelled B1 through B20. This analysis reveals the strength and direction of relationships between these barriers, indicating the extent of their interdependence. The coefficients range from weak to moderate, all below 0.6, suggesting that while some barriers are related, they largely represent distinct aspects of adoption challenges [82]. This heterogeneity in correlations highlights the diversity of obstacles, emphasizing the need for a comprehensive strategy to tackle the complex challenges in Drone and IoD adoption.

Table 4 presents the results of the descriptive analysis, where mean values exceeded the threshold of 2.5, underlining the significance of the barriers and thereby justifying their inclusion in the EFA [81].

4.4. Structural analysis of Drone and IoD adoption barriers

Table 6 evaluates the dataset's suitability for Exploratory Factor Analysis (EFA) using the Kaiser-Meyer-Olkin (KMO) measure, Bartlett's Test of Sphericity, and Cronbach's Alpha to ensure the data's reliability and appropriateness for analysis. The KMO measure achieves a value of 0.685, surpassing the recommended threshold of 0.6, confirming data adequacy for EFA [83]. Bartlett's Test of Sphericity shows a significant result ($p < 0.001$), validating the variables' sufficient correlation for

Table 5
Correlation matrix of the barriers to drone and IOD adoption based on Pearson correlation coefficients.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18	B19	B20
B1	1	0.012	0.132	0.035	0.095	0.103	0.177	0.031	0.193*	0.069	0.057	0.145	0.084	0.074	0.023	0.130	0.256**	0.137	0.172	0.034
B2		1	−0.051	0.045	0.249**	0.093	0.197*	0.203*	0.051	0.168	−0.039	−0.085	0.159	0.093	0.155	0.172	0.200*	0.053	0.208*	0.230*
B3			1	0.186*	0.167	0.386**	0.281**	0.272**	0.010	0.011	0.004	0.259**	0.030	0.028	0.231*	0.019	0.082	0.002	0.108	0.034
B4				1	0.272**	0.233*	0.270**	0.158	0.216*	0.036	0.273**	0.108	0.173	0.219*	0.308**	0.265**	0.147	0.035	0.197*	0.164
B5					1	0.185*	0.190*	0.243**	0.127	0.102	0.156	0.107	0.108	0.132	0.015	0.246**	0.164	0.154	0.105	0.279**
B6						1	0.453**	0.077	0.326**	0.130	0.020	0.042	0.044	0.116	0.383**	0.095	0.076	0.017	0.486**	0.187*
B7							1	0.186*	0.097	0.176	0.061	0.013	0.132	0.137	0.324**	0.236**	0.013	0.252**	0.429**	0.160
B8								1	0.101	0.072	0.144	0.336**	0.182*	0.232	0.099	0.250**	0.353	0.269**	0.042	0.265**
B9									1	0.060	0.188*	0.094	0.004	0.013	0.188*	0.016	0.024	0.212*	0.345**	0.002
B10										1	0.014	0.036	0.149	0.091	0.080	0.182	0.107	0.130	0.080	0.256**
B11											1	0.359**	0.240	0.152	0.203*	0.171	0.091	0.054	0.034	0.194*
B12												1	0.376**	0.274**	0.090	0.252	0.394**	0.310**	0.098	0.160
B13													1	0.549**	0.218	0.139	0.300**	0.213*	0.125	0.216*
B14														1	0.207	0.148	0.289**	0.365**	0.071	0.177
B15															1	0.186*	0.187*	0.007	0.455**	0.233*
B16																1	0.272**	0.223*	0.187*	0.271**
B17																	1	0.152	−0.087	0.122
B18																		1	0.127	0.253**
B19																			1	0.276**
B20																				1

Note: The study did not incorporate significance levels for 2-tailed tests because there was no requirement for this data in the assessment.

Table 6
Kaiser-Meyer-Olkin (KMO), Bartlett's test of Sphericity and Cronbach Alpha.

Kaiser-Meyer-Olkin Measure of Sampling Adequacy 0.685		
Bartlett's Test of Sphericity	Approx. Chi-Square	585.892
	df	190
	Sig.	0.001(<)
Cronbach's Alpha (No of items=21)		0.77

df = degrees of freedom. Sig = Significance.

factor analysis [84]. Furthermore, a Cronbach's Alpha of 0.77 indicates robust internal consistency among the survey items, supporting the decision to proceed with EFA [82].

The second phase of this study utilized Exploratory Factor Analysis (EFA) to analyze the structure of barriers to drone and Internet of Drones (IoD) adoption, as shown in Table 7. This analysis grouped barriers (B1 to B20) into six distinct dimensions, representing 59 % of the total variance, which, while below the Yong & Pearce [85] criterion of 75 %, aligns with the 52 % average observed in similar studies [86] and meets the accepted threshold of over 50 % [87]. The principal component analysis identified six factors with eigenvalues over one, indicating significant dimensions within the dataset [79].

A Varimax rotation further refined these factors, ensuring clarity in the classification and adherence to standard factor loading thresholds [88,89]. The minimized cross-loadings confirmed the distinctiveness of each factor (M. [90]). This structured approach facilitated a clear understanding of how barriers are interrelated and categorized based on their underlying characteristics, with factor loadings emphasizing the strength of associations within specific dimensions.

The resultant EFA framework effectively categorized the barriers into coherent groups, addressing Research Question 2 (RQ2). We corroborated these findings' practical applicability and accuracy through industry consultations, with Table 8 detailing the refined barrier categories. This phase highlighted each barrier's interconnections and distinct nature and validated the analytical methodology employed, ensuring the findings' relevance to industry practices.

4.5. *Hierarchical prioritization of drones and IoD adoption barriers in manufacturing*

The AHP provides a structured framework for dissecting complex decisions, incorporating essential tiers like objectives, criteria, and sub-criteria [79]. Although alternatives like ANP, ELECTRE, and TOPSIS exist, AHP's intuitiveness makes it preferable for comparative dilemmas [91]. AHP's unique hierarchical approach notably simplifies intricate tasks [92].

The AHP is a valuable tool for ranking subjective factors by facilitating paired comparisons, which aids decision-makers in determining optimal priorities [93]. Given its effectiveness in prioritising barriers, this research incorporated AHP to assess obstacles to Drone and IoD adoption in manufacturing.

4.5.1. *Formulation of research objective and pairwise comparisons*

Initiating the AHP demands precise articulation of the research objective [93]. Luthra et al. [91] indicate that AHP does not mandate a large sample, for which the quality of expert input is vital. Consistent with prior studies, this research engaged five experts adept in Drones and IoD [77]. The participants in this study were professionals with substantial expertise in integrating UAV technology within the industrial manufacturing domain. Each possessed a minimum of a decade of professional engagement in Drone technology. Table 9 profiles these experts. The AHP aimed to determine global weights to rank Drone and IoD adoption barriers in manufacturing. The results of this hierarchical analysis, depicted in Fig. 2, highlight the relative importance of each barrier, and provide a clear visual representation of how these barriers interrelate and impact the adoption of drones in the context of

Table 7
EFA framework for six distinct Barrier dimensions.

Variable	Barriers to Drone and IoD adoption	Factors 1	2	3	4	5	6
B6	Data leakage	0.771					
B19	Risk of explosion	0.736					
B7	Lack of skilled pilots and operators	0.681					
B15	The risk of damaging assets and people	0.643					
B14	Poor communication between Drones		0.763				
B13	Poor data transfer		0.76				
B18	Lack of ATEX-certified Drones		0.562				
B12	Insufficient navigation accuracy		0.519				
B2	High cost of Drone systems			0.675			
B20	High failure rate			0.583			
B5	Noise			0.531			
B16	The complexity of integrating the Drones and Internet of Drones			0.519			
B10	A time-consuming process for integrating Drones			0.503			
B3	Challenges with government regulations				0.717		
B8	Insurance uncertainty in the event of a crash				0.64		
B11	Limited flying area					0.777	
B4	Socially unacceptable					0.595	
B9	An inability to carry a large amount of weight						0.414
B1	Limited battery capacity						0.801
B17	Long battery charging time						0.587
Eigenvalues		**3.918**	**2.446**	**1.541**	**1.381**	**1.291**	**1.225**
Total variance explained (%)		**19.59**	**31.81**	**39.52**	**46.42**	**52.87**	**59.0**

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization. Rotation converged in 8 iterations.

Table 8
Categorisation of Barriers to Drones and IoD adoption in the manufacturing industry.

Factor	Category	Barriers
1	Safety and Human Resource Barriers (SHR)	Data Leakage (SHR1) Risk of explosion (SHR2) Lack of skilled pilot (SHR3) The risk of damaging assets and people (SHR4)
2	Communication and Technological Barriers (CT)	Poor communication between Drones (CT1) Poor data transfer (CT2) Lack of ATEX-certified Drones (CT3) Insufficient navigation accuracy (CT4)
3	Financial and Operational Barriers (FO)	The high cost of Drone systems (FO1) High failure rate (FO2) Noise (FO3) The complexity of integrating Drones and the Internet of Drones (FO4) A time-consuming process for integrating Drones (FO5)
4	Legislation and Risk Barriers (LR)	Challenges with government regulations (LR1) Insurance uncertainty in the event of a crash (LR2)
5	Social and Regulatory Barriers (SR)	Limited flying area (SR1) Socially unacceptable (SR2)
6	Payload Capacity and Battery Barriers (PCB)	An inability to carry a large amount of weight (PCB1) Limited battery capacity (PCB2) Long battery charging time (PCB3)

Table 9
Drone expert panel for AHP.

Expert	Position	Location	Work Experience (Years)
1	Systems Engineer	EMEA	14
2	Drone Pilot	USA	17
3	Drone Developer	Netherlands	14
4	CEO	United Kingdom	26
5	Drone Consultant	Brazil, Europe, APAC	21

manufacturing settings. This prioritization is crucial for stakeholders aiming to address the most significant challenges first, thereby streamlining efforts towards enhancing drone adoption in manufacturing.

The three-tier order includes the primary goal (Level I), barrier dimensions from EFA (Level II), and the 20 specific obstacles (Level III). The Five experts conducted pairwise comparisons among barriers using Saaty's nine-point scale [94].

4.5.2. Calculation of relative weights and evaluating consistency ratio

This study employed the AHP to aggregate expert pairwise comparison data, determining the relative importance of barriers to drone adoption in manufacturing. The results, displayed in Table 10, utilize the median as the aggregation method for its robustness against outliers. Table 10 outlines the pairwise comparison matrix with relative weights for the six main barrier dimensions identified through EFA. The relative importance of each dimension is quantified, leading to a ranked order based on their impact on based on their effect on drone adoption in manufacturing.

- *Safety and Human Resource Barriers (SHR)* are deemed the most significant, with a weight of 0.3377, reflecting the critical role of addressing safety concerns and human resources in supporting drone integration.
- *Payload Capacity and Battery Barriers (PCB)* follow with a weight of 0.2335, highlighting the technological challenges related to carrying capacity and battery life as substantial deterrents.
- *Financial and Operational Barriers (FO)* receive a weight of 0.1455, indicating concerns about drone technology's costs and operational effectiveness.
- *Legislation and Risk Barriers (LR)* receive a weight of 0.0971, suggesting these are significant yet manageable factors affecting adoption.
- *Social and Regulatory Barriers (SR),* with a weight of 0.0932, and *Communication and Technological Barriers (CT)* at 0.0929, represent less immediate but still noteworthy barriers affecting drone adoption.

To ensure the reliability of the Analytic Hierarchy Process (AHP) rankings, we calculated the consistency ratio (CR) for each pairwise comparison matrix, adhering to the threshold of CR $\leq$ 0.2, as

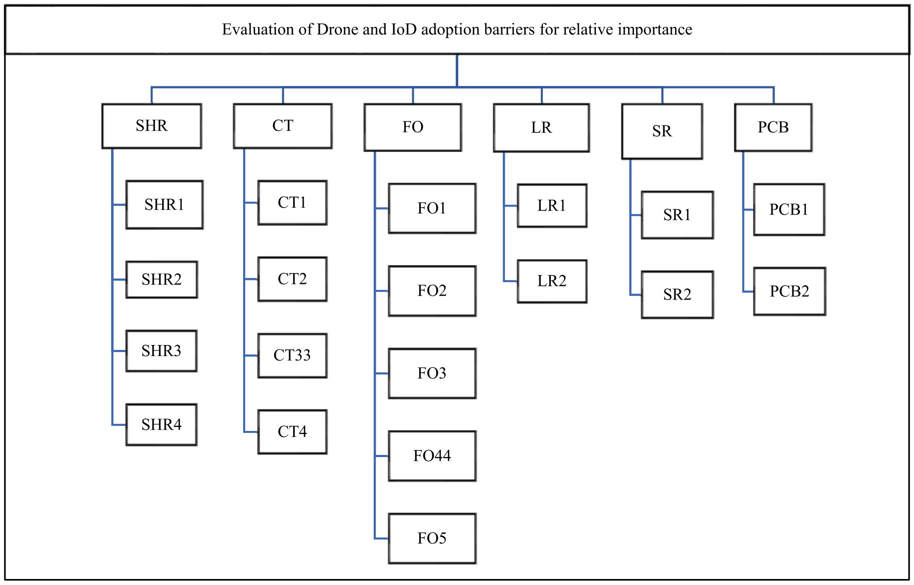

Fig. 2. Drone and IoD adoption barriers to decision hierarchy.

Table 10
Pairwise comparison matrix of the six main barriers and their relative weights.

Major Barrier Dimensions	SHR	CT	FO	LR	SR	PCB	Relative Weight	Rank
Safety and Human Resource Barriers (SHR)	1	7	7	4	2	0.5	0.3377	Ist
Communication and Technological Barriers (CT)	0.14	1	1	1	2	2.5	0.0929	6th
Financial and Operational Barriers (FO)	0.14	1	1	4	1	1	0.1455	3rd
Legislation and Risk Barriers (LR)	0.25	1	0.25	1	1	1	0.0971	4th
Social and Regulatory Barriers (SR)	0.5	0.5	1	1	1	0.5	0.0932	5th
Payload Capacity and Battery Barriers (PCB)	2	4	1	1	2	1	0.2335	2nd

recommended by Pauer et al. [95]. This level indicates a reasonable consistency among expert judgments. We occasionally asked experts to revise their responses to meet this criterion, ensuring that the final priorities reflected a logical and coherent assessment.

Our rigorous approach to verifying consistency affirmed the reliability of our findings, enabling a confident identification of the most critical barriers to drone adoption. The outcomes, detailed in Table 11, provide a hierarchical breakdown of specific obstacles within each dimension, organized by their relative weights and global ranks.

- *Safety and Human Resource Barriers (SHR):* The risk of explosion (SHR2) is the most critical, highlighting the urgent need for robust safety protocols. Other significant barriers include data leakage (SHR1) and lack of skilled pilots (SHR3), which emphasize concerns

Table 11
Ranking of Drones and IoD adoption barriers in the manufacturing industry.

Dimension of Barriers	Relative Weights	Barriers	Relative Weights	Relative Rank	Global Weights	Global Rank
Safety and Human Resource Barriers (SHR)	0.3377	Data Leakage (SHR1)	0.0888	4th	0.029971	12th
		Risk of explosion (SHR2)	0.3365	1st	0.113619	2nd
		Lack of skilled pilot (SHR3)	0.2564	3rd	0.08653	5th
		The risk of damaging assets and people (SHR4)	0.3184	2nd	0.107508	3rd
Communication and Technological Barriers (CT)	0.0932	Poor communication between Drones (CT1)	0.1383	3rd	0.012854	17th
		Poor data transfer (CT2)	0.5146	1st	0.047826	9th
		Lack of ATEX-certified Drones (CT3)	0.2112	2nd	0.019630	14th
		Insufficient navigation accuracy (CT4)	0.1359	4th	0.012628	18th
Financial and Operational Barriers (FO)	0.1455	The high cost of Drone systems (FO1)	0.1803	3rd	0.026229	13th
		High failure rate (FO2)	0.5075	1st	0.073846	6th
		Noise (FO3)	0.0439	5th	0.006384	20th
		The complexity of integrating Drones and the Internet of Drones (FO4)	0.0488	4th	0.007097	19th
		A time-consuming process for integrating Drones (FO5)	0.2246	2nd	0.032686	10th
Legislation and Risk Barriers (LR)	0.0971	Challenges with government regulations (LR1)	0.7292	1st	0.070835	7th
		Insurance uncertainty in the event of a crash (LR2)	0.1458	2nd	0.014167	16th
Social and Regulatory Barriers (SR)	0.0932	Limited flying area (SR1)	0.3333	2nd	0.031075	11th
		Socially unacceptable (SR2)	0.6667	1st	0.062151	8th
Payload Capacity and Battery Barriers (PCB)	0.2335	An inability to carry a large amount of weight (PCB1)	0.4353	2nd	0.101650	4th
		Limited battery capacity (PCB2)	0.4866	1st	0.113626	1st
		Long battery charging time (PCB3)	0.0782	3rd	0.018254	15th

over information security and the need for specialized drone operation skills.

- *Payload Capacity and Battery Barriers (PCB)*: Limited battery capacity (PCB2) ranks as the primary concern, followed by the inability to carry significant weight (PCB1) and long battery charging times (PCB3), pointing to necessary technological improvements in battery efficiency.
- *Financial and Operational Barriers (FO):* High failure rates (FO2) top this category, alongside challenges in drone integration (FO5) and the high cost of drone systems (FO1), reflecting economic and operational feasibility issues.
- *Legislation and Risk Barriers (LR):* Challenges with government regulations (LR1) are the foremost legislative barriers, followed by insurance uncertainties in the event of a crash (LR2), which underscore the financial and operational risks.
- *Social and Regulatory Barriers (SR):* Social acceptability (SR2) and limited flying areas (SR1) are primary concerns, indicating essential areas for improvement to enhance drone integration.
- *Communication and Technological Barriers (CT)*: Poor data transfer (CT2) is the leading issue, followed by the lack of ATEX-certified drones (CT3) and poor inter-drone communication (CT1), highlighting the importance of reliable and safe communication technologies.

These aggregated results illustrate the complex factors influencing drone adoption in manufacturing. By prioritising these barriers, stakeholders can strategically address the predominant challenges, facilitating more effective integration of drone technology into manufacturing operations.

Our study delineates primary and secondary obstacles in analyzing the barriers to drone adoption in manufacturing, providing a strategic framework for industry stakeholders. The most critical challenge identified is *Limited Battery Capacity (PCB2)*, highlighting the necessity for advancements in battery technology to enhance drone operational times and capabilities, which is crucial for sustained and efficient drone use. Innovations such as higher-density battery materials or solar-assist panels could significantly extend operational times, revolutionizing drone utility in continuous manufacturing operations and setting new standards for energy efficiency in drone technologies.

The Risk of Explosion (SHR2) closely follows, which underscores the need for stringent safety protocols and the development of explosion-proof drone models using advanced materials and containment strategies. This barrier could transform the risk profile of drones in industrial settings. The third significant barrier, the *Risk of Damaging Assets and People (SHR4)*, emphasizes the need for enhanced safety standards and advanced sensory and autonomous decision-making technologies to mitigate risks to operations and personnel.

The fourth critical barrier, the *Inability to Carry a Large Amount of Weight (PCB1)*, affects the versatility of drones in demanding industrial applications that require heavier payloads. Addressing this, alongside the *High Failure Rate (FO2)*, which ranks fifth, is essential for expanding drone applications and building manufacturer confidence. Reliability enhanced through predictive maintenance technologies powered by IoT and machine learning could preempt potential failures and improve operational efficiency.

Conversely, the least impactful barriers include the *Complexity of Integration (FO4)* and *Noise (FO3)*. Although these factors have a lower immediate impact, they underscore areas for operational improvement and broader acceptance of drone technology. Streamlining integration processes and developing quieter drones can lead to better operational harmony and facilitate the widespread adoption of drones in manufacturing. Ongoing research, collaboration between technology developers and industry stakeholders, and adaptive regulatory frameworks should underpin these efforts to keep pace with technological advances and evolving safety standards.

5. Discussion

The research conducted an in-depth analysis of the barriers to integrating Drone technology and IoD in the manufacturing industry.

5.1. Dimension 1: Safety and Human Resources Barriers (SHR)

Within the 'Safety and Human Resources Barriers (SHR)' dimension in drone integration in manufacturing, the 'Risk of explosion (SHR2)' emerges as the most critical, particularly in environments with flammable materials where drones may trigger explosions [4]. Addressing this includes adopting explosion-proof drone technology and stringent operational protocols to enhance safety. Technological innovations, such as volatile compound sensors, are recommended to halt operations in hazardous conditions pre-emptively, alongside industry-specific safety regulations and regular audits of drone operations.

The second principal barrier, 'Risk of damaging assets and people (SHR4)', necessitates effective airspace management to prevent drone collisions with manufacturing assets and personnel. Advanced collision-avoidance technologies and robust geofencing systems, potentially managed by AI, are essential to mitigate risks. Regulatory frameworks should clearly define drone operational zones and timings to minimize interactions with personnel and infrastructure, supported by managerial practices establishing designated facility drone areas.

The 'Lack of skilled pilots (SHR3)' highlights the need for technical expertise in drone operations. Utilizing drone simulators and simulation-based training environments incorporating virtual reality can enhance operator skills in a risk-free setting. Strategic educational partnerships are crucial to maintaining a supply of trained operators, supported by policies advocating for recognized drone piloting as a legitimate profession.

Lastly, 'Data Leakage (SHR1)' identifies the susceptibility of drone-collected data to cybersecurity threats. Implementing advanced cybersecurity measures, such as encryption and secure transmission protocols, regular security audits, and robust data governance frameworks, is vital. We recommend establishing comprehensive data protection standards specific to drone operations to guide manufacturers and operators in securing data effectively.

These barriers underscore the complex challenges of adopting drones in manufacturing, highlighting the need for focused strategies on safety, workforce development, and cybersecurity. Insightful policy development and practice adjustments are necessary to mitigate these risks, fostering the secure integration of drone technologies in manufacturing.

5.2. Dimension 2: payload Capacity and Battery Barriers (PCB)

In the typology of barriers to drone integration, the 'Payload Capacity and Battery Barriers (PCB)' category is pivotal. These barriers significantly impact drone technology, necessitating innovative solutions and policy revisions to boost operational efficiency and enhance capabilities.

The primary barrier, 'Limited battery capacity (PCB2)', underscores the energy sustainability issues in drone operations, affecting the operational duration and necessitating frequent recharging. Advancements in battery technology could offer higher energy density and quicker recharging capabilities. Managerial strategies might include optimizing battery use through strategic operation scheduling and exploring renewable energy sources for charging.

Another significant constraint is the 'Inability to carry a large amount of weight (PCB1)', with current drone models typically supporting payloads not exceeding 2.5 kg. This limitation restricts their use in broader industrial tasks, limiting the range of materials transportable by drones. Addressing this requires research into lightweight materials and enhanced propulsion systems to increase payload scalability. Collaborations with material scientists and engineers are essential to develop drone designs that can handle increased payloads. Hybrid propulsion systems combining electric motors with internal combustion engines or fuel cells could provide necessary lifting power and extend operational ranges beyond traditional battery limits.

Furthermore, integrating robotic mechanisms for load handling and manipulation, such as robotic arms or grippers, could allow drones to manage dynamic load adjustments during flight, enhancing stability and carrying capacity.

The 'Long battery charging time (PCB3) barrier introduces significant operational delays. Innovations like lithium-ion batteries with advanced cathode materials or supercapacitors could reduce charging times drastically. Battery swapping stations and inductive charging systems could minimize downtime by allowing quick battery exchanges or wireless charging during brief landings. Integrating solar panels could extend operational times between charges, and smart scheduling algorithms could optimize charging periods to maximize availability during peak operational times.

Addressing these challenges involves embracing ongoing research and developments in battery technology and drone design. Innovations to improve power efficiency, explore alternative energy sources, and advance materials engineering could revolutionize drone payload and endurance capabilities, enhancing their operational range and effectiveness. Such technological advances are crucial for drones' broader implementation and impact in the manufacturing sector and beyond.

5.3. Dimension 3: Financial and Operational Barriers (FO)

In the 'Financial and Operational Barriers (FO)' dimension, critical challenges hinder the effective deployment of drone technology in industrial settings. Notably, the 'High failure rate (FO2)' reflects the adverse effects of inadequate maintenance, reporting a significant 25 % failure rate in drone operations [63]. Addressing this necessitates rigorous maintenance protocols, predictive maintenance systems utilizing IoT technology, and advanced fail-safe mechanisms to enhance reliability and operational efficiency.

The 'Time-consuming process for integrating drones (FO5)' underscores the complexity of developing navigation algorithms and ensuring robust data protection. Streamlined development processes, modular drone designs, and digital twins could significantly reduce integration times and improve data security.

The 'High cost of drone systems (FO1)' indicates the substantial investments required to equip drones with efficient communication and data handling capabilities. Cost-effective technologies, economies of scale, and models such as drones-*as*-a-service could mitigate these financial burdens, spreading costs over time and reducing initial expenditures.

The 'Complexity of integrating drones and IoD (FO4)' illustrates the difficulties of assimilating these technologies within complex manufacturing operations. Simplifying integration through modular designs, standardized communication protocols, and specialized software platforms can facilitate smoother transitions and lessen operational complexities.

Lastly, 'Noise (FO3)' addresses the auditory disruptions caused by drones, which can impact workplace communication and the environment. Developing quieter drone models and implementing operational guidelines to minimize noise exposure is crucial.

Overcoming these barriers through innovative technological solutions and strategic managerial policies is vital for enhancing the operational efficiency and cost-effectiveness of drone technology in manufacturing. These efforts can transform manufacturing processes and outcomes by addressing the specific needs and challenges within the sector.

5.4. Dimension 4: Legislation and Risk Barriers (LR)

Within the 'Legislation and Risk Barriers (LR)' category, identified as the fourth most significant obstacle to drone integration in manufacturing, two principal barriers emerge that challenge the widespread operational deployment and safety of drone technologies.

The foremost challenge, 'Challenges with government regulations (LR1)', underscores the lack of definitive regulatory frameworks in many developing countries, hindering the commercial deployment of drones. The current regulatory patchwork, often lagging behind technological advancements, poses significant barriers to the growth and utility of drones across various sectors [96]. We recommend establishing regulatory sandboxes to address these regulatory challenges, allowing drone companies to test their technology under supervised conditions. This initiative would enable regulators to evaluate technological impacts in real time, fostering adaptive frameworks that evolve with technological advancements. Moreover, creating flexible, technology-specific legislation is crucial, allowing for swift adaptations without overhauling the entire system. Automated compliance systems are also essential, helping operators ensure continual adherence to flight restrictions, privacy norms, and safety regulations through real-time data monitoring.

The second significant barrier, 'Insurance uncertainty in the event of a crash' (LR2), points to the ambiguities surrounding liability and insurance claims post-drone accidents. The immature state of drone insurance protocols complicates stakeholder navigation through post-accident liabilities, presenting risks to operators and businesses. Addressing this requires establishing industry-wide risk assessment standards and implementing advanced telematics to capture comprehensive operational data, thus aiding accurate risk evaluation. Furthermore, blockchain technology could create a transparent and immutable ledger for insurance transactions, enhancing trust and streamlining claims processing. Additionally, exploring usage-based insurance models could align premium costs more closely with drone usage, incentivizing operators towards best practices.

A holistic approach is necessary to overcome these barriers. Regulatory frameworks must be adaptable and comprehensive to standardize drone operations globally and simplify compliance processes. For insurance, clear guidelines should detail the methods for liability, risk assessment, and claim handling to mitigate associated risks. Monitoring legislative developments and actively participating in policy discussions is imperative to influence drone-related regulations. Evaluating impacts on public safety, privacy, and operational risks is crucial, alongside public engagement, to educate people on drone benefits and risks, ensuring community support for their sustainable integration.

5.5. Dimension 5: Social and Regulatory Barriers (SR)

The dimension termed 'Social and Regulatory Barriers (SR)' emerges as the fifth critical area, embodying significant barriers to integrating drones across various settings.

The first barrier, 'Social unacceptability (SR2),' underscores societal hesitance towards drones, fueled by concerns over job displacement, privacy violations, and integration into daily life. Addressing these requires robust public engagement initiatives to educate on drone benefits, address privacy concerns, and discuss potential employment impacts transparently. Community involvement in drone project planning and deployment fosters ownership and acceptance, enhancing societal acceptance.

Partnering with local civic organizations, educational institutions, and non-profits is crucial for promoting the positive impacts of drones in emergency response and environmental monitoring. Additionally, establishing ethical standards and certification programs for drone operators will enhance their professional image and societal trust.

The second barrier, 'Limited flying area (SR1),' highlights spatial constraints within manufacturing environments that restrict drone mobility, often complicated by obstructions like machinery and structural elements (Zhang & Ansari, 2019). Innovative design solutions are essential for improving drone manoeuvrability and agility.

Advanced navigation systems that utilize AI and machine learning can enable drones to autonomously navigate confined spaces, using dynamic obstacle detection and avoidance technologies to adjust flight paths. Deploying Indoor Positioning Systems (IPS) tailored for indoor environments enhances drone navigation capabilities within complex layouts.

Utilizing Building Information Modeling (BIM) to create detailed 3D maps enables drones to plan optimal flight paths and navigate effectively. Implementing Virtual Reality (VR) simulations for drone operators facilitates training in virtual environments, which mirrors actual manufacturing settings, preparing operators for safe navigation in real-world operations.

Furthermore, developing specific regulations tailored to indoor aviation ensures safe and effective drone operations within constrained environments. These efforts are vital for overcoming drones' spatial challenges in manufacturing and optimizing operational efficiency and effectiveness. This comprehensive approach involving technological innovations, managerial foresight, and policy adaptations is crucial for enhancing drone integration and acceptance within broader societal and manufacturing contexts.

5.6. Dimension 6: Communication and technological barriers (CT)

Within the 'Communication and Technological Barriers (CT)' category, four barriers present distinct challenges in drone integration, with 'Poor data transfer (CT2)' identified as the primary concern. Inefficiencies in drone data exchange can be mitigated by developing advanced data transmission protocols, ensuring secure and reliable data flow in mobile scenarios (Zhang & Ansari, 2019). Enhancements such as dedicated communication channels and edge computing can streamline data handling, improving response times and reliability.

The 'Lack of ATEX-certified Drones (CT3)' indicates a significant shortfall in drones certified for operation in hazardous environments. Addressing this barrier involves equipping drones with sensors for detecting volatile compounds and designing intrinsic safety features that prevent ignition in explosive atmospheres [97]. When combined with rigorous training and industry-specific regulations, these measures will enhance drone safety and compliance.

'Poor communication between Drones (CT1)' is another notable barrier, especially in multi-drone operations. Implementing mesh networking can enhance connectivity and resilience by allowing drones to form a dynamic network. Furthermore, employing advanced frequency management techniques and exploring quantum communication can bolster the security and efficiency of drone communications.

The 'Insufficient navigation accuracy (CT4)' barrier, significant in indoor manufacturing settings, necessitates investments in advanced navigation systems such as LiDAR or ultrasonic sensors. Technologies like RTK GPS and visual odometry can enhance navigation precision, which is crucial in GPS-denied environments [59]. Additionally, integrating sensor fusion techniques and deploying Ultra-Wideband (UWB) technology can improve location tracking accuracy indoors.

Addressing these challenges requires a multifaceted approach involving technological advancements, strategic management initiatives, and policy interventions. Engaging stakeholders in developing and enforcing safety and operational standards is crucial for fostering a conducive environment for advanced drone operations. Collectively, these efforts will enable drones to overcome communication and technological barriers, enhancing their integration and efficacy in manufacturing and other industrial settings.

5.7. Managerial and policy implications

We must develop comprehensive managerial and policy frameworks to effectively integrate Drones and the Internet of Drones (IoD) within manufacturing ecosystems. These frameworks should address barriers that significantly impact the adoption processes, ensuring a detailed understanding of strategic planning and deployment.

Safety is paramount, particularly in environments with flammable materials, necessitating stringent protocols and ATEX-certified drones to ensure safe operational distances. Robust data security measures, including strong encryption and vigilant cyber defence strategies, are required. Furthermore, we advocate for comprehensive training and certification programs enriched with simulation-based exercises to enhance drone piloting proficiency, which is critical. We recommend using advanced antenna technologies to improve data transfer reliability.

Financial and operational challenges require conducting cost-benefit analyses to find cost-effective solutions for drone maintenance and integration. Implementing Drone-*as*-a-Service (DaaS) models can minimize upfront costs and provide scalability. Streamlining integration with advanced algorithms can improve efficiency and investment returns. We advise performing regular maintenance every 100 flight hours to ensure drone reliability, which involves inspecting control, structural, payload, navigation, and electronic systems.

Compliance with national regulations, including licensing and insurance, is essential. Industry leaders should engage with policymakers to create a favourable regulatory environment and establish clear insurance protocols. A flexible operational strategy is necessary to adapt quickly to new or evolving drone legislation.

Public acceptance of drones demands transparent communication about their roles and benefits, alongside targeted personnel training. Developing public engagement initiatives is crucial to educate and inform the community about the benefits and safety of drone technology. Decisions on payload capacity should reflect operational needs, balancing delivery-oriented tasks with diverse functions. We require innovative solutions for navigating limited flying areas, such as designing custom drones for indoor use. Addressing battery life limitations involves strategically placing charging stations for rapid recharging.

Investing in advanced communication and navigation technologies is crucial to enhancing the reliability and efficiency of drone operations. Adopting emerging technologies such as 5G can significantly improve drone communication capabilities. Developing contingency plans to manage communication failures ensures continuous operation during critical missions.

Comprehensive policy implications are necessary to address the challenges posed by drone integration across various sectors. These should include developing industry-specific safety regulations and standards, particularly for operations in hazardous environments, and supporting innovation through subsidies and incentives for advanced drone technology research. Policies should also promote harmonising international drone regulations to facilitate global operations and ensure that legislation keeps pace with technological advancements. We recommend offering financial incentives such as tax breaks and grants to encourage investment in drone technology. Additionally, clear guidelines for drone integration into business operations are necessary to streamline adoption processes. To build public trust and acceptance, supporting public awareness campaigns and educational programs about the benefits and safety of drones while implementing robust privacy protections and data security measures to address societal concerns is crucial. Lastly, promoting the development of communication standards and protocols will enhance drone interoperability and safety, facilitating the adoption of new technologies such as 5G to improve communication capabilities in drone operations. These policy measures will collectively enhance the operational effectiveness, safety, and societal acceptance of drones in various industries.

6. Conclusions

In manufacturing, incorporating Drones and the IoD marks a significant step toward enhancing operational practices. This research delineates the challenges in adopting these technologies, contributing to filling a gap in the academic literature and seeking to improve our theoretical knowledge and practical applications concerning the assimilation of these technologies in a manufacturing setting. The study theoretically contributes by identifying and categorising twenty barriers into six categories through an Exploratory Factor Analysis (EFA). Applying the Analytic Hierarchy Process (AHP) assigns a hierarchical structure to these challenges, providing a global perspective previously understudied in the scholarly literature.

The research offers a structured framework of challenges across domains such as safety and human resources, communication, and technology, financial and operational, legislation and risk, social and regulatory, and payload capacity and battery. This ranking contributes to practice by informing industry stakeholders in strategising for effective Drone and IoD integration. The study's combination of empirical research with quantitative methodologies like EFA and AHP introduces an effective analytical perspective to understand the barriers to Drones and IoD integration in manufacturing contexts, benefiting practitioners in overcoming these obstacles.

6.1. Limitations and future research directions

This study provides an in-depth analysis of the challenges associated with adopting drones and Internet of Drones (IoD) systems in manufacturing. Despite the comprehensive nature of the research, several limitations may affect the robustness and generalizability of the results.

- *Sampling Limitations:* The primary limitation is the reliance on convenience sampling involving 120 global manufacturing industry experts. While efficient, this method may not capture the full diversity of manufacturing scenarios and geographic regions. As such, the results might be biased towards those already familiar with or interested in drone technologies, potentially excluding smaller enterprises or emerging markets.
- *Geographical Representation:* The geographic diversity within the sample is another limitation. The majority of experts might share similar experiences influenced by their regional market operations, which could reflect biases and limit the global applicability of the findings.
- *Methodological Constraints:* Exploratory Factor Analysis (EFA) and Analytical Hierarchy Process (AHP) introduce certain limitations. EFA depends on the initial choice and several factors that could affect the results. AHP, while structured, may introduce subjectivity through its pairwise comparison process and the potential bias of expert judgments.

Given these limitations, the study suggests several areas for future research, outlined as follows.

- *Enhanced Sampling Techniques:* Future studies should utilize more robust sampling methods, such as stratified or random sampling, to improve the representativeness of the results and ensure they reflect a broader range of manufacturing contexts and regions.
- *Integration of Additional Decision-Making Frameworks:* To address the methodological constraints, incorporating decision-making frameworks such as the Delphi method or other multi-criteria decision-making (MCDM) techniques could balance the criteria weighting and reduce biases inherent in AHP.
- *Conducting Sensitivity Analyses:* A need exists for sensitivity analysis in future research to test the robustness of findings and explore how modifications to the analyzed barriers could influence proposed solutions. This analysis would also help understand the relative importance of the different obstacles under various scenarios.
- *Periodic Updating of Findings:* Given the rapid evolution in drone technology and regulatory frameworks, it is crucial to periodically update the research findings to ensure they remain relevant and reflect the current technology and market conditions.
- *In-depth Examination of Specific Barriers:* Future research should delve deeper into the underlying causes of each identified barrier, particularly examining the role of government policy and how variations between countries affect drone adoption in manufacturing.
- *Comprehensive View of Adoption Barriers:* A more comprehensive approach is needed to consider technical, infrastructural, economic, and political factors affecting drone and IoD system adoption. Manufacturers can explore integrating drones with advanced manufacturing processes to achieve efficiency and sustainability goals.
- *Mixed Methods and Longitudinal Designs:* Employing mixed methods and longitudinal study designs can provide a more dynamic understanding of the evolving nature of adoption barriers across different geographical, industrial, cultural, economic, and environmental contexts.
- *Stakeholder Perceptions:* Understanding the perceptions of different stakeholders through psychological and sociological analyses is vital. These analyses will help address the motivational and attitudinal drivers behind the adoption of drones in the manufacturing sector.
- *Policy and Incentive Schemes:* Investigating incentive schemes and policy interventions across various landscapes is crucial. This research could inform strategies to enhance drone adoption rates and sustainability outcomes.

CRediT authorship contribution statement

Dauren Askerbekov: Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Jose Arturo Garza-Reyes:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Ranjit Roy Ghatak:** Writing – review & editing, Validation, Investigation, Conceptualization. **Rohit Joshi:** Writing – review & editing, Visualization, Supervision, Conceptualization. **Jayakrishna Kandasamy:** Writing – review & editing, Visualization, Validation, Conceptualization. **Daniel Luiz de Mattos Nascimento:** Writing – review & editing, Visualization, Validation, Conceptualization.

Data availability

Data will be made available on request.

References

[1] L.S. Dalenogare, G.B. Benitez, N.F. Ayala, A.G. Frank, The expected contribution of Industry 4.0 technologies for industrial performance, Int. J. Prod. Econ. 204 (2018) 383–394, https://doi.org/10.1016/j.ijpe.2018.08.019. Scopus.
[2] M. Ghobakhloo, Industry 4.0, digitization, and opportunities for sustainability, J. Clean. Prod. 252 (2020) Scopus, https://doi.org/10.1016/j.jclepro.2019.119869.
[3] A. Raj, G. Dwivedi, A. Sharma, A.B. Lopes De Sousa Jabbour, S. Rajak, Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: an inter-country comparative perspective, Int. J. Prod. Econ. 224 (2020) 107546, https://doi.org/10.1016/j.ijpe.2019.107546.
[4] O. Maghazei, T. Netland, Drones in manufacturing: exploring opportunities for research and practice, J. Manuf. Technol. Manag. 31 (6) (2019) 1237–1259, https://doi.org/10.1108/JMTM-03-2019-0099.
[5] M. Ayamga, S. Akaba, A.A. Nyaaba, Multifaceted applicability of drones: a review, Technol. Forecast. Soc. Change 167 (2021) 120677, https://doi.org/10.1016/j.techfore.2021.120677.
[6] O. Maghazei, M.A. Lewis, T.H. Netland, Emerging technologies and the use case: a multi-year study of drone adoption, J. Oper. Manag. 68 (6–7) (2022) 560–591, https://doi.org/10.1002/joom.1196. Scopus.
[7] How Do Drones Help Farmers?, AUVSI, 2018. https://www.auvsi.org/how-do-drones-help-farmers.
[8] H. Puppala, P.R.T. Peddinti, J.P. Tamvada, J. Ahuja, B. Kim, Barriers to the adoption of new technologies in rural areas: the case of unmanned aerial vehicles for precision agriculture in India, Technol. Soc. 74 (2023), https://doi.org/10.1016/j.techsoc.2023.102335. Scopus.
[9] M. Moshref-Javadi, S. Lee, M. Winkenbach, Design and evaluation of a multi-trip delivery model with truck and drones, Transport. Res. E Logist. Transport. Rev. 136 (2020) 101887, https://doi.org/10.1016/j.tre.2020.101887.
[10] A. Rejeb, K. Rejeb, S.J. Simske, H. Treiblmaier, Drones for supply chain management and logistics: a review and research agenda, Int. J. Logist. Res. Appl.

26 (6) (2023) 708–731, https://doi.org/10.1080/13675567.2021.1981273. Scopus.
[11] S. Chowdhury, A. Emelogu, M. Marufuzzaman, S.G. Nurre, L. Bian, Drones for disaster response and relief operations: a continuous approximation model, Int. J. Prod. Econ. 188 (2017) 167–184, https://doi.org/10.1016/j.ijpe.2017.03.024. Scopus.
[12] M. Shafiee, Z. Zhou, L. Mei, F. Dinmohammadi, J. Karama, D. Flynn, Unmanned aerial drones for inspection of offshore wind turbines: a mission-critical failure analysis, Robotics 10 (1) (2021) 1–27, https://doi.org/10.3390/robotics10010026. Scopus.
[13] Commercial Drone Market Size, Share & Trends Report 2030. (n.d.). Retrieved April 29, 2024, from https://www.grandviewresearch.com/industry-analysis/global-commercial-drones-market.
[14] U. Choi, C. Moon, J. Ahn, Energy minimization of dynamic multi-UAV communication network for cooperative MultiHop data gathering, IEEE Trans. Aero. Electron. Syst. 59 (3) (2023) 3082–3099, https://doi.org/10.1109/TAES.2022.3221031. Scopus.
[15] The state of drones in 2024: How many drones are registered in the U.S., and how many pilots are certified?, 2024 (n.d.). Retrieved April 29, 2024, from, https://www.thedronegirl.com/2024/04/01/drones-in-2024/.
[16] Leveraging the power of drones to reach the last mile | UNICEF Supply Division. (n.d.). Retrieved April 29, 2024, from https://www.unicef.org/supply/leveraging-power-drones-reach-last-mile.
[17] F. Borghetti, C. Caballini, A. Carboni, G. Grossato, R. Maja, B. Barabino, The use of drones for last-mile delivery: a numerical case study in milan, Italy, Sustainability 14 (3) (2022) 1766, https://doi.org/10.3390/su14031766.
[18] Nordic Drone Initiative. (n.d.). Nordic Innovation. Retrieved April 29, 2024, from https://www.nordicinnovation.org/programs/nordic-drone-initiative.
[19] A.O. Aiyetan, D.K. Das, Use of Drones for construction in developing countries: barriers and strategic interventions, International Journal of Construction Management 23 (16) (2023) 2888–2897, https://doi.org/10.1080/15623599.2022.2108026. Scopus.
[20] N. Koshta, Y. Devi, S. Patra, Aerial bots in the supply chain: a new ally to combat COVID-19, Technol. Soc. 66 (2021), https://doi.org/10.1016/j.techsoc.2021.101646. Scopus.
[21] B. Sah, R. Gupta, D. Bani-Hani, Analysis of barriers to implement drone logistics, Int. J. Logist. Res. Appl. 24 (6) (2021) 531–550, https://doi.org/10.1080/13675567.2020.1782862.
[22] I. Jeelani, M. Gheisari, Safety challenges of UAV integration in construction: conceptual analysis and future research roadmap, Saf. Sci. 144 (2021) Scopus, https://doi.org/10.1016/j.ssci.2021.105473.
[23] A. Raghunatha, P. Thollander, S. Barthel, Addressing the emergence of drones – a policy development framework for regional drone transportation systems, Transp. Res. Interdiscip. Perspect. 18 (2023) 100795, https://doi.org/10.1016/j.trip.2023.100795.
[24] K. Telli, O. Kraa, Y. Himeur, A. Ouamane, M. Boumehraz, S. Atalla, W. Mansoor, A comprehensive review of recent research trends on unmanned aerial vehicles (UAVs), Systems 11 (8) (2023) 400, https://doi.org/10.1016/10.3390/systems11080400.
[25] W. Lee, Federated reinforcement learning-based UAV swarm system for aerial remote sensing, Wireless Commun. Mobile Comput. 2022 (2022), https://doi.org/10.1155/2022/4327380. Scopus.
[26] D. Mourtzis, J. Angelopoulos, N. Panopoulos, Uavs for industrial applications: identifying challenges and opportunities from the implementation point of view, Procedia Manuf. 55 (2021) 183–190, https://doi.org/10.1016/j.promfg.2021.10.026.
[27] Y. Zhong, Z. Wang, A.V. Yalamanchili, A. Yadav, B.N.R. Srivatsa, S. Saripalli, S.T. S. Bukkapatnam, Image-based flight control of unmanned aerial vehicles (UAVs) for material handling in custom manufacturing, J. Manuf. Syst. 56 (2020) 615–621, https://doi.org/10.1016/j.jmsy.2020.04.004. Scopus.
[28] K.A. Kas, G.K. Johnson, Using unmanned aerial vehicles and robotics in hazardous locations safely, Process Saf. Prog. 39 (1) (2020), https://doi.org/10.1002/prs.12066. Scopus.
[29] A. Alamouri, A. Lampert, M. Gerke, An exploratory investigation of UAS regulations in Europe and the impact on effective use and economic potential, Drones 5 (3) (2021) 63, https://doi.org/10.3390/drones5030063.
[30] D. Stroud, M. Weinel, A safer, faster, leaner workplace? Technical-maintenance worker perspectives on digital drone technology 'effects' in the European steel industry, New Technol. Work. Employ. 35 (3) (2020) 297–313, https://doi.org/10.1111/ntwe.12174.
[31] D. Mourtzis, J. Angelopoulos, N. Panopoulos, Unmanned Aerial Vehicle (UAV) path planning and control assisted by Augmented Reality (AR): the case of indoor drones, Int. J. Prod. Res. (2023), https://doi.org/10.1080/00207543.2023.2232470. Scopus.
[32] I.S. Damoah, A. Ayakwah, I. Tingbani, Artificial intelligence (AI)-enhanced medical drones in the healthcare supply chain (HSC) for sustainability development: a case study, J. Clean. Prod. 328 (2021), https://doi.org/10.1016/j.jclepro.2021.129598. Scopus.
[33] M. Hassanalian, A. Abdelkefi, Classifications, applications, and design challenges of drones: a review, Prog. Aero. Sci. 91 (2017) 99–131, https://doi.org/10.1016/j.paerosci.2017.04.003.
[34] M. Ali, K.N. Qureshi, T. Newe, K. Aman, A.O. Ibrahim, M. Almujaly, W. Nagmeldin, Decision-based routing for unmanned aerial vehicles and internet of Things networks, Appl. Sci. 13 (4) (2023), https://doi.org/10.3390/app13042131. Scopus.
[35] K. Mahroof, A. Omar, N.P. Rana, U. Sivarajah, V. Weerakkody, Drone as a service (DaaS) in promoting cleaner agricultural production and circular economy for ethical sustainable supply chain development, J. Clean. Prod. 287 (2021), https://doi.org/10.1016/j.jclepro.2020.125522. Scopus.
[36] H. Shakhatreh, A.H. Sawalmeh, A. Al-Fuqaha, Z. Dou, E. Almaita, I. Khalil, N. S. Othman, A. Khreishah, M. Guizani, Unmanned aerial vehicles (Uavs): a survey on civil applications and key research challenges, IEEE Access 7 (2019) 48572–48634, https://doi.org/10.1109/ACCESS.2019.2909530.
[37] A. Abdelmaboud, The internet of drones: requirements, taxonomy, recent advances, and challenges of research trends, Sensors 21 (17) (2021) 5718, https://doi.org/10.3390/s21175718.
[38] S. Park, Y. Choi, Applications of unmanned aerial vehicles in mining from exploration to reclamation: a review, Minerals 10 (8) (2020) 663, https://doi.org/10.3390/min10080663.
[39] N. Guimarães, L. Pádua, P. Marques, N. Silva, E. Peres, J.J. Sousa, Forestry remote sensing from unmanned aerial vehicles: a review focusing on the data, processing and potentialities, Rem. Sens. 12 (6) (2020) 1046, https://doi.org/10.3390/rs12061046.
[40] B. Alzahrani, O.S. Oubbati, A. Barnawi, M. Atiquzzaman, D. Alghazzawi, UAV assistance paradigm: state-of-the-art in applications and challenges, J. Netw. Comput. Appl. 166 (2020) 102706, https://doi.org/10.1016/j.jnca.2020.102706.
[41] A.M. Raivi, S.M.A. Huda, M.M. Alam, S. Moh, Drone routing for drone-based delivery systems: a review of trajectory planning, charging, and security, Sensors 23 (3) (2023) 1463, https://doi.org/10.3390/s23031463.
[42] G. Grieco, G. Iacovelli, P. Boccadoro, L.A. Grieco, Internet of drones simulator: design, implementation, and performance evaluation, IEEE Internet Things J. 10 (2) (2023) 1476–1498, https://doi.org/10.1109/JIOT.2022.3207324.
[43] M. Gharibi, R. Boutaba, S.L. Waslander, Internet of drones, IEEE Access 4 (2016) 1148–1162, https://doi.org/10.1109/ACCESS.2016.2537208. Scopus.
[44] S. Mitropoulos, M. Maliappi, C. Douligeris, A. Veletsos, Reengineering the certification process for aircraft equipment, Int. J. Bus. Process Integrat. Manag. 11 (1) (2022) 64, https://doi.org/10.1504/IJBPIM.2022.10050171.
[45] P. Boccadoro, D. Striccoli, L.A. Grieco, An extensive survey on the Internet of Drones, Ad Hoc Netw. 122 (2021) 102600, https://doi.org/10.1016/j.adhoc.2021.102600.
[46] V. Garg, S. Niranjan, V. Prybutok, T. Pohlen, D. Gligor, Drones in last-mile delivery: a systematic review on Efficiency, Accessibility, and Sustainability, Transport. Res. Transport Environ. 123 (2023), https://doi.org/10.1016/j.trd.2023.103831. Scopus.
[47] B. Fan, Y. Li, R. Zhang, Q. Fu, Review on the technological development and application of uav systems, Chin. J. Electron. 29 (2) (2020) 199–207, https://doi.org/10.1049/cje.2019.12.006.
[48] O. Sami Oubbati, M. Atiquzzaman, T. Ahamed Ahanger, A. Ibrahim, Softwarization of uav networks: a survey of applications and future trends, IEEE Access 8 (2020) 98073–98125, https://doi.org/10.1109/ACCESS.2020.2994494.
[49] Y. Shen, X. Xu, B. Zou, H. Wang, Operating policies in multi-warehouse drone delivery systems, Int. J. Prod. Res. 59 (7) (2021) 2140–2156, https://doi.org/10.1080/00207543.2020.1756509. Scopus.
[50] S.S. Ali, S. Khan, N. Fatma, C. Ozel, A. Hussain, Utilisation of drones in achieving various applications in smart warehouse management, Benchmark Int. J. 31 (3) (2024) 920–954, https://doi.org/10.1108/BIJ-01-2023-0039.
[51] M. Deja, M.S. Siemiątkowski, G.-Ch Vosniakos, G. Maltezos, Opportunities and challenges for exploiting drones in agile manufacturing systems, Procedia Manuf. 51 (2020) 527–534, https://doi.org/10.1016/j.promfg.2020.10.074.
[52] P. Kitjacharoenchai, P. Sittivijan, Integration of three vehicle fleet types for delivering relief supplies during a natural disaster, Applied Science and Engineering Progress 16 (4) (2023), https://doi.org/10.14416/j.asep.2023.03.002. Scopus.
[53] B. Hou, X. Ma, K. Diao, Z. Zhong, S. Wu, Seismic performance assessment of water distribution systems based on multi-indexed nodal importance, WATER 13 (17) (2021), https://doi.org/10.3390/w13172362.
[54] J. Pasha, Z. Elmi, S. Purkayastha, A.M. Fathollahi-Fard, Y.-E. Ge, Y.-Y. Lau, M. A. Dulebenets, The drone scheduling problem: a systematic state-of-the-art review, IEEE Trans. Intell. Transport. Syst. 23 (9) (2022) 14224–14247, https://doi.org/10.1109/TITS.2022.3155072. Scopus.
[55] P. Kitjacharoenchai, B.-C. Min, S. Lee, Two echelon vehicle routing problem with drones in last mile delivery, Int. J. Prod. Econ. 225 (2020), https://doi.org/10.1016/j.ijpe.2019.107598. Scopus.
[56] C. Goerzen, Z. Kong, B. Mettler, A survey of motion planning algorithms from the perspective of autonomous uav guidance, J. Intell. Rob. Syst. 57 (1–4) (2010) 65–100, https://doi.org/10.1007/s10846-009-9383-1.
[57] C. Lin, D. He, N. Kumar, K.-K.R. Choo, A. Vinel, X. Huang, Security and privacy for the internet of drones: challenges and solutions, IEEE Commun. Mag. 56 (1) (2018) 64–69, https://doi.org/10.1109/MCOM.2017.1700390. Scopus.
[58] Z. Lv, The security of Internet of drones, Comput. Commun. 148 (2019) 208–214, https://doi.org/10.1016/j.comcom.2019.09.018.
[59] R. Shakeri, M.A. Al-Garadi, A. Badawy, A. Mohamed, T. Khattab, A.K. Al-Ali, K. A. Harras, M. Guizani, Design challenges of multi-UAV systems in cyber-physical applications: a comprehensive survey and future directions, IEEE Communications Surveys and Tutorials 21 (4) (2019) 3340–3385, https://doi.org/10.1109/COMST.2019.2924143. Scopus.
[60] P. Kardasz, J. Doskocz, Drones and possibilities of their using, J. Civ. Environ. Eng. 6 (3) (2016), https://doi.org/10.4172/2165-784X.1000233.
[61] J.N. Yasin, S.A. Sayed Mohamed, M.-H. Haghbayan, J. Heikkonen, H. Tenhunen, M.M. Yasin, J. Plosila, Energy-efficient formation morphing for collision avoidance

in a swarm of drones, IEEE Access 8 (2020) 170681–170695, https://doi.org/10.1109/ACCESS.2020.3024953. Scopus.
[62] S. Zhang, N. Ansari, Latency aware 3d placement and user association in drone-assisted heterogeneous networks with fso-based backhaul, IEEE Trans. Veh. Technol. 70 (11) (2021) 11991–12000, https://doi.org/10.1109/TVT.2021.3112483. Scopus.
[63] E. Petritoli, F. Leccese, L. Ciani, Reliability and maintenance analysis of unmanned aerial vehicles, Sensors 18 (9) (2018) 3171, https://doi.org/10.3390/s18093171.
[64] D.R. Asokan, F.A. Huq, C.M. Smith, M. Stevenson, Socially responsible operations in the Industry 4.0 era: post-COVID-19 technology adoption and perspectives on future research, Int. J. Oper. Prod. Manag. 42 (13) (2022) 185–217, https://doi.org/10.1108/IJOPM-01-2022-0069. Scopus.
[65] H. Li, F. Wang, Z. Zhan, Drone routing problem with swarm synchronization, Eur. J. Oper. Res. S0377221723007725 (2023), https://doi.org/10.1016/j.ejor.2023.10.015.
[66] R. Luppicini, A. So, A technoethical review of commercial drone use in the context of governance, ethics, and privacy, Technol. Soc. 46 (2016) 109–119, https://doi.org/10.1016/j.techsoc.2016.03.003.
[67] C. Stöcker, R. Bennett, F. Nex, M. Gerke, J. Zevenbergen, Review of the current state of uav regulations, Rem. Sens. 9 (5) (2017) 459, https://doi.org/10.3390/rs9050459.
[68] B. Rao, A.G. Gopi, R. Maione, The societal impact of commercial drones, Technol. Soc. 45 (2016) 83–90, https://doi.org/10.1016/j.techsoc.2016.02.009.
[69] N. Wang, N. Mutzner, K. Blanchet, Societal acceptance of urban drones: a scoping literature review, Technol. Soc. 75 (2023) Scopus, https://doi.org/10.1016/j.techsoc.2023.102377.
[70] B. Aydin, Public acceptance of drones: knowledge, attitudes, and practice, Technol. Soc. 59 (2019) Scopus, https://doi.org/10.1016/j.techsoc.2019.101180.
[71] S.R. Hashemi, R. Esmaeeli, H. Aliniagerdroudbari, M. Alhadri, H. Alshammari, A. Mahajan, S. Farhad, New intelligent battery management system for drones, Energy 6 (2019), https://doi.org/10.1115/IMECE2019-10479. V006T06A028.
[72] Y. Zhi, Z. Fu, X. Sun, J. Yu, Security and privacy issues of uav: a survey, Mobile Network. Appl. 25 (1) (2020) 95–101, https://doi.org/10.1007/s11036-018-1193-x.
[73] O. Maghazei, T. Netland, Drones in manufacturing: exploring opportunities for research and practice, J. Manuf. Technol. Manag. 31 (6) (2020) 1237–1259, https://doi.org/10.1108/JMTM-03-2019-0099. Scopus.
[74] L. Abualigah, A. Diabat, P. Sumari, A.H. Gandomi, Applications, deployments, and integration of internet of drones (Iod): a review, IEEE Sensor. J. 21 (22) (2021) 25532–25546, https://doi.org/10.1109/JSEN.2021.3114266.
[75] R. Campaci, M. Favaretto, T. Grasso, T. Borzone, A. Vignali, R. Benedetti, M. Cattoi, D. Maffei, Design and Development of an UAV Certified for Explosive Atmospheres, 2023. OMC-2023-399.
[76] T.G. Reio, B. Shuck, Exploratory factor analysis: implications for theory, research, and practice, Adv. Develop. Hum. Resour. 17 (1) (2015) 12–25, https://doi.org/10.1177/1523422314559804.
[77] S. Luthra, S.K. Mangla, L. Xu, A. Diabat, Using AHP to evaluate barriers in adopting sustainable consumption and production initiatives in a supply chain, Int. J. Prod. Econ. 181 (2016) 342–349, https://doi.org/10.1016/j.ijpe.2016.04.001.
[78] P.M. Nardi, Doing Survey Research: A Guide to Quantitative Methods, fourth ed., Routledge, 2018 https://doi.org/10.4324/9781315172231.
[79] S. Luthra, S.K. Mangla, Evaluating challenges to Industry 4.0 initiatives for supply chain sustainability in emerging economies, Process Saf. Environ. Protect. 117 (2018) 168–179, https://doi.org/10.1016/j.psep.2018.04.018.
[80] R. Maskey, J. Fei, H.-O. Nguyen, Use of exploratory factor analysis in maritime research, The Asian Journal of Shipping and Logistics 34 (2) (2018) 91–111, https://doi.org/10.1016/j.ajsl.2018.06.006.
[81] K.S. Taber, The use of cronbach's alpha when developing and reporting research instruments in science education, Res. Sci. Educ. 48 (6) (2018) 1273–1296, https://doi.org/10.1007/s11165-016-9602-2.
[82] C.-W. Chien, T. Brown, R. McDonald, S. Rodger, Convergent and discriminant validity of a naturalistic observational assessment of children's hand skills, Hong Kong J. Occup. Ther. 21 (2) (2011) 64–71, https://doi.org/10.1016/j.hkjot.2011.10.003.
[83] R. Eisinga, M.T. Grotenhuis, B. Pelzer, The reliability of a two-item scale: Pearson, Cronbach, or Spearman-Brown? Int. J. Publ. Health 58 (4) (2013) 637–642, https://doi.org/10.1007/s00038-012-0416-3.
[84] N. Shrestha, Factor analysis as a tool for survey analysis, Am. J. Appl. Math. Stat. 9 (1) (2021) 4–11, https://doi.org/10.12691/ajams-9-1-2.
[85] A.G. Yong, S. Pearce, A beginner's guide to factor analysis: focusing on exploratory factor analysis, Tutorials in Quantitative Methods for Psychology 9 (2) (2013) 79–94, https://doi.org/10.20982/tqmp.09.2.p079.
[86] R.K. Henson, J.K. Roberts, Use of exploratory factor analysis in published research: common errors and some comment on improved practice, Educ. Psychol. Meas. 66 (3) (2006) 393–416, https://doi.org/10.1177/0013164405282485.
[87] B. Williams, A. Onsman, T. Brown, Exploratory factor analysis: a five-step guide for novices, Australasian Journal of Paramedicine 8 (2010) 1–13, https://doi.org/10.33151/ajp.8.3.93.
[88] J. Osborne, What is rotating in exploratory factor analysis? Practical Assess. Res. Eval. 20 (1) (2019) https://doi.org/10.7275/hb2g-m060.
[89] P. Samuels, Advice on Exploratory Factor Analysis [Monograph], ResearchGate, 2017. https://www.researchgate.net/publication/319165677_Advice_on_Exploratory_Factor_Analysis.
[90] M. Zhang, Y.K. Tse, B. Doherty, S. Li, P. Akhtar, Sustainable supply chain management: confirmation of a higher-order model, Resour. Conserv. Recycl. 128 (2018) 206–221, https://doi.org/10.1016/j.resconrec.2016.06.015.
[91] S. Luthra, K. Govindan, D. Kannan, S.K. Mangla, C.P. Garg, An integrated framework for sustainable supplier selection and evaluation in supply chains, J. Clean. Prod. 140 (2017) 1686–1698, https://doi.org/10.1016/j.jclepro.2016.09.078.
[92] P.H. Dos Santos, S.M. Neves, D.O. Sant'Anna, C.H.D. Oliveira, H.D. Carvalho, The analytic hierarchy process supporting decision making for sustainable development: an overview of applications, J. Clean. Prod. 212 (2019) 119–138, https://doi.org/10.1016/j.jclepro.2018.11.270.
[93] T.L. Saaty, Decision making with the analytic hierarchy process, Int. J. Serv. Sci. 1 (1) (2008) 83, https://doi.org/10.1504/IJSSCI.2008.017590.
[94] R.W. Saaty, The analytic hierarchy process—what it is and how it is used, Math. Model. 9 (3) (1987) 161–176, https://doi.org/10.1016/0270-0255(87)90473-8.
[95] F. Pauer, K. Schmidt, A. Babac, K. Damm, M. Frank, J.-M.G. von der Schulenburg, Comparison of different approaches applied in Analytic Hierarchy Process – an example of information needs of patients with rare diseases, BMC Med. Inf. Decis. Making 16 (1) (2016) 117, https://doi.org/10.1186/s12911-016-0346-8.
[96] F. Outay, H.A. Mengash, M. Adnan, Applications of unmanned aerial vehicle (UAV) in road safety, traffic and highway infrastructure management: recent advances and challenges, Transport. Res. Pol. Pract. 141 (2020) 116–129, https://doi.org/10.1016/j.tra.2020.09.018. Scopus.
[97] A. Restas, Drone applications for preventing and responding hazmat disaster, World J. Eng. Technol. 4 (3) (2016) 76–84, https://doi.org/10.4236/wjet.2016.43C010.