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Investigation of Operational Parameters that Affect the Use of Drones in Goods' Stock Count Process: Evidence from Experimental Results

Nikolaos Christoforos Thomaidis , Vasileios Zeimpekis*

University of the Aegean, School of Engineering, Department of Financial & Management Engineering (Greece)

fmer21003@fme.aegean.gr
**Corresponding author: vzeimp@fme.aegean.gr*

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Abstract:

Purpose: Recently, the complexity of managing warehouses has been amplified significantly due to factors that include increased requests for more frequent and smaller order fulfilment, reduction of operational cost, and improvement of customer experience. Product stock count is a critical process in order to address the aforementioned challenges. This article presents experimental results from the adoption of drones coupled with RFID tags used for real time goods' stock count.

Design/methodology/approach: The research methodology adopted combines three different methods, namely Systematic Literature Review (SLR) for identifying parameters that affect the performance of drones in stock count process, survey via questionnaire and interviews to logistics managers to map needs and requirements in warehouse operations, as well as laboratory testing via Design of Experiment (2^4 full factorial design & ANOVA) methodology to investigate how certain parameters corelate and affect the reading accuracy of RFID tags as well as the time needed by a drone for stock count completion.

Findings: The results of the experiments are encouraging, showing that the use of drones coupled with RFID tags may support faster, cost-effective, and safer stock count in warehouses. In both ambient and chilled storage environment a 100% RFID tag reading accuracy was achieved. Less stock-count completion time when compared to manual stock-count was achieved in both cases.

Research implications: Understanding the effect of technical and operational parameters of RFID technology in conjunction with unmanned aerial vehicles (UAVs)-drones may have the potential to radically transform the stock count process by considerably increase the efficiency and accuracy of the process.

Practical implications: Real-time stock count via drones has significant cost-saving implications for organizations. The elimination of manual stock counting saves operational expenses and increases staff safety. Furthermore, real-time data collection of existing product stock allows managers to efficiently allocate resources, enhancing overall efficiency and performance.

Originality/value: This research is among the first studies that aim to present evidence from experimental results that assess the use of drones coupled with RFID technology for real-time stock count. The results from laboratory experiments demonstrate the effect of certain operational parameters, such as drone speed, number of rack levels, and RFID tag location on products, during the execution of the stock count process in terms of RFID reading accuracy and stock-count completion time.

Keywords: drones, logistics, industry 4.0, stock count, warehouse, RFID technology

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1. Introduction

A supply chain system is a complex set of processes that aims to increase customer service and achieve a sustainable competitive advantage. This system involves various activities such as demand forecasting, inventory management, transportation, storage and shipping of products, as well as the necessary information systems to coordinate these activities. Researchers argue that in order to achieve high customer experience and manage operational costs, logistics operations need to be organized with emphasis on warehouses and distribution centers (de Koster, Le-Duc, & Roodbergen, 2007; Wawrla, Maghazei & Netland, 2019).

Indeed, managing warehouses has become increasingly complex due to factors such as the demand for more frequent and smaller order fulfilment, increased e-commerce sales, international competition, and the need for faster response times (de Koster et al., 2007; Marchet, Melacini & Perotti, 2015). Many companies currently use information systems, special equipment, and automation to increase productivity, reduce handling time, and improve customer service.

The concept of Industry 4.0 has paved the way for smart warehouses where the latest advances in technological enablers like big data and robotics are used. Unmanned Aerial Vehicles (UAVs) – drones, are considered a key technology for smart warehouses since they can carry out repetitive and demanding tasks with almost no human intervention or supervision task (Harik, Guérin, Guinand, Brethé & Pelvillain, 2016; Van Gils, Ramaekers, Caris & de Koster, 2018). UAVs are also expected to provide several advantages over conventional material handling equipment, such as the ability to collect, store, and dispatch products, and exchange information with warehouse management systems (Wawrla et al., 2019).

This article presents evidence from experimental results that assess the use of UAVs coupled with RFID technology for real-time stock count execution. The research question can be formulated as follows: Can stock count process become more efficient and accurate by using UAVs and RFID technology? The research thus focuses on understanding the effect that technical and operational parameters of RFID technology in conjunction with unmanned aerial vehicles (UAVs)-drones may have, to radically transform the stock count process.

This research, to the best knowledge of the authors, is among the first studies that aim to present evidence from experimental results that assess the use of drones coupled with RFID technology for real-time stock count. The results from laboratory experiments are encouraging and demonstrate the effect of certain operational parameters, such as UAV speed, number of rack levels, and RFID tag location on products, during the execution of the stock count process in terms of RFID reading accuracy and efficiency. A 2^4 full factorial design was used to test UAV and RFID technology in a warehouse with products that are stored in ambient and chilled environment.

The article is structured as follows: Section 2 briefly describes the research methodology followed. Section3 presents the findings from the literature review conducted by using the Systematic Literature Review (SLR) methodology. Then, Section 4 presents the results from requirements analysis conducted via a survey and interviews with logistics experts. Subsequently Section 5 introduces the Design of Experiments (DoE) methodology and presents the results from laboratory tests conducted to evaluate the efficiency and accuracy of using UAVs for stock count. Finally, Section 6 discusses the theoretical contribution and limitations of the research conducted, presents managerial implications derived by the adoption of drones in stock count process and concludes with the way forward.

2. Research Methodology

Based on the principle of Näslund, (2002) who argues that "it is necessary to use at least two different research methodologies if somebody wants to develop and advance logistics research", it was decided to adopt a research methodology which combines three different research methods (Table 1). The first method is a systematic literature review (SLR) for parameters' selection for UAV system evaluation. The second method deals with the conduction of a survey via questionnaire and interviews for requirements analysis, while the third method focuses on laboratory (Lab) tests for system testing and evaluation. The combination of the three methods adopted in this article, can overcome the potential bias and sterility of single method approaches and is known as triangulation (Collis & Hussey, 2003).

Phase	Method	Output
1	Systematic literature review (SLR) of operational and technical parameters of UAVs for logistics operations	Parameters' selection for UAV system evaluation
2	Survey & Interviews with logistics experts	Requirements' analysis concerning the adoption of UAVs in logistics operations
3	Laboratory testing	Testing, evaluation, and optimization of system by using the selected parameters of Phase 1

Table 1. Three-phase triangulated research methodology

3. Literature Review on Unmanned Aerial Vehicles (UAVs)-Drones

The systematic literature review was focused on the identification of technical and operational characteristics of Unmanned Aerial Vehicles (UAVs) and parameters that affect UAVs performance when adopted in logistics processes. The steps of selecting the protocol are described as follows:

Step 1: Determination of Inclusion Criteria and Search

In order to achieve comprehensive research, a series of search terms / keywords and induction criteria were determined. Our literature search covered published academic research articles between 2015 and 2020 in Web of Science, Science Direct, and Scopus. The search process was conducted by means of three research strings, separated by the respective Boolean operators as follows: "real-time stock count" AND "RFID technology" AND "Unmanned Aerial Vehicles". A number of inclusion criteria (e.g., peer-reviewed articles, published after 2015, available full-original text in English) were then applied.

Step 2: Read and Selection Based on Title and Abstract

In this step a review of selected studies (from step 1) has taken place based on the titles and abstracts of studies. During this review, a series of studies out of the research scope were excluded from our list since they were focusing on UAV system design as well as in other applications such as military, maritime, and agricultural.

Step 3: Read and Selection Based on Full Text and Snowballing

During the last step of the protocol, the reading of full versions of available studies as well the refining of our list took place. In this phase, by taking into consideration the remaining papers, we reviewed the references of the selected studies and we added to our list the papers, which met our inclusion criteria which were identified during the first step of protocol. To this end, our final corpus involved 46 studies. Out of the total 46 papers reviewed, 70% (32 articles) were journal papers and 30% (14 articles) were conference papers. The limited number of published articles in academic journals and conferences, along with the distribution of the reviewed studies over time, indicates that the field is relatively new from a research perspective.

The time distribution graph in Figure 1a, shows that the number of articles on the use of drones in logistics processes has increased significantly in recent years, with publications ranging from 2015 to 2021 respectively. Figure 1b, reveals that more than half of the articles were published in the last three years, indicating a significant interest and development in the area of UAVs in logistics operations. The highest number of papers was published in 2019, with 15 papers (8 journal papers and 7 conference papers) identified.

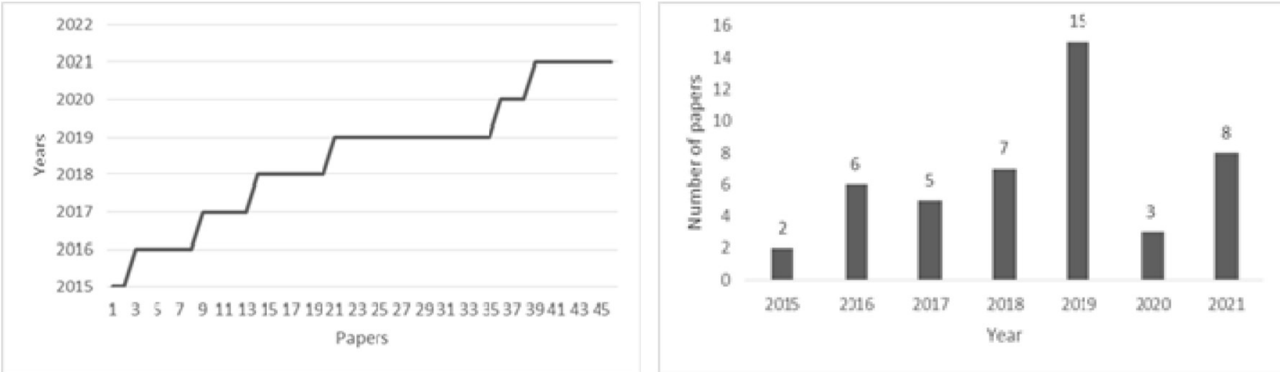


Figure 1. a) number of reviewed articles, b) time distribution of the reviewed articles

From the articles reviewed, eight categories of technical characteristics are identified, namely: a) UAV flight control, b) UAV weight type, c) UAV wing type, d) Propulsion system e) Wing span, f) Flight range, g) Flight range and, h) Operational altitude and four categories of operational characteristics are identified, namely: a) flight zone, b) mission, c) environment and d) applications. Below a description of each parameter is given.

UAV flight control: UAVs operate without a pilot on-board and can be controlled in two ways: autonomously or remotely by a human pilot. Autonomous drones can make decisions and perform complex tasks without human intervention, while remotely piloted drones require direct control from a human operator (Otto, Agatz, Campbell, Golden & Pesch, 2018).

UAV weight type: Drones can be classified in terms of weight (Derpich, Miranda & Sepulveda, 2018). Specifically, they can be classified by the minimum take-off weight combined with how the drones are intended to be used and where they are expected to operate. Drones may be classified into three classes (Class I, II, and III) according to their type and weight range as argued by Hassanalian and Abdelkefi, (2017).

UAV wing type: UAVs can be categorized by their wing type as fixed-wing, rotary-wing, and hybrid aircrafts (Delavarpour, Koparan, Nowatzki, Bajwa & Sun, 2021; Derpich et al., 2018). Fixed-wing UAVs require runways for takeoff and landing, can fly at high altitudes and speeds, and cover vast areas with centimeter-level accuracy. Rotary-wing UAVs fly at lower altitudes and speeds, cover smaller areas, and collect sub-centimeter resolution data. Hybrid aircrafts combine the advantages of fixed-wing and rotary-wing UAVs and are suitable for tasks that require both endurance and maneuverability, with large control surfaces and high thrust-to-weight ratio Delavarpour et al. (2021).

Propulsion system: Different categories of propulsion systems are used in drones, with the most common types being the gas turbine, electric motor-based, and battery-based propulsion systems (Macrina, Pugliese, Guerriero & Laporte, 2020). Gas turbines are internal combustion engines that convert chemical energy into mechanical energy, while electric motors use electricity to create rotational motion and drive propeller blades for propulsion. Batteries are electrochemical energy storage devices that convert stored chemical energy into electrical energy. These systems are silent, lightweight, self-contained, and reliable, but have limited endurance and recharge limits. Rechargeable batteries are the most commonly used. Although electric motors have low operational cost, require low maintenance, and are robust, they are sensitive to water or other conductive liquids and can be affected by electromagnetic interferences. Gas turbines are widely used and reliable but have a very heavy mechanism (Macrina et al., 2020).

Wing span: Another important technical characteristic of drones is wing span. There is a spread spectrum of drones from UAV class with maximum wing span of 61 m and weight of 15,000 kg to smart dust (SD) with minimum size of 1 mm and weight of 0.005 g. Between UAV and SD at both ends of the defined spectrum, there are various types of drones, which are called micro drones, such as micro unmanned air vehicle (µUAV), mini air vehicle (mAV), nano air vehicle (nAV), and pico air vehicle (pAV) (Hassanalian & Abdelkefi, 2017).

Flight range: An important characteristic of drones is the flight range (Derpich et al., 2018). The flight range is directly related to the weight carried by the drone. Hassanalian and Abdelkefi (2017), classify drones based on their weight and range as follows: micro and mini-UAV close range, lightweight UAVs small range, lightweight UAVs medium range, average UAVs, medium heavy drones, heavy medium range UAVs, heavy drone large endurance, and unmanned combat aircraft.

Flight endurance: Flight endurance is a key technical characteristic of UAVs, closely linked to flight range (Otto et al., 2018). Endurance enables designers to select the appropriate type of UAV based on mission distance (Rejeb, Rejeb, Simske & Treiblmaier, 2021). UAVs are classified into three categories: long, medium, and low endurance. Long endurance UAVs can stay airborne for 24 hours or more, while medium endurance UAVs have endurance between 5 and 24 hours. Low endurance UAVs have less than 5 hours of endurance (Arjomandi, Agostino, Mammone, Nelson & Zhou, 2006).

Operational altitude: The maximum operational altitude is a significant technical characteristic for UAVs, which can be classified into three categories based on their maximum ceiling: low altitude, medium altitude, and high-altitude UAVs. Low altitude UAVs fly up to 1000m and are used for commercial applications such as parcel delivery and surveillance. Medium altitude UAVs have a maximum altitude between 1000m and 10000m. High altitude UAVs can fly over 10000m, but there is a concern that they may interfere with commercial and military manned aircraft. Therefore, high-tech collision avoidance systems are being developed and integrated into these UAVs that fly in populated airspace (Arjomandi et al., 2006).

Table 2 shows the technical characteristics of UAVs as resulted from the literature review.

	Technical characteristics							
	UAV flight control	UAV weight type	UAV wing type	Propulsion system	Wing span	Flight range	Flight endurance	Operational altitude
Otto et al. (2018)	●							
Hassanalian and Abdelkefi (2017)	●	●	●	●	●	●	●	
Delavarpour et al. (2021)	●		●					
Macrina et al. (2020)				●				
Arjomandi et al. (2006)				●			●	●
Rejeb et al. (2021)							●	
Derpich et al. (2018)		●	●	●		●		●
Otto et al. (2018)							●	

Table 2. Technical characteristics of UAVs: Results from literature review

Furthermore, typical processes that drones may execute in warehouses and distribution centers are as follows: a) Inventory management, b) Intra-logistics, c) Picking, d) Inspection, and f) Facility physical security & surveillance (Derpich et al., 2018; Sorbelli, Coro, Pinotti & Shende, 2019; Macrina et al., 2020; Rejeb et al., 2021),. The latter are described below.

Inventory management-Stock count: UAVs have the potential to automate and improve inventory management processes. They can be used for tasks such as inventory audit, cycle counting, item search, buffer stock maintenance, and stock count, and may help decrease cycle count times and labor costs, increase inventory accuracy rates, and avoid the risk of employees working at heights (Sorbelli et al., 2019). Traditional inventory management processes have downsides such as being error-prone and highly repetitive, but drones can add value and support the execution of these processes. Various cases have demonstrated the use of drones for inventory management (Bae, Han, Cha & Lee, 2016; Beul, Droeschel, Nieuwenhuisen, Quenzel, Houben & Behnke, 2018; Fernández-Caramés, Novoa, Míguez & Lamas, 2019) whereas other researchers have examined the use of UAVs to replace human operators for scanning purposes or to automate inventory tasks and keep traceability of industrial items attached to RFID tags.

Intra-logistics: Drones have the potential to be used in intra-logistics operations for tasks such as on-site delivery of products and spare parts, as well as transportation of goods from warehouses to production lines. Derpich et al. (2018), propose a solution to the assignment of drones to machines or workstations, while Kloetzer, Burlacu, Enescu, Caraiman and Mahulea (2019) study a type of UAV routing problem applied to an indoor warehouse. The latter uses mathematical programming and simulations to transport goods from storage to delivery areas by low energy drones with finite capacities.

Picking: Picking is a crucial activity in a warehouse and accounts for a significant portion of operating costs. It is also the highest priority for improving productivity and requires a considerable amount of time and human effort. Movement within corridors is the most time-consuming aspect of picking. Drones have become an increasingly popular solution for warehouse picking tasks as they reduce time consumption and increase customer service. Automated picking systems using drones can gather items requested in a customer order and transport them to a predefined location on the drone's cart. Sorbelli et al. (2019), compared the efficiency of automated picking systems employing drones with traditional systems employing workers pushing carts and determined the conditions under which drones are more efficient.

Inspection: Drones can replace manual inspection operations in warehouses and indoor use cases for inspection are growing. They are a perfect fit for tasks that require monitoring and inspection in dangerous areas or high altitudes, such as inspecting racks, pallet placements, walls, and ceilings in warehouses (Wawrla et al., 2019; Yap, Eu & Low, 2016).

Facility physical security & Surveillance: Physical security in warehouses involves protecting personnel, assets, and data from physical threats like fire, burglary, and terrorism. Unmanned Aerial Vehicles (UAVs) are one of the technologies used for physical security (Rejeb et al., 2021). Drones equipped with various sensors can be used for facility protection, surveillance, and inspections in difficult to access or unsafe locations (Hell & Varga, 2019). Automated and optimized drone systems can minimize the human factor in physical security operations, saving time and cost (Wawrla et al., 2019; Macrina et al., 2020).

4. Mapping of Users' Requirements

In order to map users' requirements for automating logistics processes via drones, a 5-step methodology was adopted. The latter is depicted in Figure 2.

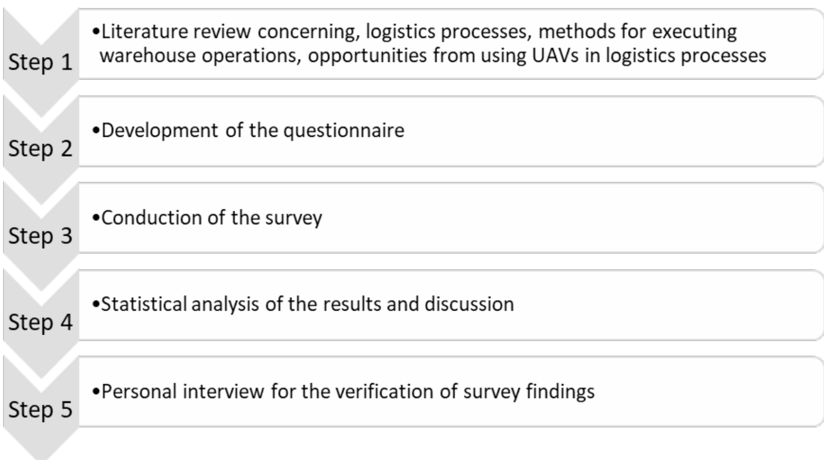


Figure 2. Steps for mapping users' requirements

The methodology is analysed as follows:

- Step 1: In this step, we identified warehouse operations that could be automated by adopting UAVs. We have also considered the results from the initial literature review conducted (Section 3).
- Step 2: In this step we prepared a structured questionnaire with 20 questions that were classified in three sections, namely: a) Company Profile, b) Current methods and inefficiencies for executing logistics operations, c) Potential use of UAVs for performing logistics processes.
- Step 3: The structured questionnaire was distributed to 35 companies to investigate current logistics practices and the potential use of drones for logistics processes including product stock count in warehouses.
- Step 4: A descriptive statistics analysis was performed in order to identify the main inefficiencies of performing warehouse operations. Furthermore, the potential use of UAVs in various logistics processes was identified.
- Step 5: We contacted 5 logistics industry executives in order to confirm the findings of the survey. We decided to interview a rather small number of experts for the following reasons:
    - The selected executives were key decision-makers in their respective organizations. Their insights carry significant weight due to their expertise and roles in shaping logistics and IT strategies.
    - The focus of Step 5 was on obtaining in-depth insights rather than a broad overview. By selecting high-level executives, we were able to delve deeply into the strategic aspects of logistics processes, gaining nuanced and comprehensive information.
    - Furthermore, the goal was to gather rich and detailed information from a select group of experts rather than a larger but potentially less influential and informed sample.
    - A smaller sample size was necessary to maintain the confidentiality of the data and ensure executives felt comfortable sharing proprietary insights.

4.1. Questionnaire Analysis

From the distribution of the questionnaire, we received 35 responses. More than half of the companies that participated in the survey were 3PL companies (52%), while manufacturing and wholesale companies participated with a percentage of 31% and 17% respectively. The results (Figure 3) highlight that companies face high operating costs, human errors, low productivity as well as high risk of accidents involving staff during the execution of logistics processes. Specifically, the stock count process, stock control of re-usable products, and stock control of raw materials and/or final products are particularly inefficient.

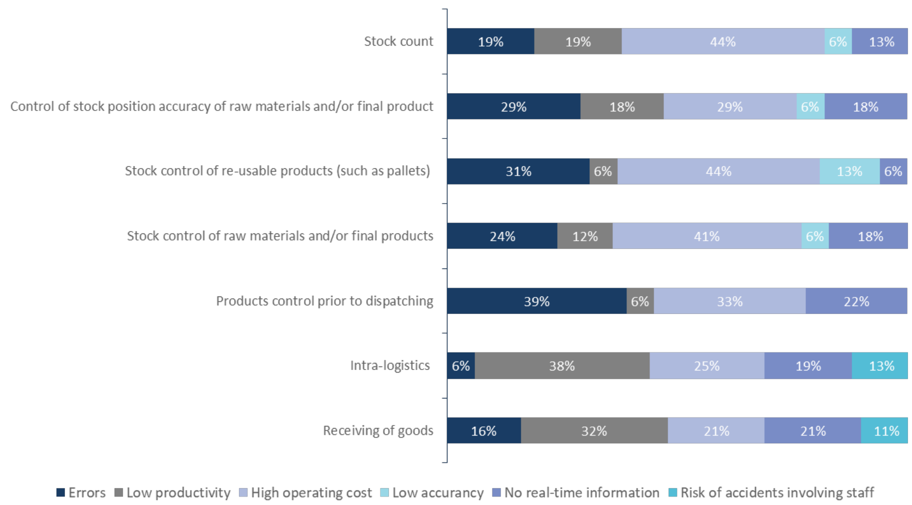


Figure 3. Inefficiencies encoutered during the execution of logistics processes

Furthermore, the results revealed that 58% of the companies are aware of the use of UAVs for certain logistics processes, and 78% were interested in identifying methods to automate logistics processes. In addition, the majority of the respondents (86%) were interested in automating the stock count process using UAVs (Figure 4).

Another interesting finding from the survey was that the majority of the respondents are interested in automating logistics processes in order to increase productivity, reduce errors and operating costs, and have end-to-end visibility of the available stock (Figure 5).

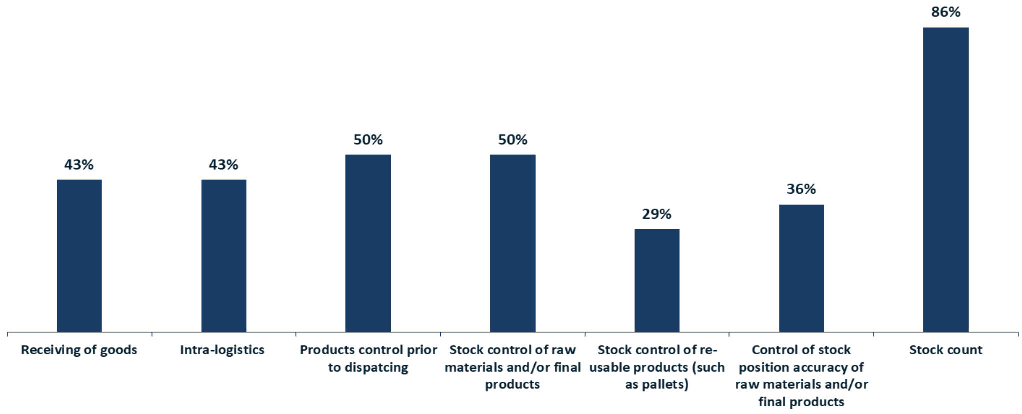


Figure 4. Processes that can be automated by adopting UAV technology

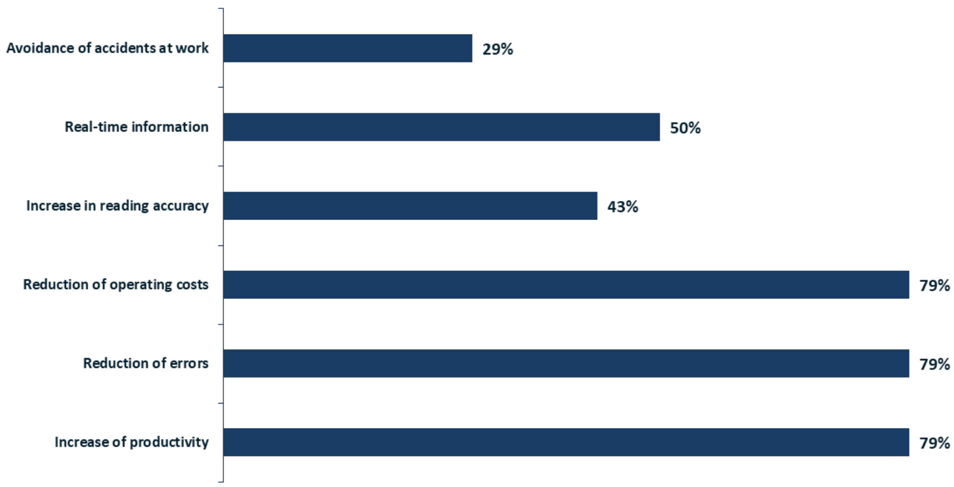


Figure 5. Main reasons for automating logistics processes vua UAV technology

4.2. Confirmation of the Findings of the Survey Via Interviews

The interviews were conducted with 5 logistics industry executives in order to confirm the findings of the survey. The responses from the interviews confirmed that there is an interest from logistics operator in using UAVs to increase productivity and decrease operational costs. Of particular importance is the interest shown by logistics executives in exploring the adoption of UAVs in logistics processes such as inventory control and stock count. The interviewees argued that there is room for improvement in order to reduce operating costs, increase productivity and accuracy in controlling inventories. They also estimated the time period for the adoption of UAV technology to be a period of 3-5 years. They also underlined that cost of ownership, Return on Investment (ROI), and existing legislation are key factors for the adoption of UAV technology.

5. Laboratory Setup and Experimental Results

5.1. Design of Experiments

In order to carry out the experimental procedure for the investigation of parameters that affect the performance of drones during real-time stock count process, the methodology of Design of Experiments (DoE) was adopted (Montgomery, 2012). DoE methodology supports researchers to recognize the effects of a series of factors on the performance of a process or system. Furthermore, this approach assists the researchers in recognizing the best settings configuration for these factors (Gialos & Zeimpekis, 2020). The steps of this procedure, proposed by Montgomery (2012), are the following:

- Choice of factors and levels: The parameters that were taken into consideration are UAV speed, UAV flight altitude/read distance, Tag location, and Number of levels per rack. A 2-level approach was adopted for conducting the experiments.
- Choice of experimental design: The experimental design adopted is a full factorial design that has four factors at two levels (High and Low) (Montgomery, 2012) and all possible combinations of the four factors across their levels are used in the design. The assumptions that are taken into considerations according to Anderson and McLean (1974) are as follows.
    - The factors are fixed: A factor is fixed if its levels are purposely designed (or set) by the experimenter and not selected at random.
    - The designs are completely randomized: This assumption is required as the experiment must be performed in random order so that the environment in which the treatments are applied is as uniform as possible. In our case randomization has been ensured through our Design of Experiments and the statistical processing of data in MiniTAB.
    - The normality assumptions are satisfied: it is usually assumed that errors have a normal distribution with mean zero and variance. In our case we have checked the normality assumption through the Kolmogorov-Smirnov test.
- Formulate Research Hypothesis and perform the experiment: As noted above there are 2^4 (i.e., 16) possible treatments, thus the aim is to test appropriate hypotheses about the treatment effects and estimate them.
- Statistical analysis of data: During the statistical analysis of data, four basic steps were followed (Montgomery, 2012):
    - Fit the full model: The object in this step was to select factors that have large effects. Having created a factorial design and collected the response data, the model was fitted to the results and certain graphs that evaluated the effects were generated.
    - Fit a reduced model: In this step a new model was fitted using only the terms that have been identified as important by examining the results of the full model.
    - Evaluate the reduced model: By using ANOVA the reduced model was evaluated and information was provided on how good the model was.
    - Draw conclusions about the model: By examining specific statistical plots, conclusions about the factors and possible interactions between them were drawn.

5.2. Experimental Equipment

The storage system as well as the equipment that was used for conducting the experiments are presented below.

- Storage system: The experiments that are described in this article were carried out by taking into consideration a Back-to-Back storage rack system. The latter is a well-known and vastly used storage system in modern warehouses. It consists of multiple levels of shelves and is quite flexible.
- Equipment: To perform the experiment, the drone Mavic Air 2 from DJI was used. For the reading of RFID tags that was placed on products, the Chainway R5 Wearable RFID Reader was used with a circular

polarized antenna. Furthermore, the Dogbone MR6 RFID tags were used during the experiment. It is important to mention that the RFID reader was mounted on the UAV performing in that way the counting of the products during the flight.

5.3. Description of Parameters

The parameters that were taken into consideration based on the findings of the literature review and the equipment available are presented below.

- **UAV speed:** Drones must adjust their speed so that they can scan all the required products and avoid mistakes, and at the same time move as fast as possible to save time (Hassanalian & Abdelkefi, 2017; Rejeb et al., 2021). For the control of the factor of UAV speed, four different speeds (0,5 m/s, 1 m/s, 1.5 m/s and 2 m/s) were examined (Figure 6).

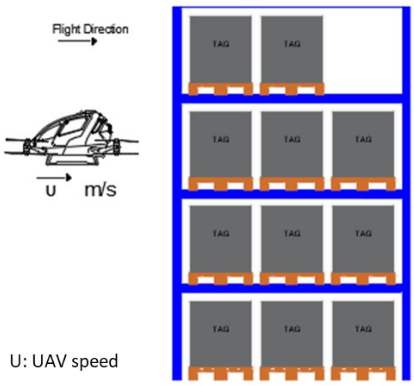


Figure 6. UAV speed parameter

- **UAV flight altitude/read distance:** A test to investigate the accuracy of reading an RFID tag was performed by taking into consideration multiple UAV flight altitudes (Figure 7). Indeed, an experimental setup was developed for multiple altitudes of 0.7 m, 1.6 m, 2.3 m, and 3.9 m respectively.

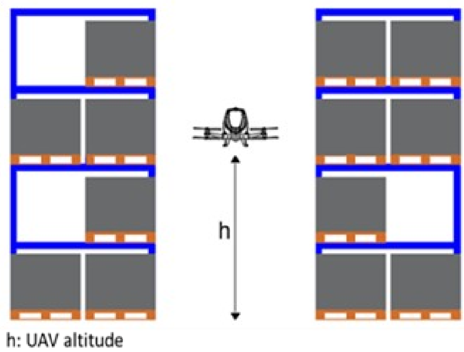


Figure 7. UAV flight altitude / read distance

- **Tag location:** The tag location is defined as the centroid of the probable region which is recorded by the latitude and longitude of the UAV when a tag is identified (Durić, Jovanović & Sibalija, 2018). This test examined if the position of the RFID tag according to the flight path of the UAV affects its reading by the RFID reader. Specifically, it was investigated whether the RFID tag is read on all four sides of a carton on a fixed flight path of the UAV (Figure 8).

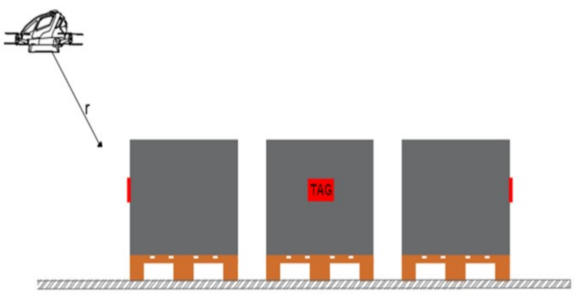


Figure 8. Tag location

- **Number of levels per rack:** This test has two cases to be investigated, single and double level per rack. In the first case, the UAV flies and scans RFID tags per level of each rack, whereas in the second case the UAV flies in the middle of the two levels of a rack and scans simultaneously the products of both levels (Figure 9).

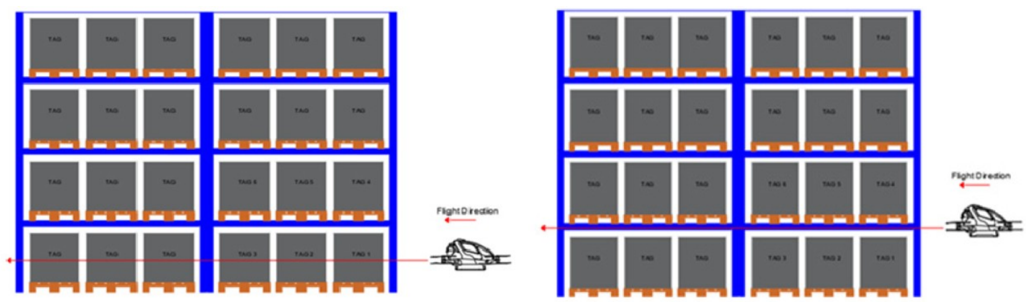


Figure 9. Number of levels (single and double)

5.4. Experimental Results

The experimental results took place in two phases. In Phase A, a series of experiments were conducted for determining the values of levels of DoE. In Phase B, experiments were conducted in order to assess how the selected, from Phase A, parameters affect the performance of UAVs during stock count.

5.4.1. Experimental Results for the Selection of Factors to be Investigated and Values of Levels of Doe (Phase A)

The selection of the values of levels of each parameter resulted from the execution of individual tests for each of them (Figure 10). Multiple values for the levels of each factor(parameter) were examined, as described in previous section, so as to define the suitable values that will be adopted during the conduction of the final experiments (Phase B of laboratory tests).

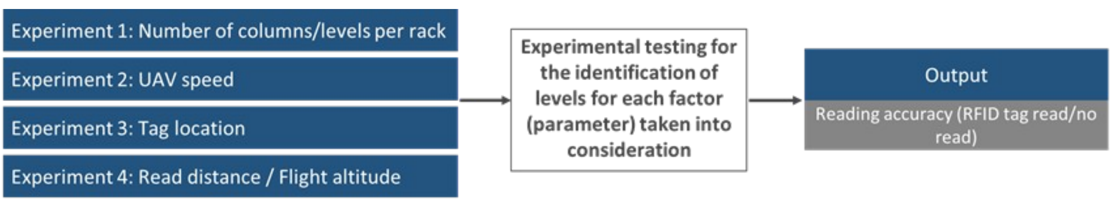


Figure 10. Phase A set of laboratory tests

The Phase A tests were carried out in two different warehouses (Figure 11). The first one had an ambient environment and dry products were stored whereas the second one had a chilled environment and liquid products were stored. The ambient warehouse had a height of 8m, consisted of shelves with 7 levels and the storage of product was in item-level, box and pallet. The second warehouse had a height of 10.9 m, consisted of shelves with

5 levels and products were stored in pallet level. It is worth mentioning that during experiments only 4 levels of each rack were considered.

a) Ambient warehouse b) Chilled warehouse

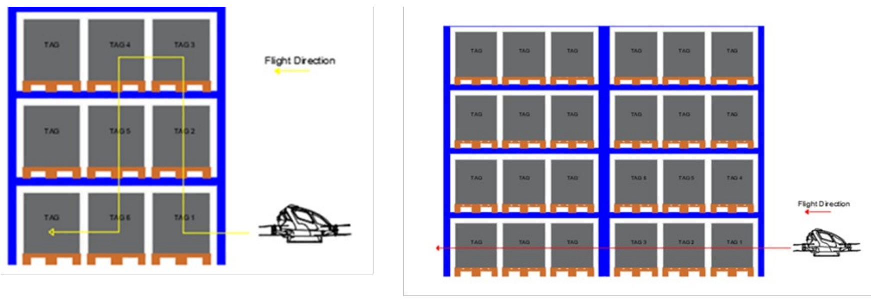
Figure 11. Warehouses used for Phase A tests

Moreover, for both warehouses, the experiments were carried out by considering two different positions of the RFID reader. The RFID reader in one case was positioned on the upper side of the UAV and in the other case it was positioned underneath the UAV (Figure 12).

a) Upper side b) Underside

Figure 12. Different positions of RFID reader mounted on the drone

In addition, the experiments for each parameter were performed for two different ways of flight of the UAV within of the warehouse. In the first way of flight the UAV follows an S-shape movement and in the second a straight movement within the aisles of the warehouse (Figure 13).



a) S-shape flight way b) Straight flight way

Figure 13. S-shape and straight flight

During the conduction of laboratory tests, an additional experiment was conducted. Results showed successful RFID tag reading when the UAV was flying in the middle of a corridor, leading to simultaneous reading across racks to reduce stock count time. Additionally, it was observed that straight flight paths were faster than S-shaped ones, so the simultaneous stock count experiment was only performed for the straight path. Results were encouraging, with 100% reading of RFID tags in both warehouses for both positions of the RFID reader (upper side and underneath).

According to the results from the Phase A of laboratory tests and the extra experiment performed, the parameters and values of their levels that were selected are as follows: b) number of levels: 1 level and 2 level, b) UAV speed: 0.5m/s and 1.5m/s, c) Tag location: front side and back side of the pallet, d) UAV tag reading method: Along a rack and Across racks. Furthermore, it is worth mentioning that the RFID reader performs better when positioned underneath the UAV.

5.4.2. Experimental Results for Assessing Selected Parameters that Affect the Performance of Uavs During Stock Count (Phase B)

The purpose of this experiment (Phase B of laboratory tests) is to investigate whether certain parameters: a) Number of levels, b) UAV speed, c) Tag location, and d) UAV tag reading method, affect the accuracy and total stock count time in stock count process of warehouses. To carry out the experiment under investigation, the Design of Experiments (DoE) methods was used (Figure 14).

Table 3 presents the selected factors as well as their corresponding levels which will be used for the experiments. As mentioned before the levels of each factor were selected by taking into consideration the experimental results for the selection of factors to be investigated and values of levels of DoE.

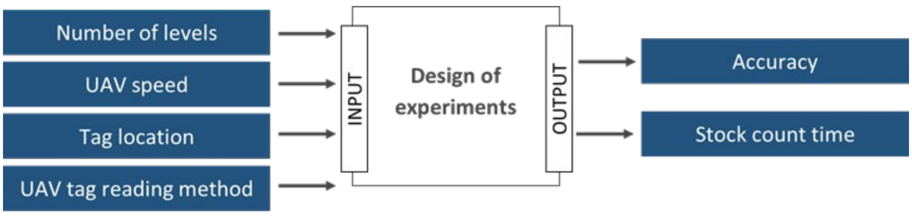


Figure 14. Phase B set of laboratory tests

Factors	Level 1	Level 2
Number of Levels	1 level	2 levels
UAV Speed	0,5 m/s	1 ,5 m/s
Tag Location	Back side	Front side
UAV tag reading method	Along a rack	Across racks

Table 3. Parameters to be investigated and their levels

5.4.3. Case Study 1: Warehouse with Ambient Temperature (Phase B1)

For the evaluation of stock count process two outputs that affect the productivity and performance were measured. The first parameter was the stock count time and the second was the accuracy of stock count process (i.e., the readability of the RFID tags). The stock count time was measured with a common stopwatch, while the accuracy was calculated by taking into consideration the RFID tag read rate during the conduction of the experiments. In the results presented below, we achieved a 100% RFID tag reading accuracy. In order to investigate whether the parameters under consideration were statistically significant, certain null hypotheses were introduced, as follows.

The first null hypothesis ($H_{0,1}$) states that the stock count time was the same when either the number of levels was 1 level or 2 levels:

$$H_{0,1}: t_{1\ level} = t_{2\ levels}$$

The second null hypothesis ($H_{0,2}$) states that the stock count time was equal when either the UAV speed was 0,5 m/s or 1,5 m/s:

$$H_{0,2}: t_{0,5\ m/s} = t_{1,5\ m/s}$$

The third null hypothesis ($H_{0,3}$) states that the stock count time was equal either when the tag location was back side or front side:

$$H_{0,3}: t_{\text{back side}} = t_{\text{front side}}$$

The fourth null hypothesis ($H_{0,4}$) states that the stock count time was equal either when the UAV tag reading method was along a rack or across the racks:

$$H_{0,4}: t_{\text{along a rack}} = t_{\text{across the racks}}$$

Following data collection, a quantitative analysis of the results was performed by using ANOVA. The results of the ANOVA showed that for cases: $H_{0,1}$, $H_{0,2}$ and $H_{0,4}$, the null hypothesis was rejected while for case $H_{0,3}$ the null hypothesis cannot be rejected. This means that the parameters "Number of levels", "UAV speed" and "UAV tag reading method" significantly affects the stock count time (Figure 15).

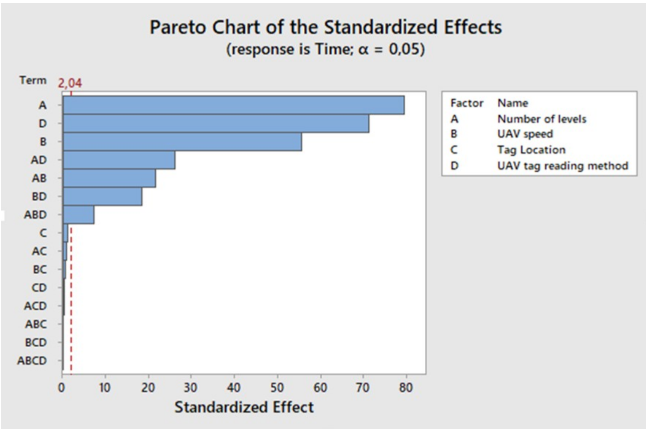


Figure 15. Pareto chart of the standardized effects – Case study 1

We also investigated the system configuration that results in the shortest stock count time. More specifically, it can be observed that the stock count time is lower when the number of rack levels that the drone is simultaneously reading RFID tags are 2, the tag is placed in the front side of a carton, the speed of the UAV is 1.5 m/s and the tag reading method of the UAV is across the racks (Figure 16).

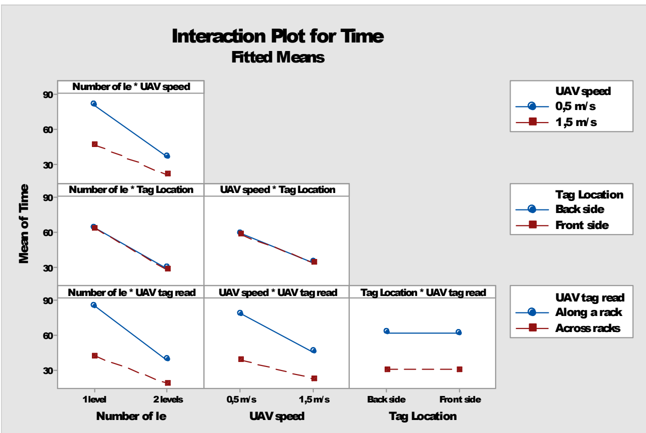


Figure 16. Interaction plots for parameters – Case study 1

5.4.4. Case Study 2: Warehouse with Chilled Temperature (Phase B2)

Similarly with Case Study 1, for the parameter of accuracy only cases where we had 100% RFID tag reading accuracy were considered. For the evaluation of the parameter of stock count time, certain null hypotheses were introduced, as follows.

The first null hypothesis ($H_{0,1}$) states that the stock count time was the same when either the number of levels was 1 level or 2 levels:

$$H_{0,1}: t_{1\ level} = t_{2\ levels}$$

The second null hypothesis ($H_{0,2}$) states that the stock count time was equal when either the UAV speed was 0,5 m/s or 1,5 m/s:

$$H_{0,2}: t_{0,5\ m/s} = t_{1,5\ m/s}$$

The third null hypothesis ($H_{0,3}$) states that the stock count time was equal either when the UAV tag reading method was along a rack or across the racks:

$$H_{0,3}: t_{along\ a\ rack} = t_{across\ the\ racks}$$

Following data collection, a quantitative analysis of the results was performed by using ANOVA. The results of the ANOVA showed that for cases: $H_{0,1}$, $H_{0,2}$ and $H_{0,3}$, the null hypothesis was rejected. This means that parameters "Number of rack levels", "UAV speed" and "UAV tag reading method" significantly affects the stock count time (Figure 17).

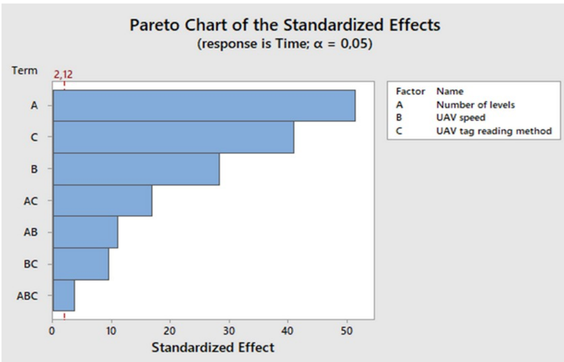


Figure 17. Pareto chart of the standardized effects – Case study 2

We also investigated the system configuration that results in the shortest stock count time. More specifically, it can be observed that the stock count time is lower when the number of rack levels that the drone is simultaneously reading RFID tags are 2, the speed of the UAV is 1.5 m/s and finally when the tag reading method of the UAV is across the racks. The tag location does not affect the stock count time (Figure 18).

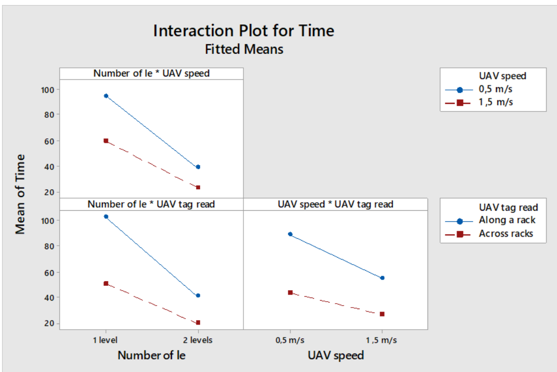


Figure 18. Interaction plots for parameters – Case study 2

6. Conclusions

6.1. Theoretical Contribution

This article presented evidence from experimental results that assess the use of UAVs coupled with RFID technology for real-time stock count execution. The results from laboratory experiments demonstrate the effect of certain operational parameters, such as UAV speed, number of rack levels, and RFID tag location on products, during the execution of the stock count process in terms of RFID reading accuracy and efficiency. A 2^4 full factorial design was used to test UAV and RFID technology in a warehouse with products that are stored in ambient and chilled environment.

The findings of this study are important as they reveal the parameters that affect the performance of drones during the stock count process. After analyzing the results, it was found that there were a number of factors and combinations of factors that significantly affect the efficiency of the drones. The results showed that the number of rack levels that are simultaneously scanned save stock count time. Additionally, a higher UAV speed saves more stock count time as it completes the same flight distance in less time. Furthermore, when RFID tags are placed on the front side of products, there is a higher reading accuracy as the RFID tag is not affected by the material of the product. Finally, the across-racks reading method is certainly better as it scans twice as many products during a flight in a corridor.

To this end, the results of the experiments are encouraging, showing that the use of UAVs coupled with RFID tags may support faster, cost-effective, and safer stock count in warehouses.

6.2. Managerial Implications

The use of RFID reader technology in conjunction with Unmanned Aerial Vehicles (UAVs) for stock count has important management implications that may considerably help enterprises in a variety of logistics processes. These consequences may be examined from inventory management, efficiency, cost savings, safety, and resource allocation viewpoints. In terms of stock count, the real-time data collected by RFID-equipped UAVs provides accurate and up-to-date information on the position and status of stored products. This data may be utilized to improve inventory management by helping managers to make better decisions and be prepared adequately for storage capacity needed in the future. The use of UAVs equipped with RFID readers considerably improves the efficiency of the stock count procedure. The automation of the stock count process saves the time and effort necessary for human stock counting, making inventory management more efficient and effective. Automated stock count via drones has significant cost-saving implications for businesses. Quitting manual stock counting decreases labor expenses, saving the organization money. Furthermore, the real-time data collected allows managers to more efficiently allocate resources, enhancing overall efficiency and performance. In terms of safety, the use of UAVs removes the need for workers to operate in dangerous areas in order to physically count goods. This decreases the chance of harm and increases staff safety, therefore enhancing overall working conditions. Moreover, the combination of RFID reader technology with UAVs for stock count has significant consequences for resource allocation. The real-time data collected by UAVs outfitted with RFID readers allows managers to better allocate resources, enhancing overall efficiency and performance.

6.3. Research Limitations

Although this article presented some useful results and managerial implications concerning the use of UAVs and RFID technology for real-time stock count, there are some limitations that should be stated. In first instance, RFID tags were used for stock count in pallet level. It would be interesting to assess stock count in carton and item level. Furthermore, laboratory tests have been conducted with a specific type and model of UAV and certain types of RFID tags. It would be interesting to evaluate other alternatives as well. Lastly, additional parameters (e.g., material of stored products) that affect the reading accuracy and efficiency of RFID tags could also be taken into consideration. These limitations as well as additional suggestions for future research are presented in the following section.

6.4. Agenda for Future Research

Based on the findings of this research, a future research agenda on the design, development and testing of stock count system via the use of UAV is presented below.

Examination of stock count process on different products and working environments: In this study, the performance of the stock count process using UAVs in dry and liquid products in warehouse facilities was investigated. To verify the successful operation of the automatic stock count process, it would be useful in the future to consider different types of products (such as metal or aluminium) and different working environments (such as outdoors).

Improve UAV devices and RFID readers: In most case studies, commercial drones were used for the stock count process. However, commercial drones have some disadvantages when used in the stock count process, such as the weight of the UAV device and battery life. Therefore, in the future, it would be important to consider case studies in which the drone is designed according to the user's needs. The use of a customized drone when performing the stock count process will likely draw positive conclusions about the efficiency of the stock count system. In addition, various combinations of RFID readers and RFID tags can be tested as well as signal amplification antennas can be used during the inventory process to amplify the signal.

Extend lab tests to field tests: The results presented in this research are mainly from laboratory tests. However, a warehouse environment is very different from a laboratory environment due to daily workload and working conditions. Therefore, it is important to test the proposed stock count system in a real-life environment to examine potential problems and gather additional useful conclusions.

Comparison of a stock count system via the use of UAV with other stock count systems: The stock count system using UAVs is still in an early stage and it is not widely known. Therefore, it would be necessary in the future to use it in pilot projects in storage facilities of various companies. In this way, companies will be able to evaluate this technology and compare it with existing stock count technologies.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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