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Investigation of operational and technical parameters that affect the use of UAVs for the automation of logistics processes in warehouse facilities and distribution centers

MRes. Thesis by

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MRes thesis publications

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Awards

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Executive Summary

A supply chain system includes processes aimed at increasing the level of customer service and achieving a sustainable competitive advantage. To achieve high customer service and manage operational costs, it is necessary to organize logistics operations with an emphasis on warehouses. Recently, the complexity of managing warehouses has increased significantly due to factors such as increased demand for more frequent and smaller size order execution, increased e-commerce sales, international competition, and the need for faster response times to end customers. For this reason, the increase of productivity and the reduction of handling time are critical to maintaining a competitive edge. However, this is not always possible, as most warehouses are still operated in a manual fashion although they incorporate some sort of information systems. Indeed, currently, a significant number of companies make use of warehouse management systems (WMS), and equipment, such as RF-scanners, to fulfill their needs and efficiently manage their warehouses. With these technologies, they increase their warehouse's productivity and reduce operational costs however there are still various challenges to be addressed.

The concept of Industry 4.0 fosters the evolution of typical warehouses towards smart distribution centers through the use of some of the latest emerging technologies. One such technology is Unmanned Aerial Vehicles (UAVs), which have evolved lately in terms of technology (e.g., control units, sensors, UAV frames) and their cost has significantly been reduced. Unmanned Aerial Vehicles are increasingly seen as a potential widespread future mode of transportation for numerous applications in the logistics industry and also a promising option for logistics operations in warehouses (e.g., stock counting, receiving, etc.). Unmanned Aerial Vehicles (UAVs) are considered to be a key technology for smart warehouses, as they allow for the execution of repetitive and demanding tasks with minimal human intervention or supervision. In the long term, drones represent an economical and safe (in terms of reducing staff injuries) solution for logistics tasks.

Based on the opportunities provided by drones, this MRes dissertation focuses on investigating parameters that affect the performance of UAVs in executing the stock count process in a warehouse. The main objective is the design of an innovative stock count system that adopts the use of a UAV coupled with RFID technology. The methodology followed for the development and testing of this stock count systems includes 3 main steps: The first step embraces the identification of the technical characteristics and applications of UAVs, their operational characteristics and the parameters that affect their operational performance in the stock count process (through a literature review). The second step focuses on the evaluation, ranking and final selection of the parameters which are taken into consideration during the testing of stock count system with the use of UAVs while the third step is related to the laboratory tests conducted to evaluate and optimize the use of UAVs in the stock counting process.

The review of the parameters was conducted by adopting the methodology of a systematic literature review (SLR), in which certain criteria were taken into consideration to identify relevant

articles. Following this methodology, 46 articles were initially identified in the literature, of which 25 were relevant to the final corpus. The limited number of published articles related to the research area under study suggests that this field is still at an early stage, understudied, and promising for further research.

Focusing on the results obtained from the systematic literature review and specifically on the investigation for identifying technical and operational parameters that affect the stock count process via the use of UAVs, eight categories of technical characteristics and four categories of operational characteristics (missions, flight zone, operational environment, and applications) were identified. In addition, five indoor warehouse applications in which UAVs can be used were presented and analyzed.

After the completion of the systematic literature review, the next step was to map the user requirements related to the automation of the inventory process through the use of UAVs. Two research methods were adopted to capture these requirements. The first method involved the use of a structured questionnaire distributed to a specific sample of companies and the second method involved personal interviews with logistics company executives through a set of open-end questions in order to evaluate and confirm the survey research findings.

Subsequently, the evaluation of the stock count system under consideration was conducted, through two different phases of laboratory testing. The first phase of laboratory tests aimed to determine the factors and levels to be used in the second phase of laboratory tests, through independent experiments for each parameter. The second phase of experiments evaluated the selected parameters in terms of reading efficiency and accuracy. The factorial design that was used to set-up the experimental design included four factors in the first experiment with two levels (2^4 full factorial design) and three factors in the second experiment with two levels (2^3 full factorial design) per factor respectively. The aim of the tests (first and second phase) was to determine the optimal combinations between the selected parameters and their levels as well as to determine the optimal combination of these parameters in order to succeed in having high reading efficiency and accuracy.

Upon completion of the experiments, a statistical analysis was conducted using ANOVA. The results showed that the performance of the system is significantly affected by certain parameters. Regarding the total stock count time, based on the ANOVA results in both experiments, the parameters "number of levels," "UAV speed," and "UAV tag reading method" were statistically significant. The results of the experiments were encouraging showing that UAVs can be used for stock count process with positive impact on cut-costing, staff safety and working performance.

Executive Summary in Greek (Επιτελική Σύνοψη)

Ένα σύστημα εφοδιαστικής αλυσίδας περιλαμβάνει διαδικασίες που αποσκοπούν στην αύξηση του επιπέδου εξυπηρέτησης των πελατών και στην επίτευξη βιώσιμου ανταγωνιστικού πλεονεκτήματος. Για την επίτευξη υψηλής εξυπηρέτησης των πελατών και τη διαχείριση του λειτουργικού κόστους, είναι απαραίτητη η οργάνωση των λειτουργιών εφοδιαστικής με έμφαση στην ορθή οργάνωση των αποθηκευτικών χώρων. Τον τελευταίο καιρό η πολυπλοκότητα της διαχείρισης των αποθηκών έχει αυξηθεί σημαντικά λόγω διαφόρων παραγόντων, όπως η ανάγκη για συχνότερη και μικρότερη εκτέλεση παραγγελιών, οι αυξημένες πωλήσεις ηλεκτρονικού εμπορίου, ο διεθνής ανταγωνισμός και η απαίτηση των πελατών για ταχύτερο χρόνο ανταπόκρισης. Για τον λόγο αυτό, η αύξηση της παραγωγικότητας και η μείωση του χρόνου διεκπεραίωσης είναι κρίσιμες, ωστόσο δεν είναι πάντα εφικτές, καθώς οι περισσότερες αποθήκες λειτουργούν συνήθως με εργαζόμενους που εκτελούν τις βασικές διαδικασίες χρησιμοποιώντας συνήθως κάποιου είδους πληροφοριακά συστήματα. Πράγματι, επί του παρόντος, ένας σημαντικός αριθμός εταιρειών χρησιμοποιεί ένα πληροφοριακό σύστημα (π.χ. σύστημα διαχείρισης αποθήκης-WMS) και εξοπλισμό (π.χ. σαρωτές RF) για την εκτέλεση των παραγγελιών. Με τις τεχνολογίες αυτές οι εταιρίες αυξάνουν την παραγωγικότητα της αποθήκης τους και μειώνουν το λειτουργικό κόστος παρόλα αυτά υπάρχουν ακόμα σημαντικές προκλήσεις που πρέπει να διερευνηθούν.

Η έννοια της Βιομηχανίας 4.0 (Industry 4.0) προωθεί την εξέλιξη των τυπικών αποθηκών προς έξυπνα κέντρα διανομής μέσω της χρήσης ορισμένων από τις τελευταίες αναδυόμενες τεχνολογίες. Μία από αυτές τις τεχνολογίες είναι τα μη επανδρωμένα εναέρια οχήματα (UAV), τα οποία έχουν εξελιχθεί τελευταία από πλευράς τεχνολογίας (π.χ. μονάδες ελέγχου, αισθητήρες, πλαίσια UAV) και το κόστος τους έχει μειωθεί σημαντικά. Τα μη επανδρωμένα εναέρια οχήματα θεωρούνται όλο και περισσότερο ως ένα ευρέως διαδεδομένο μελλοντικό μέσο μεταφοράς για πολυάριθμες εφαρμογές στον κλάδο της εφοδιαστικής και επίσης ως μια πολλά υποσχόμενη επιλογή όσον αφορά τις λειτουργίες εφοδιαστικής στις αποθήκες (π.χ. καταμέτρηση αποθεμάτων, παραλαβή κ.λπ.) Τα μη επανδρωμένα εναέρια οχήματα (UAV) θεωρούνται βασική τεχνολογία για τις έξυπνες αποθήκες, δεδομένου ότι επιτρέπουν την εκτέλεση επαναλαμβανόμενων και απαιτητικών εργασιών χωρίς σχεδόν καμία ανθρώπινη παρέμβαση ή επίβλεψη. Μακροπρόθεσμα, τα μη επανδρωμένα αεροσκάφη αποτελούν μια οικονομική και ασφαλή (όσον αφορά τους τραυματισμούς του προσωπικού) λύση για εργασίες εφοδιαστικής.

Με βάση τις δυνατότητες και τα πλεονεκτήματα που προσφέρουν τα μη επανδρωμένα αεροσκάφη, η παρούσα εργασία θα ασχοληθεί με τη διαδικασία απογραφής σε μια αποθήκη και θα επικεντρωθεί στη διερεύνηση παραμέτρων που επηρεάζουν την εκτέλεση της εν λόγω διαδικασίας με τη χρήση μη επανδρωμένων αεροσκαφών. Ο βασικός σκοπός της παρούσας διπλωματικής αφορά στο σχεδιασμό ενός καινοτόμου συστήματος καταγραφής αποθεμάτων που υιοθετεί τη χρήση ενός UAV σε συνδυασμό με την τεχνολογία RFID. Η μεθοδολογία που ακολουθήθηκε για την ανάπτυξη και τη δοκιμή αυτού του συστήματος καταμέτρησης αποθεμάτων περιλαμβάνει τρία βασικά βήματα. Το πρώτο βήμα αφορά τον προσδιορισμό των τεχνικών χαρακτηριστικών και των εφαρμογών των UAV, των λειτουργικών χαρακτηριστικών τους και των παραμέτρων που επηρεάζουν τις λειτουργικές επιδόσεις τους στη διαδικασία καταμέτρησης αποθεμάτων (μέσω βιβλιογραφικής επισκόπησης). Το δεύτερο βήμα εστιάζει στην αξιολόγηση, κατάταξη και τελική επιλογή των εξεταζόμενων παραμέτρων που λαμβάνονται υπόψη κατά τη δοκιμή του συστήματος καταμέτρησης αποθεμάτων με τη χρήση UAV, ενώ το τρίτο βήμα σχετίζεται με τις εργαστηριακές δοκιμές που διεξάγονται για την αξιολόγηση και τη βελτιστοποίηση της χρήσης των UAVs στη διαδικασία καταμέτρησης αποθεμάτων.

Η καταγραφή των παραμέτρων πραγματοποιήθηκε μέσω της μεθοδολογίας της συστημικής βιβλιογραφικής επισκόπησης, κατά την εφαρμογή της οποίας λαμβάνονται υπόψη ορισμένα κριτήρια μέσω των οποίων πραγματοποιείται ο εντοπισμός των σχετικών άρθρων. Ακολουθώντας την εν λόγω μεθοδολογία, εντοπίστηκαν αρχικά 46 άρθρα στη βιβλιογραφία από τα οποία επιλέχθηκαν 25 τα οποία είναι συναφή με το αντικείμενο μελέτης της συγκεκριμένης εργασίας. Ο περιορισμένος αριθμός των δημοσιευμένων άρθρων σχετικά με το αντικείμενο που μελετάται υποδηλώνει ότι το συγκεκριμένο πεδίο βρίσκεται ακόμα σε πρώιμο στάδιο, δεν έχει μελετηθεί αρκετά και είναι πολλά υποσχόμενο για περαιτέρω έρευνα.

Εστιάζοντας στα αποτελέσματα που προέκυψαν από την βιβλιογραφική επισκόπηση και συγκεκριμένα στην αναζήτηση των τεχνικών και λειτουργικών παραμέτρων που επηρεάζουν την διαδικασία απογραφής με την χρήση των UAVs προέκυψαν 8 κατηγορίες τεχνικών χαρακτηριστικών και 4 τύποι λειτουργικών χαρακτηριστικών (αποστολές, ζώνη πτήσης, επιχειρησιακό περιβάλλον και εφαρμογές). Επιπρόσθετα, παρουσιάστηκαν και αναλύθηκαν οι 5 εφαρμογές εντός των αποθηκών στις οποίες μπορούν να χρησιμοποιηθούν τα UAV’s.

Μετά την ολοκλήρωση της συστημικής βιβλιογραφικής επισκόπησης, το επόμενο στάδιο αφορά την καταγραφή των απαιτήσεων των χρηστών που σχετίζονται με την αυτοματοποίηση της διαδικασίας απογραφής μέσω της χρήσης UAV. Για την καταγραφή των απαιτήσεων υιοθετήθηκαν δύο ερευνητικές μέθοδοι. Η πρώτη αφορά την χρήση ενός δομημένου ερωτηματολογίου που διανεμήθηκε σε συγκεκριμένο δείγμα εταιρειών και η δεύτερη αφορά προσωπικές συνεντεύξεις με στελέχη εταιρειών logistics μέσω ενός συνόλου ανοικτών ερωτήσεων προκειμένου να αξιολογηθούν και να επιβεβαιωθούν τα ευρήματα της έρευνας.

Το επόμενο στάδιο αφορά την αξιολόγηση του υπό εξέταση συστήματος απογραφής, μέσα από δυο διαφορετικές φάσης εργαστηριακών δοκιμών. Η πρώτη φάση είχε ως στόχο μέσα από ανεξάρτητα πειράματα για κάθε παράμετρο, τον καθορισμό των παραγόντων και των επιπέδων που θα χρησιμοποιηθούν στη δεύτερη φάση εργαστηριακών δοκιμών. Η δεύτερη φάση αφορά την αξιολόγηση των παραμέτρων για την αποτελεσματικότητα του συστήματος απογραφής ως προς την ακρίβεια ανάγνωσης και τον συνολικό χρόνο απογραφής σε δύο περιπτώσεις μελέτης. Για το σχεδιασμό των πειραμάτων χρησιμοποιήθηκε ένας πλήρης παραγοντικός σχεδιασμός (full factorial design). Ο παραγοντικός σχεδιασμός περιελάμβανε 4 παράγοντες στην πρώτη περίπτωση μελέτης με 2 επίπεδα (2^4 πλήρης παραγοντικός σχεδιασμός) και 3 παράγοντες στην δεύτερη περίπτωση μελέτης με 2 επίπεδα (2^3 πλήρης παραγοντικός σχεδιασμός). Αναλυτικότερα, κατά τη διάρκεια των πειραμάτων αξιολόγησης του συστήματος, πραγματοποιήθηκαν 3 επαναληπτικές δοκιμές προκειμένου να καθοριστούν οι ιδανικοί συνδυασμοί ανάμεσα στις παραμέτρους και στα επίπεδα τους και να καθοριστεί ο βέλτιστος συνδυασμός τους.

Με την ολοκλήρωση των πειραμάτων ακολούθησε η στατιστική ανάλυση, τα αποτελέσματα της οποίας έδειξαν ότι η απόδοση του συστήματος επηρεάζεται σημαντικά από ορισμένες παραμέτρους. Όσον αφορά τον συνολικό χρόνο ολοκλήρωσης της διαδικασίας απογραφής, με βάση τα αποτελέσματα της ANOVA και στις δύο περιπτώσεις μελέτης οι παράμετροι "αριθμός επιπέδων", " ταχύτητα UAV" και "μέθοδος ανάγνωσης ετικέτας" ήταν στατιστικά σημαντικές. Τα αποτελέσματα των πειραμάτων ήταν ενθαρρυντικά και έδειξαν ότι τα UAV μπορούν να χρησιμοποιηθούν για τη διαδικασία καταμέτρησης αποθεμάτων με θετικό αντίκτυπο στην κοστολόγηση, την ασφάλεια του προσωπικού και την απόδοση της εργασίας.

«Είμαι συγγραφέας αυτής της Μεταπτυχιακής Διπλωματικής Εργασίας και κάθε βοήθεια την οποία είχα για την προετοιμασία της είναι πλήρως αναγνωρισμένη και αναφέρεται στην εργασία. Επίσης, έχω αναφέρει τις όποιες πηγές από τις οποίες έκανα χρήση δεδομένων ή ιδεών, είτε αυτές αναφέρονται ακριβώς είτε παραφρασμένες. Επίσης, βεβαιώνω ότι αυτή η εργασία προετοιμάστηκε από εμένα προσωπικά, ειδικά για τη συγκεκριμένη μεταπτυχιακή διπλωματική εργασία».

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1 Introduction

1.1 Rationale

A supply chain system includes processes aimed at increasing the level of customer service and achieving a sustainable competitive advantage (de Koster et al., 2007). The aim of each supply chain is to provide and deliver products and services in a timely and complete manner to the final customer. Supply chain activities cover processes such as demand forecasting, inventory management, receiving, order picking, packaging, storage, and shipping of products as well as the information systems required to coordinate these activities (de Koster et al., 2007). The implementation and combination of these processes is very complex.

To achieve high customer service and manage operational cost, it is necessary to organize logistics operations with emphasis on warehouses, which are also referred to as distribution centers (DC) (de Koster et al., 2007). Warehousing constitutes a critical process of modern logistics.

Lately the complexity of managing warehouses has increased significantly due to a number of factors such as the demand for more frequent and smaller order execution, increased e-commerce sales, international competition, and the need of customers for faster response time (Marchet et al., 2015). For this reason, the increase of productivity and the reduction of handling time are critical, however not always possible, since most warehouses operate usually in a manual fashion incorporating some sort of information systems (van Gils et al., 2018).

Indeed currently, a significant number of companies use an information system (e.g., warehouse management system-WMS) and equipment (e.g. RF-scanners) to fulfil their needs and manage efficiently their warehouse. With these technologies they increase their warehouse's productivity and reduce the operational cost. Consequently, they increase the level of customer service.

The concept of Industry 4.0 fosters the evolution of typical warehouses towards smart distribution centers using some of the latest advances in technological enablers like big data and robotics (Fernández-Caramés et al., 2019). Industry 4.0 has paved the way for a world where smart warehouses will be automated and upgraded via the use of some of the latest emerging technologies. One of such technologies is Unmanned Aerial Vehicles (UAVs), which has evolved lately in terms of technology (e.g., control units, sensors, UAV frames) and their cost has significantly been reduced (Fernández-Caramés et al., 2019).

An unmanned aerial vehicle (UAV), also widely known as a drone, is an aircraft with no need of a human on board. The flight of UAVs may operate with various degrees of autonomy. One of them could be under remote control by a human operator, another one would be fully or intermittently autonomously, by computers that are on board (Bae et al., 2016). Unmanned Aerial Vehicles are considered more and more as a widespread future mode of transportation for numerous applications in the logistics industry (Moshref-Javadi and Winkenbach, 2021) and provide a promising potential to overcome the challenges connected with last mile delivery (Ghelichi et al., 2021). Furthermore, drones are also a promising option concerning logistics operations in warehouses (e.g., stock count, receiving, etc.) (Wawrla et al., 2019).

Unmanned Aerial Vehicles (UAVs) are considered a key technology for smart warehouses, since they allow carrying out repetitive and demanding tasks without almost any human intervention or supervision (Fernández-Caramés et al., 2019). On long term, drones represent an economic and safe (in terms of staff injuries) solution for logistics tasks, as well as the reduction of time consumption and injuries risks during the task (Harik et al., 2016). UAV operation system contains different types of UAVs (equipped with gripper, imaging device, and sensor), recharge centers and other resources which support UAV operation (Khosiawan and Nielsen, 2016)

Drones are expected to provide several advantages over conventional vehicles. In the last years, drones proved to be really useful in fields like remote sensing (e.g., mining), real-time monitoring, disaster management, border and crowd surveillance, military applications, delivery of goods, precision agriculture, infrastructure inspection or media and entertainment, among others (Fernández-Caramés et al., 2019). In many of such fields, UAVs perform tasks that constitute one of the foundations of Industry 4.0: to collect as much data as possible from multiple locations dynamically. In addition, UAVs not only collect data, but are also able to store, process and exchange information with information systems such as Warehouse Management Systems (Fernández-Caramés et al., 2019). For example, in the field of warehouse management, drones have the ability to fly and hover autonomously, avoid obstacles in different warehouse layouts, navigate indoor and land precisely (Wawrla et al., 2019).

Based on the possibilities and advantages offered by drones, this work will deal with the stock count process in a warehouse and will focus on the parameters that affect the execution of this process using drones.

1.2 Scope & objectives

The main aim of this thesis is the design, development and testing of the use of UAVs for the automation of stock count process in warehouse facilities and distribution centers. The objectives are as follows:

- Conduction of literature review for the identification of technical characteristics and applications of UAV's, operational characteristics of UAVs and parameters that affect UAVs operational performance in stock count process
- Evaluation, ranking and final selection of parameters which are taken into consideration during the testing of stock count system with the use of UAVs.
- Laboratory tests for the evaluation and optimization of the use of UAVs in stock count process by following a series of operational performance.

1.3 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. The first method is the systematic literature review (SLR) in order to identify technical and operational parameters that affect the use of Unmanned Aerial Vehicles (UAVs) in logistics environment. The second method deals with the conduction of a survey (via a questionnaire) coupled with interviews with logistics experts and Logistics IT executives in order to elicit requirements concerning the adoption of UAVs in logistics operations while the third method focuses on laboratory (Lab) tests for system testing and evaluation.

The combination of the three methods which will be adopted in this dissertation is known as triangulation and can overcome the potential bias and sterility of single method approaches (Collis and Hussey, 2003). As it can be seen in Table 1.1, a three-phase methodologically triangulated research is adopted to investigate the operational and technical parameters that affect the use of UAVs for the automation of logistics processes in warehouse facilities and distribution centers.

Table 1.1 The three-phased triangulated research methodology

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 (Lab) Tests	Testing, evaluation, and optimization of system by using the selected parameters of Phase 1

Phase 1

In the first phase the systematic literature review (SLR) is selected as a research method, combined with a series of research questions (RQ), which aim at the identification and categorization of parameters in the current scientific literature. The SLR method provides a significant number of benefits in a field, with the aim of identifying research gaps, and providing particular and concrete propositions for a future research agenda (Tranfield et al., 2003; Crowther and Cook, 2007; Denyer and Tranfield, 2009; Saenz and Koufteros, 2015; Lagorio et al., 2016). Indeed, the benefits of the SLR method are wide known and as a result such method is implemented in a series of field such as logistics (Gligor and Holcomb, 2012), Urban and City Logistics (Lagorio et al., 2016; Björklund and Johansson, 2018), manufacturing (Lightfoot et al., 2013), sustainability (Gimenez and Tachizawa, 2012), etc. According to Khan et al., (2003), a systematic review based on unambiguous formulated questions, identifies, and evaluates similar studies and summarizes the results of review by following a reliable methodology. More information for this method as well as the procedure it follows for the completion of the survey were presented in the first interim report

Phase 2

In phase 2, we created a questionnaire to gather the needs that exist concerning the use of UAVs for executing logistics processes in warehouses and port terminals. The questionnaire sent to logistics executives, to give us detailed answers which will help us in our research. Furthermore, a series of interviews with logistics managers took place in order to have an in-depth mapping of the requirements and at the same time validate the results of the survey.

Phase 3

In the third phase, we will accomplish two sets of laboratory tests. More specifically, by taking into consideration certain technical and operational parameters which have been identified during the first phase of this work, the first set of laboratory tests will be designed with aim to define the values of the levels of each parameter. Subsequently, the second set of laboratory tests will be executed by using the results of first laboratory tests and the Design of Experiments (DoE) method for performance evaluation of unmanned aerial vehicles (UAVs) in warehouse and port terminal operations (specifically in the stock count process).

1.4 Structure of the thesis

The structure of this thesis is organized according to the following:

Chapter 2 presents the results from the literature review conducted via the adoption of the Systematic Literature Review (SLR) methodology and presents a categorization of UAVs based on their technical characteristics. This chapter describes in detail these characteristics and at the same time presents various applications where drones can be adopted.

Chapter 3 presents and describes warehouse and port terminals processes which can be executed by UAVs. Drones have special abilities (e.g. drones can follow pre-defined flight paths and carry items) and for these reasons they can be used in order to replace manual ways of executing logistics processes (e.g. stock count).

Chapter 4 presents the results of a survey through a structured questionnaire and personal interviews with logistics company executives with aim to map the requirements related to the automation of logistics process via the use of drones.

Chapter 5 presents the theoretical background of the Design of Experiments (DoE) methodology which we will adopting in our research for the evaluation of UAV's use in terms of stock count efficiency and accuracy via a series of lab tests. Subsequently, this chapter presents the first set of laboratory tests and describes the initial experiments will be examined with aim to define the values of the levels of each parameter.

Chapter 6 discusses the evaluation results of the proposed stock count system in terms of stock count efficiency and accuracy via a series of laboratory tests that were conducted by adopting the Design of Experiments (DoE) methodology. In this chapter, the results of first set of laboratory tests are presented followed by the selected factors and their levels that have been chosen for assessing the performance of the proposed system on the second set of laboratory tests. Subsequently, the experimental design that has been used for the design and testing of the proposed system as well as the procedure for the execution of the experiment are analyzed. Finally, the statistical analysis of the test results.

Finally, Chapter 7 presents the conclusions of this thesis as well as a future research agenda in this topic.

2 Literature review on Unmanned Aerial Vehicles (UAVs)

2.1 Introduction

This chapter presents the results of a Systematic Literature Review (SLR) conducted in operational and technical parameters that affect the adoption of UAVs for the automation of logistics processes in warehouse facilities and port terminals. Initially, the descriptive analysis of the reviewed articles is made, with the time distribution of the review articles, number of papers per year and number of published papers per journal. In addition, this chapter presents the presentation of overview for each part of this research work. Finally, this chapter presents a categorization of UAVs based on their technical characteristics and applications. The investigation has identified various technical characteristics that are classified into eight (8) categories. Subsequently, a review is made in a series of business applications that drones may support.

2.2 Descriptive analysis of the reviewed articles

Table 2.1 presents the outcome obtained, in terms of number of papers, resulting from the selection protocol in the systematic literature review (SLR). The systematic literature review aimed at papers search about UAVs technical and operational characteristics and parameters that affect UAVs adoption in logistics processes.

Based on the Table 2.1, 69.6% (32 papers) of the reviewed papers are journal papers, while 30.4% (14 papers) account for conference papers. The low number of published articles (both in academic journals and conferences) in combination with the time distribution of the reviewed studies, are representative signs, that the field is quite new from a research point of view.

Table 2.1: Overview of the reviewed articles

	Type of article	
	Journal	Conference
Moshref and Winkenbach,2021	●	
Wang et al.,2021	●	
Ghelichi et al.,2021	●	
Lemardelé et al.,2021	●	
Campbell et al.,2017	●	
Goodchild and Toy,2018	●	
Pugliesea et al.,2020		●
Kevin Dorling et al.,2016	●	
Rabta et al.,2018	●	
Tavana et al.,2017	●	

	Type of article	
	Journal	Conference
Macrina et al.,2020	●	
Carlsson et al.,2017	●	
Müller et al.,2019	●	
Rejeb et al.,2021	●	
Wawrla et al.,2019	●	
Ridolfi et al.,2019		●
Derpich et al.,2018		●
Shen et al.,2020	●	
Bamburry, 2015		●
Kloetzer et al.,2019		●
Manjrekar et al.,2021	●	
Otto et al.,2018	●	
Đurić et al.,2018	●	
Sorbelli et al.,2019		●
Bartoli et al.,2019		●
Raj and Sah,2019	●	
Mireia and Monica,2019		●
Yap et al.,2016		●
Falco et al.,2019		●
Bae et al,2016		●
Beul et al.,2018	●	
Liu et al,2021	●	
Harik et al.,2016		●
Fernández-Caramés et al.,2019	●	
Cordova and Olivares,2016		●
Hell and Varga,2019	●	
Khosiawan and Nielsen,2016	●	

	Type of article	
	Journal	Conference
Perussi et al.,2019	●	
Olivares et al.,2015	●	
Companik et al.,2018	●	
Xu et al.,2017	●	
Hua and Zhang,2019		●
Hummel et al.,2019	●	
Kang et al., 2019	●	
Delavarpour et al.,2021	●	
Hassanalian and Abdelkefi,2017	●	
Total	**32**	**14**

Figure 2.1, illustrates graphically the time distribution by year of the selected articles. The number of articles considering the use of drones in logistics processes has grown rapidly during the last years. Based on the results of the figure below, it is evident that the years of publication among the identified publications vary from 2015 to 2021.

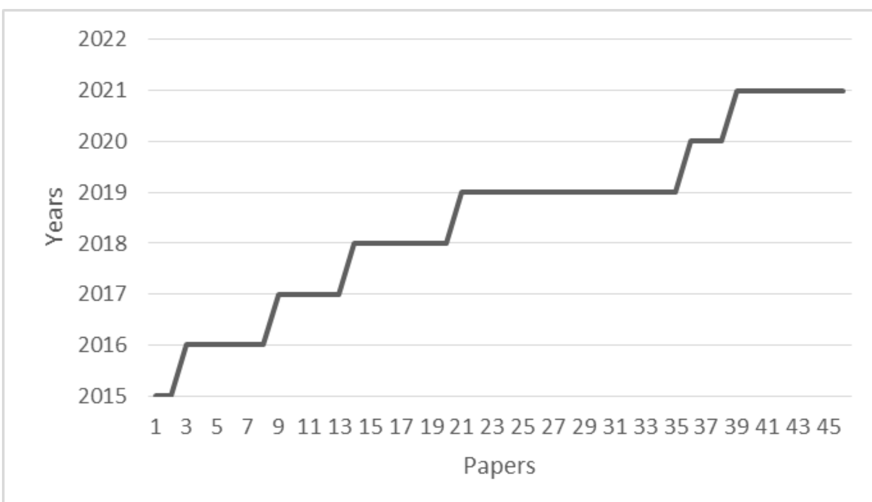


Figure 2.1 Time distribution of the review articles

Figure 2.2 depicts the number of papers per year. More than half of the articles under consideration are published in the last three (3) years, indicating that the area is significantly expanding over the last few years. The peak in the number of papers is observed in year 2019, where 15 papers (8 journal papers and 7 conference papers) were published.

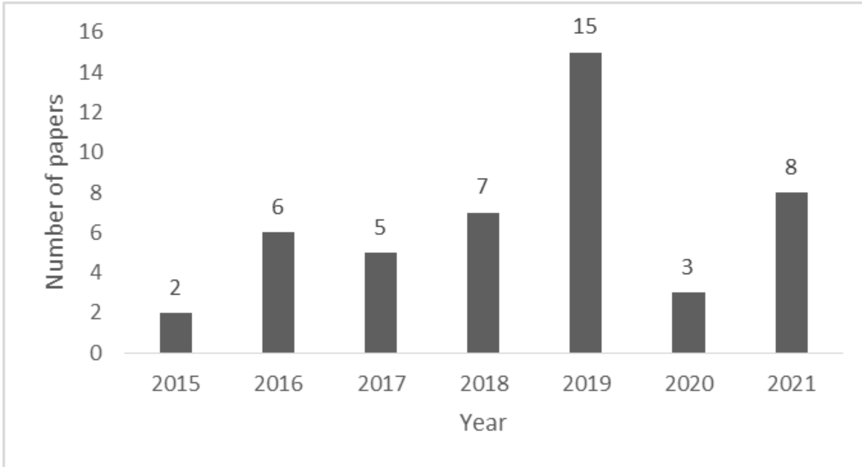


Figure 2.2 Number of published articles per year

Focusing on articles that have been published on peer-reviewed journals and by taking into consideration Table 2.2, it can be concluded that 30 journals have been used for the publication of 32 scientific articles. Also, it is worth mentioning that there is only two journals with more than one publication, while all the other journals have only one publication.

Table 2.2 Number of published articles per academic journal

Journal	Number of papers per journal
Expert Systems With Applications	2
Sensors	2
European Journal of Operational Research	1
Computers and Operations Research	1
Transportation Research Part E	1
Transportation Research Part D	1
IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS: SYSTEMS	1
International Journal of Disaster Risk Reduction	1
Transportation Research Part C	1
International Journal of Production Research	1
Internet of Things	1
Transportation Research Procedia	1
Computers & Industrial Engineering	1
Journal of Transportation Management	1
IEEE ROBOTICS AND AUTOMATION LETTERS	1
Procedia Computer Science	1
Production & Manufacturing Research	1
International Journal of Logistics Research and applications	1
Sensors and Materials	1
Progress in Aerospace Sciences	1

Journal	Number of papers per journal
Remote Sensing	1
International Journal of Supply Chain Management	1
Advanced Quality	1
Management Science	1
Supply Chain & Analytics Report	1
Eidgenössische Technische Hochschule Zürich	1
Networks	1
Interdisciplinary Description of Complex Systems	1
IEEE Transactions on Industrial Informatics	1

2.3 Findings

From the review conducted it is resulted that there is a limited number of articles that investigate parameters that affect the performance of UAVs in logistics operations. Furthermore, we concluded that to the best of our knowledge, there is no detailed classification that provides:

a) The type of available drones based on their technical and operational characteristics
b) List of logistics processes that drones may adopted
c) List of parameters that affect the performance of UAVs in stock count (in warehouses and port terminals)

To this end in the following chapters, based on the results from the SLR conducted in this chapter, we will present the following:

- A categorization of UAVs based on their technical and operational features. Eight (8) categories 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. Applications of drones in logistics operations are also examined.
- Processes that drones may execute in warehouses and port terminals. These processes are as follows: a) Inventory management, b) Intra-logistics, c) Picking, d) Inspection, and f) Facility physical security & Surveillance.
- From the aforementioned processes, we focus on stock count, which is a complex, dangerous and time-consuming process and we identify the parameters that affect UAVs operational performance. These parameters are as follows: a) UAV Flight altitude, b) UAV speed, c) Read distance, d) Signal emission angle, e) Readers pointing direction, f) Tag location, g) Tag type and, h) Transverse read range.

2.4 UAV's technical characteristics

Drones except of their length and width can be categorized by taking into consideration multiple technical characteristics. Features such as weight, wing span and wing type are important characteristics that distinguish different types of drones and provide a solid classification of UAV systems (Hassanalian and

Abdelkefi, 2017). A proposed classification of UAVs technical characteristics is shown in Figure 2.3. The categorization of technical characteristics is as follows:

- UAV flight control
- UAV weight type
- UAV wing type
- Propulsion system
- Wing span
- Flight range
- Flight endurance
- Operational altitude

Table 2.3 presents the papers of literature review that used to categorize the technical characteristics. In particular, the following table present the reports that are related to each category of technical characteristics. There are few papers for each category of technical characteristics, which proves that the UAV technology is at an early stage of research.

In the following sections these characteristics are described further.

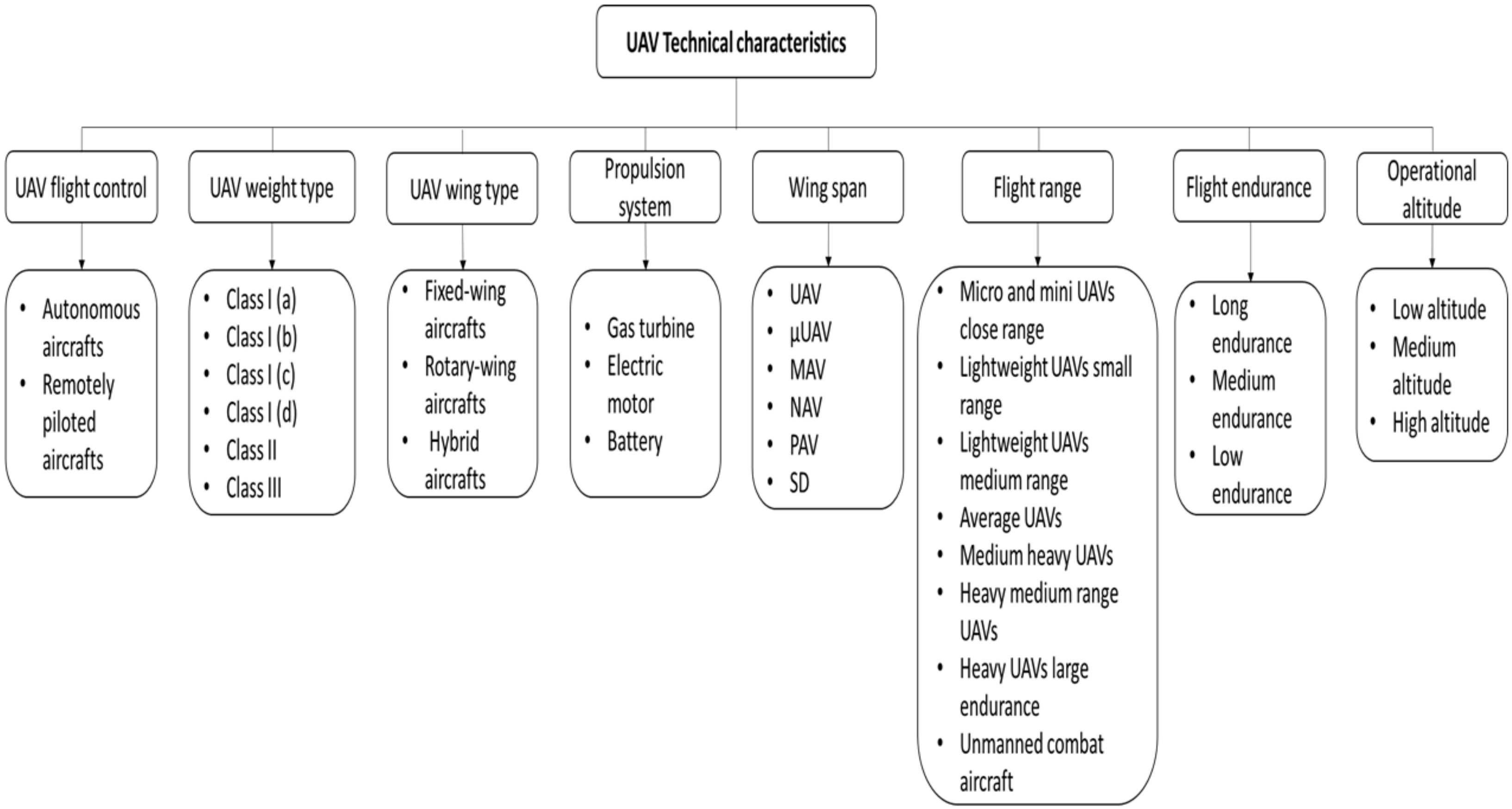


Figure 2.3 A classification of UAVs based on technical characteristics

Table 2.3 List of papers that examine technical characteristics of UAVs

	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							●	

2.4.1 UAV flight control

An important characteristic of UAV's is that they do not operate with a pilot on-board. For this reason, there are two ways of operation that are related with UAV's flight control (Otto et al., 2018):

- Autonomous aircraft: totally autonomous drones have the ability to decide how to achieve complex tasks in an uncertain environment without the intervention of a human factor.
- Remotely piloted aircraft: Drones that have to be closely remote controlled by a human pilot, who gives the orders to achieve the tasks

2.4.2 UAV weight type

Drones can be classified categories in terms of weight (Derpich et al., 2018). UAVs 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. More specifically drones may be classified into three (3) Classes according to their type and weight range as shown in Table 2.4 (Hassanalian and Abdelkefi, 2017).

Table 2.4 Drones categorization by the minimum take-off weight (Hassanalian and Abdelkefi, 2017).

Class	Type	Weight range
Class I (a)	Nano drones	W≤200g
Class I (b)	Micro drones	200g<W≤2kg
Class I (c)	Mini drones	2kg<W≤20kg
Class I (d)	Small drones	20g<W≤150kg
Class II	Tactical drones	150g<W≤600kg
Class III	MALE/HALE/Strike drones	W>600kg

2.4.3 UAV wing type

UAVs can be further categorized by the type of their wings to: a) fixed-wing aircrafts, b) rotary wing aircrafts and c) hybrid aircrafts (Delavarpour et al., 2021; Derpich et al., 2018). Below, further details concerning the various wing types are provided.

- Fixed-wing aircrafts: The Fixed-wing UAVs which are launched manually from a launcher ramp, require runways for their takeoff and landing. This type of UAVs can fly at high cruise altitudes and speeds. Fixed-wing UAVs cover vast areas, travel for a significant distance from the launch point and get a centimeter-level accuracy of ground sample distance (Delavarpour et al., 2021).
- Rotary-wing aircrafts: Rotary-wing UAVs are fly in lower altitudes with lower speeds compared to fixed-wing UAVs, performing a sub-centimeter resolution in the collected data. In addition, they cover smaller areas and require a longer flight time over the same area (Delavarpour et al., 2021).
- Hybrid aircrafts: It is the combination of the fixed-wing and rotary types of UAVs into hybrid models with the aim to take advantage of their advantages and compensate the disadvantages that exist. These UAVs are suitable for tasks that require both endurance and maneuverability and are characterized by large control surfaces capable of large deflections. In addition, hybrid UAVs have high thrust-to-weight ratio. Due to the transition between two modes of rotary-wing

and fixed-wing during the flight, aerodynamics of the systems changes drastically (Delavarpour et al., 2021).

2.4.4 Propulsion system

There is a variety of propulsion systems which are used in drones and may be classified into different categories (Hassanalian and Abdelkefi, 2017; Derpich et al., 2018)). There are 10 categories of propulsion systems (e.g. reciprocating piston engines, wankel rotary engines, propeller based systems etc.) however the most common and used types are the following three: a) the gas turbine, b) the electric motor-based and, c) the battery-based propulsion systems (Macrina et al., 2020).

- Gas turbine: The gas turbine, commonly known as combustion turbine, is an internal combustion engine that converts the chemical energy that generates into mechanical energy. Gas turbine is a widely used and reliable engine with very heavy mechanism (Macrina et al., 2020).

- Electric motor: Electric motors use electricity to create rotational motion and drive the propeller blades for propulsion. Electric motors have advantages such as low operational cost, low maintenance, are robust and do not generate negative externalities. On the other hand, there are disadvantages as they require large currents, they are sensitive to water or other conductive liquids and they can be affected by electromagnetic interferences (Macrina et al., 2020).

- Battery: Batteries are electrochemical energy storage devices. Batteries do not require fuel or oxygen and operate by converting stored chemical energy into electrical energy. The advantages of battery systems are numerous: they are silent, lightweight, and self-contained (i.e., they do not require external reactants). In addition, they are reliable, require low maintenance, have a high level of control, and perform well in high-altitude operations. The most commonly used batteries are the rechargeable ones, and their main disadvantages are the limited endurance and the limits of their recharge (Macrina et al., 2020).

2.4.5 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 and Abdelkefi, 2017). Fig. 2.4 depicts the spectrum of different types of drones and their wing span.

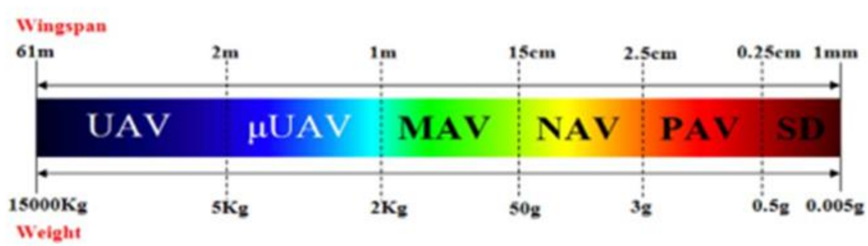


Figure 2.4 Spectrum of drones from UAV to SD and their wing span (Hassanalian and Abdelkefi, 2017).

2.4.6 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. The flight range of the different types of drones is presented in Table 2.5.

Table 2.5 The drones categorization based on their weight and flight range (Hassanalian and Abdelkefi, 2017).

Designation	Weight range	Flight range
Micro and mini UAVs close range	W≤5kg	25km≤R≤40km
Lightweight UAVs small range	5kg<W≤50kg	10km≤R≤70km
Lightweight UAVs medium range	50kg<W≤100kg	70km≤R≤250km
Average UAVs	100kg<W≤300kg	150km≤R≤1000km
Medium heavy UAVs	300kg<W≤500kg	70km≤R≤300km
Heavy medium range UAVs	500kg≤W	70km≤R≤300km
Heavy UAVs large endurance	1500kg≤W	R≤1500km
Unmanned combat aircraft	500kg<W	R≤1500km

2.4.7 Flight endurance

Another technical characteristic of UAVs is flight endurance. This characteristic is usually interrelated with flight range. As obviously the longer a UAV can stay airborne the larger its radius of operation is going to be (Arjomandi et al., 2006; Otto et al., 2018). It is important to consider range and endurance because it enables the UAV designer to determine the type of UAV required depending upon how far the mission objective is from the launch site (Arjomandi et al., 2006; Rejeb et al., 2021))

Three classifications are proposed as follows: long, medium, and short endurance (Arjomandi et al., 2006)
• The long endurance UAVs are those that can stay airborne for 24 hours or more.
• The medium endurance UAVs are those with endurance between 5 and 24 hours.
• The third class is the low endurance UAV which have less than 5 hours endurance.

2.4.8 Operational altitude

The maximum operational altitude is another important technical characteristic (Derpich et al., 2018). A low, medium, and high-altitude classification is proposed for dividing the UAVs by maximum ceiling (Arjomandi et al., 2006).

- Low altitude is any UAV that flies up to 1000m. These UAVs are the micro UAVs which can be used for various commercial applications such as parcel delivery, surveillance, etc. (Arjomandi et al., 2006).
- Medium altitude is the category of UAVs with maximum altitude between 1000m and 10000m (Arjomandi et al., 2006).

High altitude is all UAVs that can fly over 10000m. There is a concern that these UAVs may interfere with commercial and military manned aircraft and that is why high technology collision avoidance systems are being developed and integrated into these UAVs that fly in populated airspace (Arjomandi et al., 2006).

2.5 UAV's operational characteristics and areas of application

Drones can perform both outdoor and indoor missions in very challenging environments and they can be equipped with various sensors and cameras for doing intelligence, surveillance, and reconnaissance missions (Hassanalian and Abdelkefi, 2017). Furthermore, incorporating drone technology into industrial manufacturing and control processes is becoming increasingly essential. Drones can grow into an essential part of industrial controls, as they can perform a task with no human intervention for long periods of time in difficult to access or unsafe locations (Hell and Varga, 2019).

UAVs come in a wide array of configurations and sizes depending on the application for which they will be used as mentioned previously. Recent advancements in drone technology have inspired quite a few attractive commercial applications such as delivery of small parcels (Ghelichi et al., 2021)

Figure 2.5 presents the operational characteristics for UAVs coupled with different areas of application.

Operational characteristics can be categorized based on type of missions (military/ civil), flight zones (outdoor/indoor), and type of the operating environment (underwater/on the water/ground/air/space) (Hassanalian and Abdelkefi, 2017).

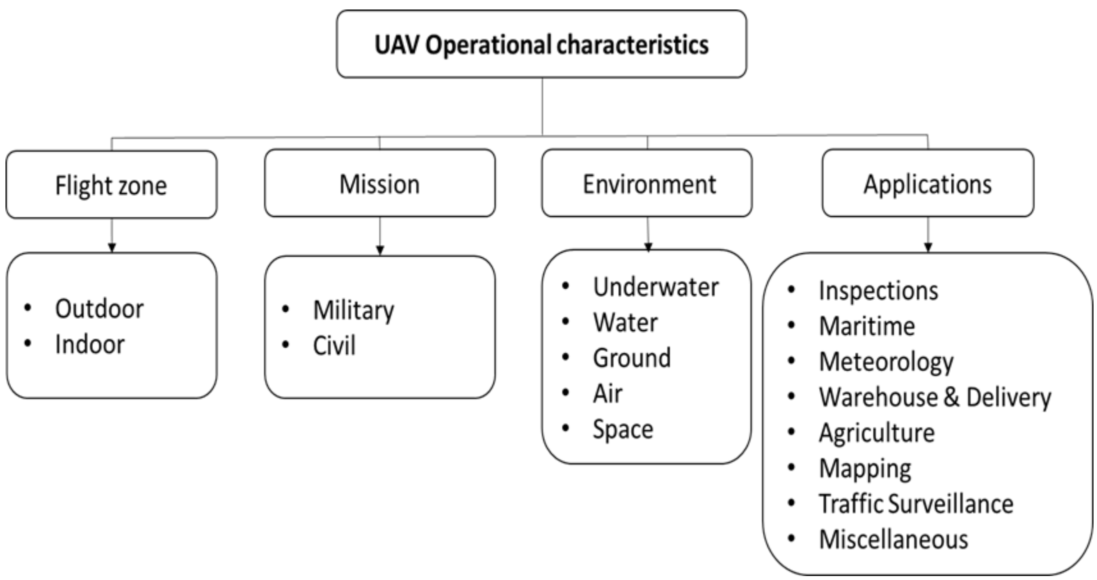


Figure 2.5 Drones operational characteristics

2.5.1 Flight zone

One of the operational characteristics of drones is the flight zone. Drones are used both outdoors and indoors workspaces to perform various processes (e.g., delivery service, stock count and surveillance) (Wawrla et al., 2019). In recent years the use of UAV has automate and upgrade these processes and with this way has improve many factors, such us delays in information update and great time consumption of the task (Harik et al., 2016).

2.5.2 Mission

The second operational characteristics of drones is the mission. There are two types of mission, the military and civil. Drones are considered as a vital part of military missions, and they can function very effectively. Drones can be used for recognition and investigation of place and with this way offer a rapid overview of the situation (Hassanalian and Abdelkefi, 2017). On the other hand, in situations of civil missions, drones are used for the identification of the location of oil spills and other similar tasks (Hassanalian and Abdelkefi, 2017).

2.5.3 Environment

The third operational characteristics of drones is the environment. Except of the usual applications of drones in ground and air environment (e.g. agriculture), drones can be applied additional in the marine environments. Drones are used in hydrology applications for measuring several parameters related to the water surface and to study marine organisms (Hassanalian and Abdelkefi, 2017). Indeed, drones have several application potentials for flow measurements in difficult-to-access water environments during adverse hydrometeorological events. Except of drones operate on the surface of the water there is another class of waterproof UAVs that operate underwater, the so-called underwater drones (Macrina et al., 2020). Finally, one more environment in which drones can be used, is space and the exploration of other planets. In planetary explorations, there is a tendency to design and fabricate some drones that can fly and perform missions in space environments and for this reason design and fabrication of space drones should be done based on that environment. For example, because of the amount of gravity on Mars, the weights of drones differ from their weights on Earth. Indeed, the weights reduce by 61.5% (Hassanalian and Abdelkefi, 2017).

2.5.4 Applications

The last category of operational characteristics of drones are the applications. There are several areas in which drones can perform various applications. These applications are related to warehouse and delivery of goods, surveillance, meteorology, inspection, miscellaneous other areas etc.

Drones are used in many logistics processes in warehouse such as inventory management, stock count and surveillance (Wawrla et al., 2019). In addition, many companies are using drones to deliver packages to customers. Drones are faster and more agile because they are not affected by congestion and can fly over buildings in a straight line, they can only deliver one parcel on a round-trip and they reduce operations costs and air pollution (Ghelichi et al., 2021). For example, given the small size, limited weight, high value, and high urgency of many medical supplies, such as blood samples and medicine, drones can serve as a promising, efficient mode of transportation for these items. While it requires significant time to distribute these items by conventional terrestrial transportation vehicles due to a limited road infrastructure, the use of drones contributed to a considerable reduction in delivery time (Javadi and Winkenbach, 2021).

One more typical application that drones are used is search and rescue missions. In search and rescue operations, every second is vital. In addition, drones can be used in environmental actions, such as observing the effects of climate change, controlling air quality, managing national parks, and monitoring different ecosystems (Macrina et al., 2020).

These drones can be used for recognition and investigation of natural disasters including forest fires, avalanches on mountains but also in the marine environments (Hassanalian and Abdelkefi, 2017). Moreover, there are new anti-drones which are used to take down naughty or offensive drones from the sky and drones that can be used as a runway for another drone, can be applied to guide (or scare) birds away from airport runways, can be used to clean windows, gutters, and solar panels, and for other applications, such as hobbies (Hassanalian and Abdelkefi, 2017).

Finally, entertainment is another interesting civilian area in which drones can be used. Recently, some authors focused on the use of drones for filming sports events (Macrina et al., 2020).

2.6 Summary

This chapter presented the results of the literature review conducted via the use of the SLR methodology. More specifically, a descriptive analysis of the reviewed articles concerning technical and operational characteristics of drones were presented. The results show that limited research is made in this topic. Furthermore, we presented a categorization of UAVs technical characteristics. We also presented a review of various operational characteristics of drones as well as possible fields where drones may be applied (business applications). The following chapter will focus on the challenges that exist concerning the adoption of UAVs in warehouses and port terminals.

3 Adopting Unmanned Aerial Vehicles (UAVs) in warehouse and port terminal operations

3.1 Introduction

This chapter presents various processes in warehouse and port terminals that can be supported or being automated (fully or semi) by adopting UAVs. The use of aerial vehicles for warehouse and port terminal processes has gained increasingly popularity over recent years since it is a promising technology that could support the transformation of existing way of working. In this chapter, logistics processes that could be supported via UAVs are presented and described in detail.

3.2 Categorization of warehouse and port terminals processes that can be supported by UAVs.

Industry 4.0 has led to automation and is currently upgrading various logistics processes throughout the use of some of the latest emerging technologies. One of such technologies is Unmanned Aerial Vehicles (UAVs), which has evolved a lot over the past years (Fernández-Caramés et al., 2019). Drones lately have started to be used in warehouses and port terminal in order to support complex (e.g. stock count) or dangerous (e.g. night surveillance) tasks (Wawrla et al., 2019).

Drones are popular due to their ability to fly and hover autonomously, avoid obstacles in different warehouse and port terminal layouts, navigate indoor, land precisely and potentially operate in fleets (Wawrla et al., 2019). According to these indicative abilities, drones can be used in many warehouse and port terminals operations and support or automate (fully or semi) traditional logistics processes. The processes are shown in Figure 3.1.

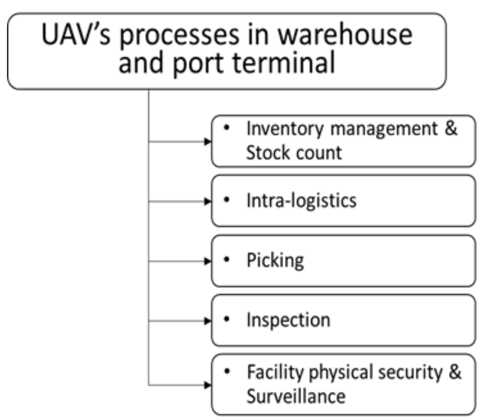


Figure 3.1 UAV's applications

Table 3.1 presents the papers of literature review that used to categorize the warehouse and port terminal operations. In particular, the following table present the reports that are related to each category of warehouse and port terminal operations. It is observed that most papers focus on the inventory management-stock count process.

Table 3.1 Overview of UAV's processes in warehouse and port terminal operations

	Inventory management-Stock count	Intra-logistics	Picking	Inspection	Facility physical security & Surveilance
Fernández-Caramés et al., 2019	●				
Wawrla et al., 2019	●	●		●	●
Bae et al., 2016	●				
Beul et al., 2018	●				
Harik et al., 2016	●				
De Falco et al., 2019	●				
Kloetzer et al., 2019		●			
Derpich et al., 2018		●			
Sorbelli et al., 2019			●		
Macrina et al., 2020				●	●
Hell and Varga, 2019					●
Rejeb et al., 2021					●
Đurić et al., 2018	●				
Raj and Sah,2019	●			●	●
Yap et al., 2016				●	●

In the following section a description of such application is made coupled with the role that UAVs may have in the support or/and automation of each process.

3.3 Inventory management-Stock count

UAVs could support the management and stock count of inventory as well as for preserving item traceability (Fernández-Caramés et al., 2019). In the area of inventory management, drones can be used for the following tasks: inventory audit, inventory management, cycle counting, item search, buffer stock maintenance, and stock taking (Wawrla et al., 2019). The main objectives of using drones for inventory management are to decrease the cycle count times and labor costs, to reduce the need for full physical counts of inventory and at the same time to increase the inventory accuracy rates, to avoid the risk of employees working at heights and to reduce the need for unnecessary movement of inventory (Manjrekar et al., 2021; Đurić et al., 2018)). Stock count is the physical verification of the quantity of items stored in warehouses and it is done with two ways. The most common counting way is the annual one-time inventory checks, and the other way is cycle counting. Cycle counting describes the process of counting a partial amount of a warehouse's inventory on a more frequent basis and is usually performed daily or weekly. (Wawrla et al., 2019). Even though cycle counting method increases the inventory accuracy, there are still several downsides in traditional inventory management processes (e.g. labor costs, error-prone and highly repetitive tasks) (Wawrla et al., 2019).

Drones can add value and support the execution of this processes. An interesting case is presented in Bae et al. (2016). The proposed inventory checking system with drones is composed of three major components. The first is a RFID reader that detects RFID tags of products, and it stores the detected tag id, location, time, and product count. The second is a drone that navigates whole workspace manually or automatically. The last is server program for inventory checking that compares database values and real product data.

In another case Beul et al., (2018), they developed a data collection program to detect and save tag information. After the flight of drones, the gathered tag data is transferred to the inventory checking server and is compared with the inventory data stored in database. At the same time, they classified the inventory status of a product into four states – normality, location error, missing, unregistered and with this way they examine the use case of automatic inventory in a warehouse. Specifically, the MAV detect, identify, and map the stored items and with this way it is possible to keep an always-up-to-date inventory record of the contents within the warehouse. (Harik et al., 2016) examine similar case with use of an UAV to replace the human operator for the scanning purposes. Fernández-Caramés et al., (2019) present the design and evaluation of a UAV-based system aimed at automating inventory tasks and keeping the traceability of industrial items attached to Radio-Frequency Identification (RFID) tags. Therefore, the system uses a blockchain and a distributed ledger to store certain inventory data collected by UAVs, validate them, ensure their trustworthiness, and make them available to the interested parties. Finally, (De Falco et al., (2019) propose an approach for using unmanned aerial vehicles for warehouse scanning and Region-based Convolutional Neural Network (R-CNN) for autonomous inventorying activities. It uses light Convolutional Neural Network (is a class of artificial neural network, applied to analyze visual imagery) models to detect and recognize on real-time the labels of packages during an aerial scanning of the environment.

3.4 Intra-logistics

The ability of drones to follow pre-defined flight paths and carry items enables them to be used for intra-logistics operations. For instance, the on-site delivery of products and spare parts as well as the ability of their transport from warehouses to workshops in factories are some of such examples (Wawrla et al., 2019).

Derpich et al., (2018) analyze the feasibility of using drones in a manufacturing factory that requires multiple transports from the warehouse to the workstations. They propose a comprehensive approach to solving the assignment of drones to machines or work stations, integrated with all the nodes using the classic problem of vehicle routing (VRP). The problem is complex because the routes must be planned in order to avoid collisions, therefore they must follow time windows in the deliveries to the workstations.

Autonomous maneuvering of drones for indoor environments is highly challenging also due to the need for optimal planning that saves drone battery and task accomplishment time, as well as due to space topology that can include different storage facilities. Kloetzer et al., (2019) study a type of vehicle routing problem applied to an indoor warehouse which is based on mathematical programming and presents supporting simulations and real-time experiments. In this case, goods must be transported from storage areas to delivery areas by limited energy drones with finite capacities for transporting goods.

3.5 Picking

Picking process is one of the main activities of a warehouse, which represents 50-75% of the total operating cost of a warehouse (Quader and Castillo-Villar, 2018). It is considered to be the highest priority in a distribution center to improve productivity (de Koster et al., 2007) and it needs about 60% of a company's workforce (Lin and Lu, 1999) as it takes a lot of time and human effort for higher productivity (Battini, 2016). The most time-consuming order picking activity is the movement of the picker within the corridors covering 50% of the total order time (Žulj et al., 2018).

Because of the great importance of picking method for warehouse and the increase of technology in last years, drones are very useful for these activities. Drones represent a great economic solution for the task, they reduce time consumption and consequently they increase the customer service. For each customer-order (CO), the automated picking system is in charge of gathering the items requested in the CO to a predefined location where the cart of the drone is positioned. For each item of the order, the drone flies to the location where the item is stored, grasps it, and brings it back to its cart (Figure 3.2) (Sorbelli et al., 2019).

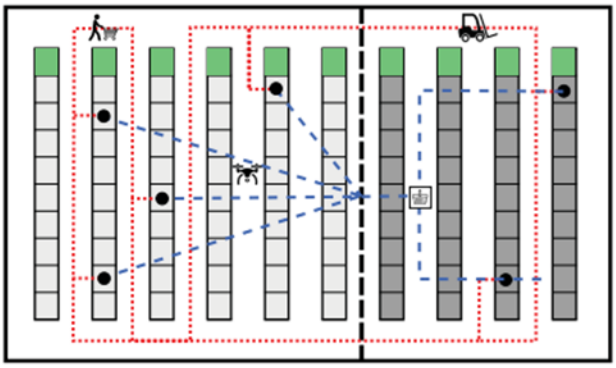


Figure 3.2 A view from the top of the warehouse: the black dots are the positions of the items in a CO. (Sorbelli et al., 2019)

Sorbelli et al., (2019) compare the efficiency of the automated picking system employing a drone with that of a traditional picking system employing a worker that pushes a cart, and they find under which conditions the drone can be more efficient.

3.6 Inspection

Drones are already used for inspection in many industries and can be a viable alternative to replace manual inspection operations in warehouses (Wawrla et al., 2019). In addition, indoor use cases of drones for inspection is also growing (Yap et al., 2016). The growth of warehouse operations and customer demand makes inspection processes expensive and difficult. Require skilled inspectors and sometimes work is obstructed during inspections. Indoor drones are a perfect fit for tasks that require monitoring and inspection in dangerous areas or high altitudes. In warehouses (indoor use cases), drones can for example inspect racks, pallet placements, walls, and ceilings (Wawrla et al., 2019).

3.7 Facility physical security & Surveillance

Physical security is the protection of personnel, hardware, software, networks and data from physical actions and events that could cause serious loss or damage to in warehouse. This includes protection from fire, flood, natural disasters, burglary, theft, vandalism, and terrorism. Every building needs a way to keep unwanted guests outside, and most organizations also need to restrict access to certain areas within their premises, even to people who have already been invited inside. The best physical security strategies make use of both technology and specialized hardware to achieve its safety goals. One of such technologies is Unmanned Aerial Vehicles (UAVs) (Rejeb et al., 2021).

Nowadays, the use of drone systems in the safety of factories has come to the fore. Physical control is essential for optimal and safe operation in factories and industrial areas. Most of the inspections can be performed with the use of human resources. However, efforts should be made to in order to make the system as automated and optimized as possible and minimize the human factor. Dedicated drones are already in use for facility protection, both indoors and outdoors and they are equipped with by various sensor systems (lidar, ultrasound, camera) that they are assisted (Hell and Varga, 2019).

Hell and Varga, (2019) mention that drones can become an integral part of industrial controls, as they can perform a task without human intervention for long periods of time in difficult to access or unsafe locations. They present the application of drones for factory security, both indoors and outdoors.

In addition, due to the increasing capability of drones and requirements to monitor, drone surveillance is becoming popular (Yap et al., 2016; Raj and Sah, 2019). Drones be used for regular surveillance routes to prohibit theft and other unwanted behavior (Wawrla et al., 2019). With this way is replaced the manual surveillance which is tedious and time consuming and a lot of effort, time and cost is saved (Macrina et al., 2020).

3.8 Summary

In this chapter, we initially presented various processes in warehouse and port terminals that can be supported or being automated (fully or semi) by adopting UAVs. Subsequently, all processes were described in detail. In the following chapter, we will focus on the use of UAVs for stock count, and we will describe various parameters that affect the UAVs performance during the execution of stock count process.

4 Mapping of user requirements

4.1 Introduction

4.1.1 The use of UAVs in warehouses

Over the past years, Unmanned Aerial Vehicles (UAVs) have rapidly taken off and currently are used in various applications (Kyrkou, et al., 2019), such as in agriculture (Tian, et al., 2020) in emergency situations (physical disasters) (Chowdhurya, et al., 2017), for border control (Koslowski & Schulzke, 2018), in intelligent transport (Menouar, et al., 2017) and in other sectors.

In logistics and especially in warehousing, the adoption of UAVs can support the execution of key processes such as stock count, returns, receiving of goods, as well as other processes such as site surveillance, monitoring of storage areas (with emphasis on surrounding areas).

Applications in inventory management and stock count tasks using UAVs include the installation of a scanner in the UAV, which performs a predetermined flight within the warehouse to perform the physical inventory (stock count) process. In such UAV applications, radio frequency identification (RFID) technology can also be used instead of the typical barcodes that usually accompany the products (Beul, et al., 2018).

Having already identified the parameters that affect the performance of UAVs during stock count process, we would like also to capture the point of view and requirements of logistics executives concerning the prospect of using UAVs in warehouse processes with emphasis on certain tasks such as stock count.

4.1.2 Requirements analysis

The aim of this section is to map the requirements related to the automation of logistics process via the use of drones. In order to achieve the above goal, two research methods were adopted: a) a survey through a structured questionnaire that was distributed to a certain sample of companies, b) personal interviews with logistics company executives via a set of open questions in order to assess and confirm the findings from the survey.

Research Method A: As mentioned above, the main aim of the questionnaire developed, was to map the current methods that companies have adopted for executing typical logistics process and at the same time to investigate whether drones could be adopted in warehouse facilities as well as in port terminals (bulk, container terminals and warehouses) for the automation of the stock count process.

Research Method B: In order to confirm and better analyze the finding from the survey, personal interviews were conducted with logistics and IT executives. The objectives of these personal interviews were as follows:

- Investigation on whether UAVs may be adopted for automating certain logistics processes in warehouses
- Confirmation of the findings from the survey
- Mapping of future trends and challenges regarding the use of UAVs

4.1.3 Methodology

The methodology for conducting the survey as well as the design of the questionnaire that was used, is presented in the following Figure (Figure 4.1).

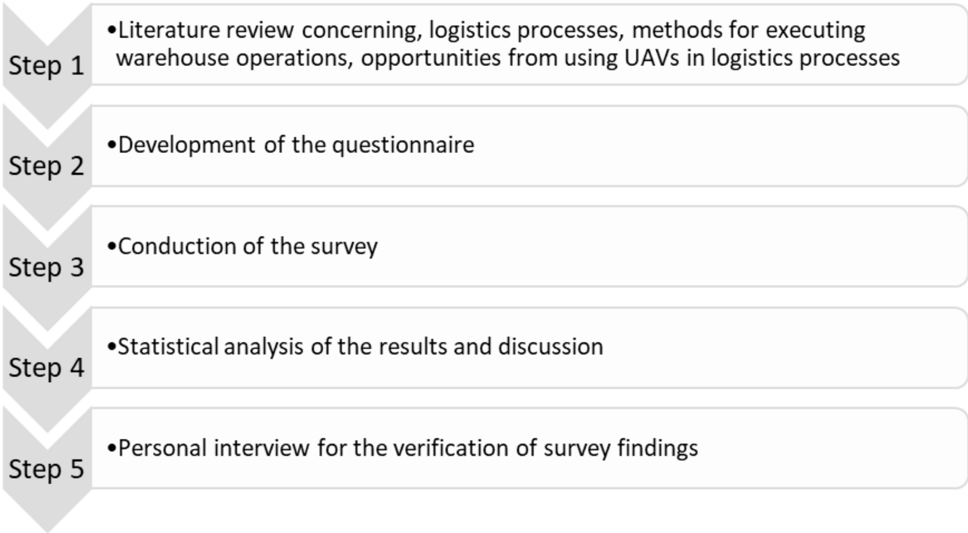


Figure 4.1 Methodological steps of this research

In Step 1 of the survey, literature review of logistics processes and the methods for executing warehouse operations are presented. In addition, problems and opportunities from using UAVs in logistics processes are reported. In Step 2, we created a questionnaire to gather the needs that exist concerning the use of UAVs for executing logistics processes in warehouses and in Step 3 the conduction of the survey, took place. The questionnaire was sent to logistics executives, to give us detailed answers which would help us in our research. Step 4 deals with the statistical analysis of the results and conclusions of the questionnaire. Finally, in Step 5 a series of interviews with logistics managers took place in order to have an in-depth mapping of the requirements and at the same time validate the results of the survey.

4.2 Questionnaire Analysis

4.2.1 Company profile

The sample of this survey comprises of 35 companies from the logistics, manufacturing and wholesales sectors (Figure 4.2). 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.

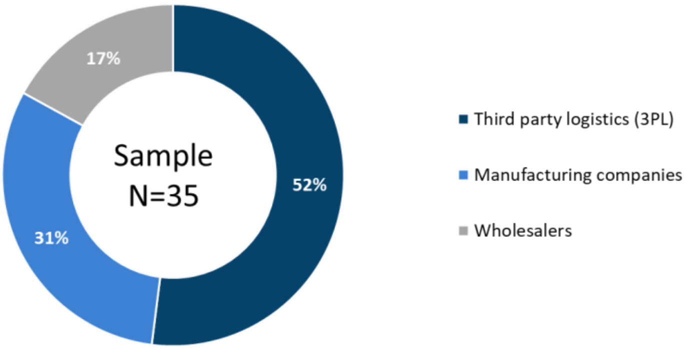


Figure 4.2 Basic activity of surveyed companies

The vast majority of logistics service providers (88.2%) of the sample have a turnover of less than €50 M. As far as manufacturing/wholesale companies are concerned, the majority (60.1%) of them are SMEs (Small-Medium Enterprises) with a turnover of less than €50 M (Figure 4.3).

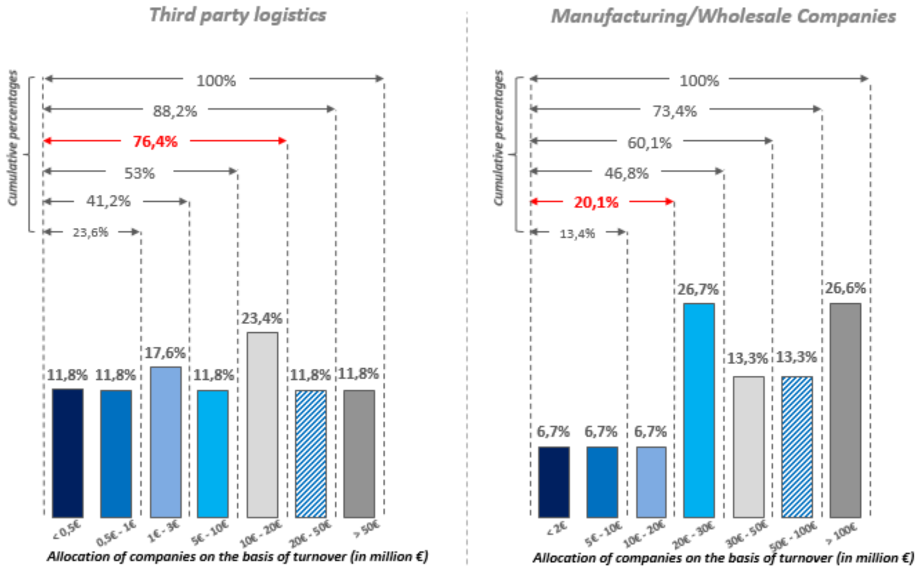


Figure 4.3 Annual Turnover of companies

Furthermore, based on the findings, it can be concluded that the majority of the companies that participated in the survey are SMEs based on the number of employees (Figure 4.4) and in terms of their turnover (Figure 4.3).

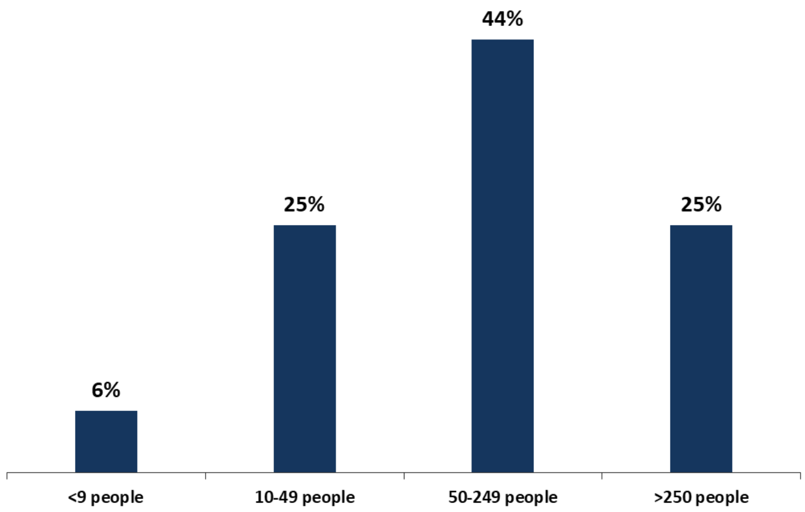


Figure 4.4 Number of employees employed by companies

4.2.2 Results regarding the execution of logistics processes: Analysis of the current situation

According to the participants' responses regarding the existing operation of the warehouses, the key inefficiencies observed during their execution are high operating costs, human errors and low productivity. Specifically, Figure 4.5 shows that the most important problem in stock count process, stock control of re-usable products and stock control of raw materials and / or final products, is the high operating costs with percentage of 44%, 44% and 41% respectively. Moreover, concerning the process of stock control of raw materials and/or final products, the problems presented (29%) are errors and high operating costs. Furthermore, human errors with 39% are the dominant problem in the process of product control prior to dispatching. Finally, it can be seen that in the processes of intra-logistics and receiving of goods, the challenge faced by companies is the low productivity with 38% and 32% respectively.

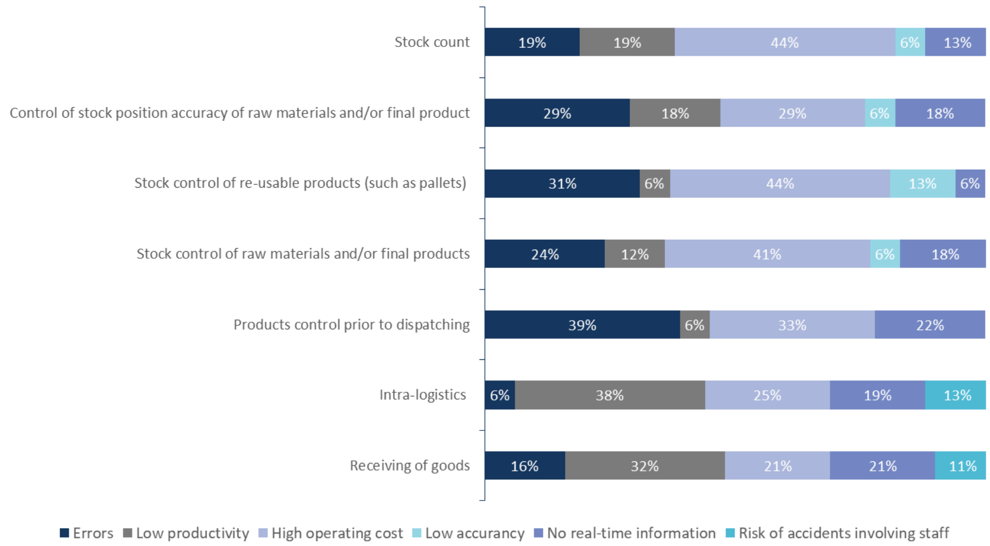


Figure 4.5 The problems encountered during the execution of logistics processes

4.2.3 Results regarding the execution of logistics processes: Exploring the adoption of UAVs

Regarding the execution of logistics processes, the findings of the questionnaire's analysis depict that a significant number of companies (58%) are aware of the use of UAVs for the execution of certain logistics processes (Figure 4.6a). Also, 78% of the companies of the sample are interested in identifying methods and techniques to automate certain logistics processes (Figure 4.6b).

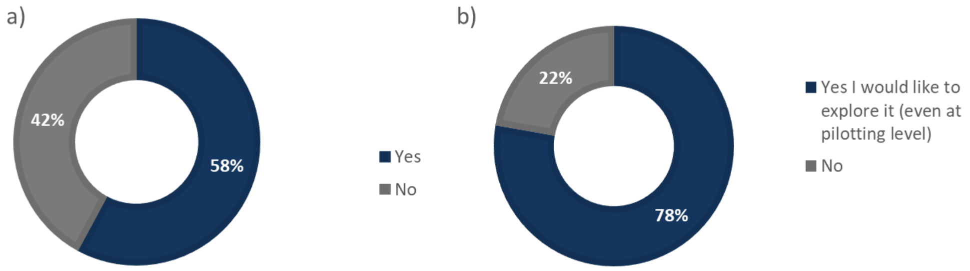


Figure 4.6 a) Information on the use of UAVs in logistics processes, b) interest of companies in the automation of logistics processes with the use of UAVs

Subsequently, the companies that participated in the survey were asked to select some of the logistics processes they want to automate. The majority (86%), as shown in Figure 4.7, are interested in automating the stock count process using UAVs followed by a 50% interested in automating the processes of products control prior to dispatching and stock control of raw materials and/or final products. Also, in the same diagram with a percentage of 43% the processes of intra-logistics and receiving of goods are observed to appeal to companies for automation. Finally, a small percentage of companies are interested in automating the process of stock control of re-usable products and the process of stock position accuracy of raw materials and/or final products.

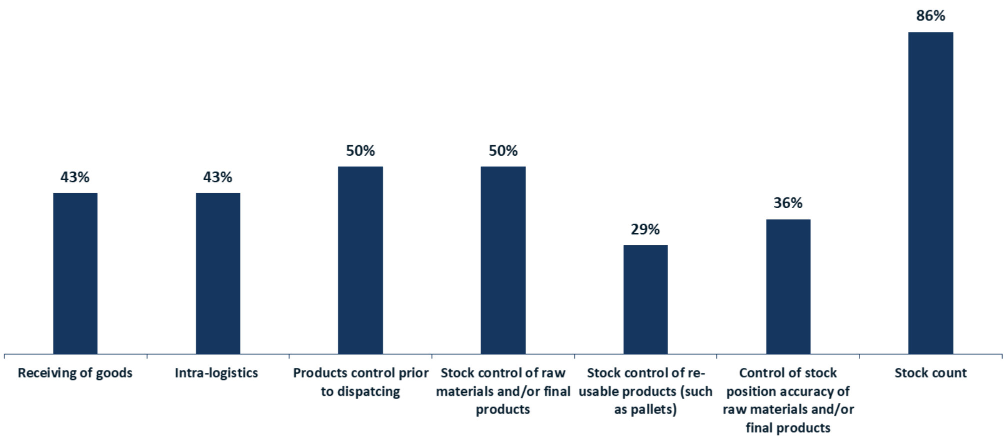


Figure 4.7 The interest in automating specific processes through the use of UAVs

Following the above question, the companies that participated in the survey were asked to state the reasons why they would automate some of the logistics processes. More specifically, according to the participants' responses, the 79% of companies would automate the logistics processes with an aim to increasing productivity, reducing errors and operating costs. In addition, several companies (43%) would choose to use UAVs to perform the warehouse processes in order to increase reading accuracy and half of the companies participated with a view to having real-time information. Finally, a percentage of 29% of companies stated that they would automate the above processes to avoid accidents at work.

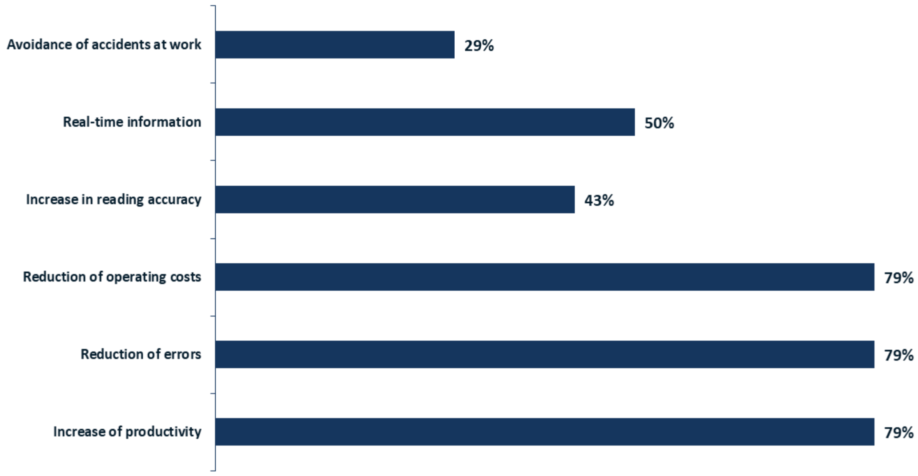


Figure 4.8 Reasons to automate logistics processes using UAVs

Another question the sampled companies were asked was whether they would be interested in participating in a pilot trial of the use of UAVs in logistics processes. The results as shown in Figure 4.9 are particularly encouraging since 71% of the companies would be interested in cooperating with the University of the Aegean, in pilot applications in logistics processes

In particular, if their experience with the pilot project was deemed positively, these companies would adopt the use of UAVs within a reasonable period of time. Specifically, for each warehouse process:

-For stock count process (answers in percentage up to 1 year: 22%, within 1-3 years: 64%, within 3-5 years: 14%)

-For control of stock position accuracy of raw materials and/or final products (answers in percentage up to 1 year: 17%, within 1-3 years: 58%, within 3-5 years: 8% and would not be willing to upgrade this procedure: 17%)

-For stock control of re-usable product (answers in percentage up to 1 year: 25%, within 1-3 years: 50%, within 3-5 years: 8% and would not be willing to upgrade this procedure: 17%)

-For stock control of raw materials and/or final products (answers in percentage up to 1 year: 15%, within 1-3 years: 62%, within 3-5 years: 8% and would not be willing to upgrade this procedure: 15%

-For products control prior to dispatching (answers in percentage up to 1 year: 31%, within 1-3 years: 46%, within 3-5 years: 15% and would not be willing to upgrade this procedure: 8%)

-For Intra-logistics (answers in percentage up to 1 year: 15%, within 1-3 years: 54%, within 3-5 years: 8% and would not be willing to this procedure: 23%)

-For receiving of goods (answers in percentage up to 1 year: 14%, within 1-3 years: 51%, within 3-5 years: 21% and would not be willing to upgrade this procedure: 14%)

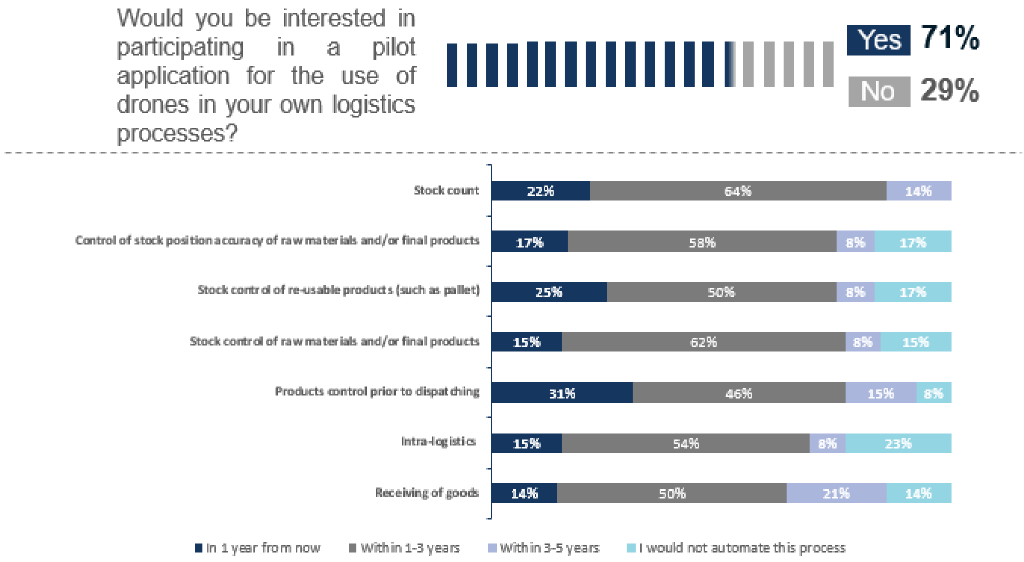


Figure 4.9 Interest in piloting the use of UAVs and time period of their adoption

Finally, it appears that the majority of companies (64%) would not upgrade their logistics processes due to their high cost. Several of the companies (50%) that participated in the survey focused on technical issues (e.g. battery life) and a percentage of 43% believe that the technology is at an early stage. While, a very small percentage do not find much benefit from such automation (Figure 4.10).

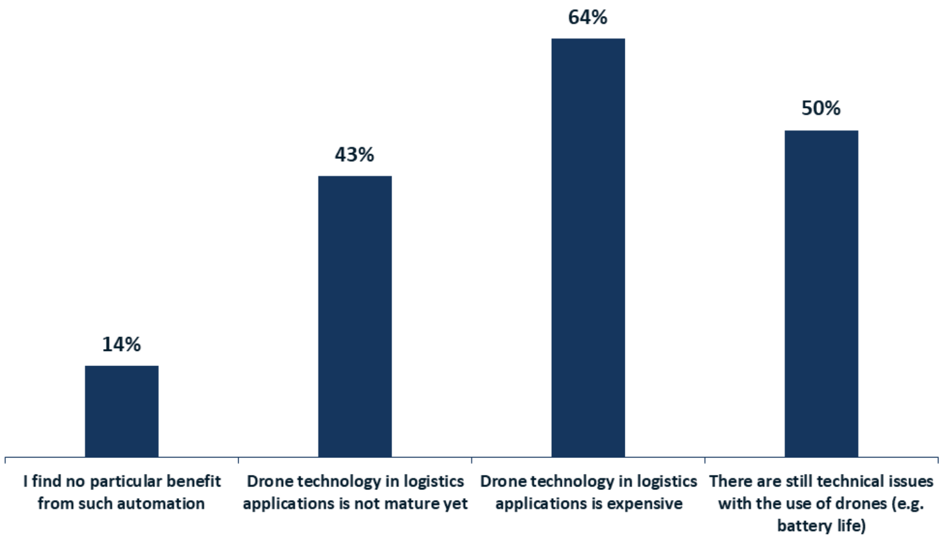


Figure 4.10 Reasons not to upgrade logistics processes using UAVs

In conclusion, from the above answers it appears that a significant percentage of the companies that participated in the survey are aware of the possibility of using the UAVs in these logistics processes and a very great percentage are willing to automate them. The sampled companies show interest in automating all processes with the majority focusing on the stock count process. The reasons that led the respondent companies to choose to automate these processes are primarily the reduction of operating costs, the reduction of errors and the increase of productivity. In addition, particularly encouraging is the willingness of companies to participate in a pilot application and their desire to adopt the UAVs technology within 1-3 years. Finally, when asked about the reasons for not adopting UAVs, the majority of the companies consider the investment cost to be quite high.

4.2.4 Future trends

In conclusion, the surveyed companies were asked to assess the adoption of the use of UAVs in logistics processes. The majority (56%), as shown in Figure 4.11, believe that the use of UAVs in logistics processes will definitely be adopted in the future, while 28% are of the opinion that it will probably be adopted. Finally, a very small percentage of 6% is not certain about the UAVs' adoption, while 11% believe that it will probably not be adopted.

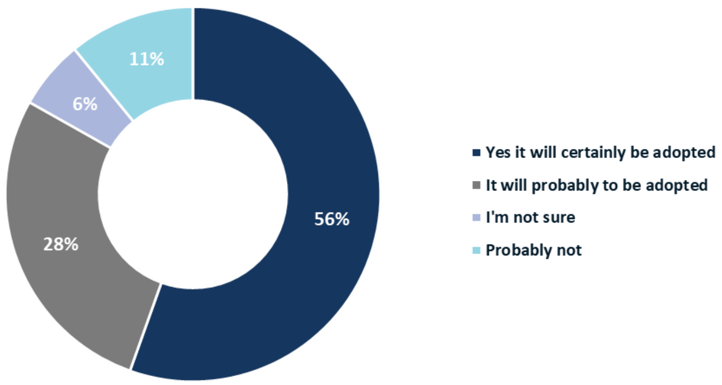


Figure 4.11 Assessment for the adoption of the UAVs technology in the logistics processes by companies that run warehouses

It is particularly encouraging that the largest percentage of the companies that participated in the survey are certain that in the future such technologies in the logistics processes will be adopted.

4.2.5 Summary of findings

In this chapter, initially the profile of the companies that responded to the questionnaire was presented. Then, the analysis of the results of the current status for the execution of the logistics processes took place. In addition, the results regarding whether the companies are willing to adopt the technology of UAVs to perform these processes were presented. Finally, the analysis of the findings took place, concluding that the majority of companies believe that the above processes with the UAV technology will definitely be adopted.

4.3 Confirmation of the findings of the survey via interviews

4.3.1 Introduction

This section focuses on confirming the findings of the above research through interviews with logistics industry executives. In particular, four (4) interviews were conducted with executives from wholesalers, retailers and logistics service providers. The analysis of the interviews confirms the interest of companies to automate warehouse processes via the use of UAVs in order to increase productive or decrease operational cost.

4.3.2 Results from interviews

In the context of a better understanding and mapping the status regarding logistics processes, as well as the inefficiencies that exist a series of interviews were conducted with executives of companies from the logistics services sector (Table 4.1). An additional aim of these interviews was to explore also the perception of executives in using UAVs for the execution of logistics processes. Finally, an important point during these interviews was the estimation of the time period of adoption of the UAVs technology, both at a corporate level and in the Greek market in general

Table 4.1 Details of interviewees who participated in the survey

#	Interviewee	Affiliation	Company	Date
1	Kochilas Evangelos	Information Technology Administrator	Dynamiki Pota SA	26/01/2022
2	Dimitrios Kybizis	Owner and CEO	Ferst Logistics SA	27/01/2022
3	Patiniotakis Nikolaos	Supply Chain Digital Transportation Manager	Dixons Southeast Europe SA	28/01/2022
4	Georgios Fardis – Antonios Danopoulos	Commercial Director – IT Director	Sarmed Logistics SA	28/01/2022

1) Dynamiki Pota SA

Interviewee: **Kochilas Evangelos**

Affiliation: **Information Technology Administrator**

Company: **Dynamiki Pota**

Date: **26/01/2022**

Company profile

Dynamiki Pota SA has developed a modern network for beverage distribution that has been active since May 2013. Dynamiki Pota SA, having developed the exclusive representation of Greek and foreign firms and at the same time having installed the most modern systems, programs and technical equipment, caters for the needs of all sales channels, Super Market, Wholesale, Ho.Re.Ca. and individual customer (Dynamics, 2022).

Main interview points

This interview was held on the 26th of January 2022 by the project team of the DeOPSyS laboratory in collaboration with Mr. Kochilas Evangelos, Information Technology administrator. Its main objective was to understand the current status at an operational level of the company's warehouse. Finally, reference was made to what extent the technology of the UAVs would help to improve these processes.

Currently the wholesale company DYNAMIKI POTA S.A. regarding the logistics processes operates with the contribution of human resources, using RF scanners. Specifically, the stock count process of 7,500 codes (mainly pieces-bottles, boxes and very few pallets) has been completed sufficiently, with checks as well as corrections, within twelve hours, compared to the previous system that was completed within 3 days.

During the stock count process, there was a significant improvement in productivity. However, there are several inefficiencies that can be further improved. Moreover, as far as the safety of employees is concerned, there is a small probability of an accident during the inventory, in contrast to day-to-day operations (e.g. picking, receiving) where there is a higher risk of accidents due to the more intense pace of the company. In addition, Dynamiki Pota SA is receptive to the adoption of technologies that will offer new capabilities to staff and to the improvement of the workplace. Specifically, it is considering the possibility of implementing voice picking system which will help increase productivity.

For this reason, the company is interested in a fully automated UAVs-based system for logistics processes. Specifically, it focuses mainly on the stock count process at the box and pallet level, but also on other processes such as intra-logistics with the anticipated benefit of reducing errors and avoiding accidents. The factors taken into account for adopting this technology are certainly the cost of labor and installation, however it focuses on Return on Investment and the existing legislation that does not allow UAVs flights near the airport. Finally, there is significant interest in both testing and implementation at a piloting level and for subsequent investment.

2) Ferst Logistics SA

Interviewee: **Dimitrios Kybizis**

Affiliation: **Owner and CEO**

Company: **Ferst Logistics**

Date: **27/01/2022**

Company profile

The company began its activities in 1991, as SARMED, focusing on customs warehouses. All these years it has developed its services, covering today all logistics needs for its customers in cars. Since the beginning of 2020, the company's structure has changed and FERST logistics SA has taken over all the activities of the automotive industry (Ferst logistics, 2021).

Main interview points

The interview, which took place on the 27th of January 2022 by the project team of the DeOPSyS laboratory in collaboration with Mr. Dimitrios Kybizis, Owner and CEO of Ferst logistics SA, had as its main objective the understanding of the current status at an operational level of the company's warehouses. Finally, reference was made to what extent the technology of the UAVs would help to improve these processes.

The current status of the company regarding the logistics processes, due to the restrictions of the space as it is not unified (it consists of 3 independent warehouses), presents several inefficiencies. These inefficiencies refer mainly to the operational level and specifically to the low productivity, which is due to the wrong position of a car within the warehouse area. This may be because of the change of position of the vehicle and/or the failure to record its new position. The way the logistics processes are executed at customs level and at warehouse level is carried out by using the warehousing management system (WMS). More specifically, to monitor movements in real time, vehicles are scanned with barcode scanners. At the same time, the shipment of the cars is monitored by a routing system where the route which is to be followed by the truck is optimized, while for the correct delivery a proof of delivery system is applied.

In the above processes there is room for improvement in order to avoid failures and to make the best possible use of the space. For this reason, there is quite a lot of interest in the use of UAVs and their immediate adoption, where the investment cost, the Return-on-Investment (ROI) and the legislative framework of the area it is based in (Military Airport of Elefsina) play a decisive role.

3) Dixons South East SA

Interviewee: **Patiniotakis Nikolaos**

Affiliation: **Supply Chain Digital Transportation Manager**

Company: **Dixons South East Europe A.E.B.E**

Date: **28/01/2022**

Company profile

KOTSOVOLOS is the leading electrical and electronics chain in Greece and has been active in the country since 1950 when it opened its first store.

The KOTSOVOLOS chain is a member of the European group Dixons Carphone, one of the leading in the sale of electrical goods and mobile products, employing more than 42,000 people. The company's network consists of 95 physical stores in various regions of Greece, while consumers who prefer the internet for their purchases can use the integrated online store of Kotsovolos (Skywalker, 2022).

Main interview points

In the interview conducted on 28th of January 2022 by the project team of the DeOPSyS laboratory in collaboration with Mr. Patiniotakis Nikolaos, Supply chain digital transportation manager of Dixons South East Europe S.A., its main objective was to understand the current status at an operational level of the company's warehouses. Finally, reference was made to what extent the technology of the UAVs would help to improve these processes.

Currently, the execution of logistics processes are carried out in several ways. The receiving of goods process is carried out using scanners and at the same time an additional check is carried out with the receiving slip. During the picking of products, RF scanner and voice-picking technologies are applied, thus reducing the execution time of this process. The following is the stock count process, which shows a significant improvement compared to the previous inefficient way of execution. In the current status it is performed in a different way at the level of picking and storage locations, showing a decrease in runtime and an increase in reading accuracy. At this point it is important to mention that intermediate checks are carried out to help better manage the inventory.

In adopting the use of UAVs there is quite a lot of interest in the above processes. The use of UAVs is already being piloted in the stock count process. The use of this technology was based on the need to reduce operational cost and time for the completion of this specific process which involve the count of pallets (more than 75% of the stock consists of pure pallets). Specifically, the company has an annual subscription to a UAV and registers 320 places of products per hour (20-minute flights). In addition, it is necessary to have an operator and a QR code platform that defines the flight plan. At a later stage, the company is interested in recognition of pallet and detecting the absence of a box. With the piloting experience so far, the company does not point out any problems in battery and mapping issues and at the same time stresses the convenience of its use and reading of products. Nevertheless, investment cost and Return-on-Investment (ROI) are important factors in the investment of such a technology.

4) Sarmed Logistics SA

Interviewee: **Georgios Fardis – Antonios Danopoulos**

Affiliation: **Commercial Director – IT Director**

Company: **Sarmed Logistics A.E.**

Date: **28/01/2022**

Company profile

SARMED logistics SA is a pioneering Greek company active in the logistics industry, covering the entire range of supply chain services, offering advanced services for dry and cold cargo.

SARMED covers the management of all kinds of consumer goods, from very small items to heavy and bulky ones. It also specializes in customs / tax warehouses, customs clearance services and all kinds of customs formalities, as well as in the provision of specialized consulting services on customs matters (Sarmed, 2021).

Main interview points

In the following interview, which was conducted on 27th of January 2022 by the project team of the DeOPSyS laboratory in collaboration with Mr. Georgios Fardis – Mr. Antonios Danopoulos, Commercial Director – IT Director, had as its main objective the understanding of the current status at the operational level of the company's warehouses. Finally, reference was made to what extent the technology of the UAVs would help to improve these processes.

The Sarmed logistics SA consists of building complex where each warehouse is independent. In the context of logistics processes, the way they are executed depends many times on the nature of the depositor / customer but also on the way of receiving the products based on their size (e.g. piece, box and pallet). By focusing on the stock count process, the company uses two ways of performing it. More specifically, the first way is performed in the "traditional" way of using a product list as opposed to the second where computerized ways such as Warehousing Management System (WMS) and RF scanners (in some warehouses) are used.

During the stock count process, several weaknesses are observed during its execution in the "traditional" way. In particular, in terms of results and accuracy, several mistakes are made based on the human factor and the time varies depending on the customers and the nature of their stocks. That is why this process is becoming quite costly. Finally, there are no accidents of employees during the execution of the above process.

Regarding the implementation of UAVs in the respective processes, the company argues that the Greek market is not yet ready for an investment in such technology, pointing out a three-year time period for its adoption. Nevertheless, as far as the logistics processes are concerned the company is in favor of the use of UAVs with an integrated RFID. Criteria for the adoption of this technology are the real-time information, reading accuracy of the stocks and the reduction of operating costs. To conclude, there is also interest of the piloting application, in collaboration with the University of the Aegean, in order to apply the technology in real conditions and to verify the best possible solution.

4.4 Conclusions

Through all the personal interviews and the use of a questionnaire, carried out by the project team of the DeOPSyS laboratory, in collaboration with various members involved in the supply chain, such as logistics service companies and commercial companies, it drew the following conclusions in the context of the current state of operation of these processes and the adoption of UAVs

The majority of companies in Greece, whether they are logistics service companies or commercial companies, mostly maintain automated logistics processes. The main aim of the research was to draw conclusions regarding the effects of UAVs on the respective processes. The results of the survey show that in the current status the above processes need to be further improved. Also particularly important is the interest shown by businesses in exploring the adoption of UAVs in logistics processes. In particular, there is an advancement of systems regarding these processes (e.g. stock count). However, there is room for improvement in order to reduce operating costs, increase productivity and accuracy in controlling inventories, resulting in companies having an interest in adopting UAVs with RFID readers.

The extraction of the results through the personal interviews as well as from the distribution of the questionnaires to executives of commercial companies and logistics, resulted in the confirmation of the conclusions that emerged from the bibliographic review. In particular, there is great interest in upgrading and automating logistics processes where the majority of respondents focus on the stock count process (e.g. reducing operating costs, increasing productivity and increasing the level of accuracy of results).

5 Design of Experiments (DoE) for the evaluation of UAVs in stock count process

5.1 Introduction

This chapter presents the theoretical background of the Design of Experiments (DoE) methodology which we will adopting in our research for the evaluation of UAV's use in terms of stock count efficiency and accuracy via a series of lab tests. Initially the methodology as well as the intermediate steps of DoE methodology are presented for assessing the performance of proposed system. Then, the experimental design that will be used for the design and testing of the system as well as the procedure for the execution of experiment are analyzed. The remaining sections shows the statistical analysis of the results from the tests as well as the conclusions. Furthermore, this chapter describes the tests that will be performed in first set of laboratory tests to determine the factors and levels of UAV’s performance parameters of the final experiment. Specifically, by taking into consideration the results of the Systematic Literature Review, four parameters (UAV flight altitude, UAV speed, Read distance, Tag location) were selected of the total of 8 parameters, which emerged through the SLR methodology, that affect UAVs performance in stock control. The purpose of this chapter is to describe these tests that will be performed with aim to define the values of the levels of each parameter.

5.2 The concept of Design of Experiments

Researchers conduct experiments in almost all areas of research, usually to find out something about a specific process or system (Montgomery, 2012). Each experimental run is a test. Typically, an experiment can be defined as a test or series of tests in which determined changes are performed to the input variables of a process or system in order to identify the reasons for the changes that may be observed in the output response of the process / system (Montgomery, 2012).

Deliberate changes to system input variables are made in order to better understand the cause-effect relationships in the system and to arrange the changes caused by the system output. The resulting observations can lead to theories or hypotheses about what makes the system work. That is, to identify the input variables that are responsible for the observed changes in response, to develop a model that is related to the response to important input variables and to use this model to improve a process or a system (Montgomery, 2012).

Experimental design is an extremely important tool in the scientific and industrial fields to improve the product creation process. The use of experimental design in the production process can create products that are easier to manufacture and that have improved performance and field reliability, lower product costs and shorter design and development time. In addition, the designed experiments have extensive applications in marketing, market research, trading and services, as well as general business activities (Montgomery, 2012).

Design of Experiment (DOE) is a powerful technique to study the effects of a series of factors in a process or system and also assists to determine the best settings of these factors in order to improve the performance of process or system (NIST/SEMATECH, 2012).

5.3 Design of Experiments: Implementation steps

Based on the principles of DOE methodology, the necessary steps for the planning and execution of the experiment, the collection and analysis of the data are presented below. The following methodology and steps are proposed by Montgomery (Montgomery, 2012).

The steps are as follows:

Step 1: Recognition of and statement of the problem

The first step of the methodology is to understand the problem that leads to the need of experimentation and a precise statement of the problem that contributes to a better understanding of the process. In addition it is important to develop ideas about the objectives of the experiment and the final solution.

Step 2: Choice of factors, levels and ranges

A number of factors are taken into account when evaluating a process or system. These factors can be classified into two categories. In one category are the potential design factors and in the other the nuisance factors. The potential design factors are those factors that the experimenters may wish to vary in the experiment and may influence the output response. The nuisance factors may have effects that need to be accounted for, but they are usually not taken into account during the execution of an experiment.

Step 3: Choice of experimental design

Choice of design includes the selection of the experimental design technique (eg classical experimental design, orthogonal array designs, etc.), the examination of the sample size (number of replicates), the selection of an appropriate run of experimental trials, and the determination of whether or not blocking or other randomization restrictions are involved.

Step 4: Performing the experiment

In this step the research hypothesis is formulated as well as the final check of the process takes place. Before the run of experiment, it is important to monitor the process in order to ensure that everything is being done according to plan and there are no errors. Also, at this step and before the execution of experiment, it is important to have some trial runs or pilot runs in order to check the experimental technique.

Step 5: Statistical analysis of the data

After the completion of the experiment and the collection of data, the data must be analyzed through statistical methods in order to export the results and conclusions. Graphical methods are also effective in analyzing and interpreting data. Finally, the hypothesis testing as well as the confidence interval estimation procedure are useful in data analysis of a designed experiment, since a significant number of the questions that must be answered can be cast into a hypothesis testing-framework.

Step 6: Conclusions and recommendations

Once the data have been analyzed, practical conclusions must be drawn about the results and a course of action should be recommended. Graphical methods are often useful at this stage, especially in presenting experimental results.

5.4 Choice of experimental design (factorial design)

Many experiments involve studying the effects of two or more factors. Factorial design is more effective for this type of experiment, because it is an experimental strategy in which the factors vary together, instead of one at a time (Montgomery, 2012). By factorial design, we mean that in each complete test or repetition of the experiment, all possible combinations of factor levels are investigated. For example, if there are α levels of factor A and β of factor B, each repetition contains all the combinations between the levels of the two factors, the number of which is αβ (Montgomery, 2012). When factors are ordered in a factorial design, they are often said to be crossed. The result of a factor, which is often called the main effect because it refers to the primary factors of the experiment, is defined as the change that occurs after the completion of the experiment by changing the level of the factor (Montgomery, 2012).

Factorial designs have many advantages. Initially, they are more effective than one-factor-at-a-time experiments. In addition, a factorial design is necessary to avoid misleading conclusions when interactions may occur. Finally, factorial designs allow the effects of a factor to be estimated at several levels of the other factors, drawing conclusions that apply to a number of experimental conditions (Montgomery, 2012).

The purpose of the experiment of the present study is to investigate the parameters that affect the reading accuracy and the effectiveness of the stock count. To achieve this result a series of experiments will be performed with 4 factors consisting of 2 levels. The choice of the specific parameters that will be examined will be made due to the importance and the influence they have on the use of UAVs during the stock count process. The levels of each parameter that will be examined will be derived through individual tests which we will analyze in the next section.

5.5 The 2k factorial design

In most industrial processes and systems, classical experimental design (full and fractional factorial designs) are mainly used, especially when experimenters want to evaluate the performance of a system by alternating input variables (levels of factors) (Antony, 1999). Factorial designs are widely used in experiments involving various factors where it is necessary to study their common effect on a response (Montgomery, 2012). There are many special cases of the general factorial design that are important because they are widely used at the research level, but the most important of these is the 2k experiment, where each factor has only two levels (Montgomery, 2012). These levels may be quantitative, such as two values of temperature, pressure or time; or it may be qualitative, such as two machines, two operators, the "high" and "low" levels of a factor, or perhaps the presence and absence of a factor. A complete replicate of such a design requires 2 * 2 * . . . * 2 = 2k observations and is called 2k factorial design (Montgomery, 2012)

The 2k design is especially useful in the early stages of experimental work, when many factors are likely to be investigated. It provides the smallest number of runs with which k factors can be studied in a fully factorial design. Consequently, these designs are widely used in factor screening experiments (Montgomery, 2012). According to Antony (2014) when the number of factors is less than or equal to 4, full factor design is the most appropriate choice for conducting experiments.

In this study 4 different factors of 2 levels will be examined and the full factorial design is selected for the experiments. A full factorial designed experiment consists of all possible level combinations for all factors and the total number of experiments to study the k-factors at 2 levels is 2k (Antony, 2014; Montgomery, 2012). Therefore the possible combinations that result are 16 (2^4).

5.6 Interpretation of results

This section refers to the interpretation of the results will be obtained from the experiments. It is necessary to examine the statistical significance of the parameters and to determine how they affect the stock count process. The Minitab statistical package is used for statistical analysis in the present study.

In order to achieve this goal, the Analysis of variance (ANOVA) must be performed and a hypothesis test must be performed in order to detect or not differences in the mean values of more than two populations.

Case control is initially constructed and the following hypotheses are defined:

- H0: The null hypothesis states that all population means (factor level means) are equal
- H1: The alternative hypothesis states that at least one is different.

The populations, and therefore the samples, of the present study consist of the sum of the products recorded during the stock count process per case.

According to Montgomery (2012), the P value is defined as the smallest level of significance that would lead to rejection of the null hypothesis. If the p-value is less than or equal to a predetermined significance level (denoted by α or alpha), then you reject the null hypothesis (H0) and claim support for the alternative hypothesis. On the other hand, if the p-value is greater than α, then you fail to reject the null hypothesis and cannot claim support for the alternative hypothesis. In our case, it is important to mention that the α value (level of significance) which was used for this analysis was set at 5% (α=0.05).

Based on the above and the results of ANOVA analysis, we can conclude which factors and combinations of them are statistically significant. The factors and the combination of the factors for which P-value <0.05 applies and the null hypothesis (Ho) is rejected, significantly affect the efficiency of the stock count process. Conversely, for all cases where P-value> 0.05 there are no statistically significant differences between the factors and the null hypothesis is not rejected. The rejection of the null hypothesis means that the alternative hypothesis H1 is accepted in terms of significance. In other words, we accept the assumption that at least two samples have different values and significantly affect the efficiency of the stock count process.

In addition, the results of the ANOVA analysis are confirmed by an additional chart, the Pareto plot. The Pareto chart shows the absolute values of the standardized effects from the largest effect to the smallest effect. The chart also plots a reference line to indicate which effects are statistically significant. The Pareto plot uses the same level of significance.

The following conditions must apply to the integrity and application of the analysis of variance:

1) The distribution of residuals should be normal

2) The samples should be representative and the observations should be independent of each other

3) The populations from which the samples were selected have the same variance

To check these conditions it is necessary to analyze and evaluate a series of plots. The plots are the Normal probability plot of residuals, the Histogram of residuals, the Residual versus fits and the Residual versus order of the data. In more detail, the Normal probability plot of residuals is used to verify the assumption that the residuals are normally distributed and that the assumption of normal value distribution is valid. The ideal plot of residuals should follow approximately a straight line. The Histogram of residuals used to examine the shape and spread of data. The Histogram of residuals shows the distribution of residuals for all observations and should be approximately symmetrical and bell-shaped so that the values follow a normal distribution. A histogram works best when the sample size is at least 20.The residuals versus fits plot is used to verify the assumption that the residuals are randomly distributed and have constant variance. Ideally, the points should fall randomly on both sides of 0, with no recognizable patterns in the points. Finally, the residuals versus order plot is used to verify the assumption that the residuals are independent from one another. Independent residuals show no trends or patterns when they appear in time order. Ideally, the residuals on the plot should fall randomly around the center line.

The interaction plot also have an important role in the interpretation of the results. More specifically, these plots show the correlation of the factors under study. The Interaction Plot used to show the relationship between one categorical factor and a continuous response depends on the value of the second categorical factor. This plot displays means for the levels of one factor on the x-axis and a separate line for each level of another factor. In this way all the interactions of the factors are examined, and the best combination is obtained.

5.7 Experimental description

Storage system

The experiments that are described in this section will be carried out for the stock count process by taking into consideration the Back-to-Back storage system. The Back-to-Back storage system are described as follows:

The Back-to-back system is the most widespread storage in modern warehouses. The back-to-back system consists of many levels of shelves and is an inexpensive storage system. It is also quite flexible in cases of rearrangement of space. It has low exploitation of space but at the same time it is suitable for FIFO (First In First Out) products.

Equipment

To perform the stock count process using UAV's technology, an UAV model will be used. For the reading and counting of the products, an RFID reader and passive RFID tags will be used which will define each product unique. The RFID reader will be mounted on UAV device and will perform the counting of the products during the flight.

The model and specifications of the UAV as well as the specifications of the RFID reader in combination with the RFID tags are presented in the tables below:

Table 5.1 Specifications of DJI Mavic Air 2

Specifications of DJI Mavic Air 2	
Weight (Battery & Propellers Included)	595 gr
Max Horizontal Flight Speed	19 m/s (S-mode) 12 m/s (N-mode) 5 m/s (T-mode)
Max Flight Time (without wind)	31 minutes
Max Service Ceiling Altitude	5 km

Specifications of DJI Mavic Air 2	
Operating Frequency	2.400 - 2.483 GHz and 5.725 - 5.850 GHz
Operating Temperature Range	0 to 40°C (32° to 104°F)
Battery	3500 mAh LiPo 3S

Table 5.2 Specifications of Chainway R5 Wearable RFID Reader

Specifications of Chainway R5 Wearable RFID Reader	
Size	108 mm × 78 mm × 18 mm
Weight	200 g / 7.05 oz.
Product material	Plastic
Battery specification	2000 mAh (removable)
Indicator LED	Power, Work, Bluetooth
Interfaces	Type-C
Operating temperature	-20℃ to 50℃
Antenna	Circular Polarized Antenna (3dBic)
Frequency	920-925MHz/902-928MHz/865-868MHz
Reading rate	>200tags/s

Table 5.3 Specifications of Dogbone MR6 RFID tags

Specifications of Dogbone MR6 RFID tags	
IC	Impinj Monza R6
Memory	96 bit
Frequenncy	860-960 MHz
Antenna size	94 x 24 mm / 3.7 x 0.9 in
Die-cut size	97 x 27 mm / 3.8 x 1.1 in
Web Width	100 mm / 3.94 in
Operating Temperature	-40 °C to +85 °C / -40 °F to +185 °F
Delivery Format	dry, wet and tag
Adhesive	Acrylic, water borne adhesive (wet), Solvent-free permanent adhesive (tag)
Qty/Reel	5,000 pcs
Core size	76 mm / 3 in
Shelf size	+20 °C, 50 % RH / 68 °F, 50 % RH - minimum 2 years from the date of manufacturing

Description of parameters to be investigated and initial experiments

The aim of the experiments to be conducted is to examine the values of levels in the design of Experiments that will be taken into consideration for each parameter that will be investigated

The selection of the values of levels of each parameter will result from the execution of individual tests for each of them. Multiple values for each level of each factor will be examined so as to define the suitable values that will be adopted during the conduction of the final experiments (second set of laboratory tests).

Read distance

Read distance is an important parameter because it affects how quickly and correctly drones read a label (Duric et al., 2018; Fernández-Caramés et al., 2019).

For the case of the Back-to-Back Storage System, which it will be studied for 4-level shelves, the reading ability of each tag (which will be placed in the middle of the pallet of each shelf) will be carried out for all reading distances created according to all the flight altitudes that will be examined (Figure 5.1). Therefore, for each value of the flight altitude set, we will have 4 reading distance values. The output for each measurement will be read/no read.

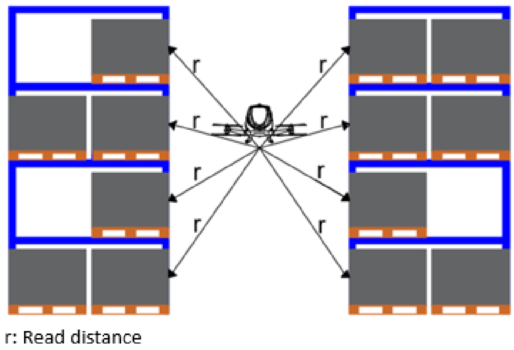


Figure 5.1 Illustration of the Read Distance factor for Back to Back system

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 and Abdelkefi, 2017; Rejeb et al., 2021).

For the control of the factor of UAV speed, four different speeds will be examined. From the execution of these individual tests for each value of UAV speed, the reading ability of the RFID tags in Back-to-Back storage systems will be examined and the selection of the values of levels of each parameter will result.

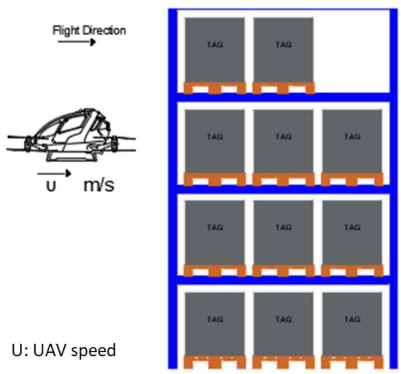


Figure 5.2 Illustration of the UAV Speed factor for Back to Back system

UAV flight altitude

Flight altitude should be constrained to as low as possible when it comes to the precision of the products localization, because a higher flight will decrease the localization precision (Kang et al., 2019).

The test to check the accuracy of reading the RFID tags will also be performed for the factor of UAV flight altitude. Specifically, it will be examined whether the tags are read at different altitudes. For Back-to-back storage system, an experimental setup will be developed for multiple altitudes of 2m, 4m, 6m and 8m respectively (Figure 5.3). The output for each measurement will be read/no read and from the results that will be obtained, we will choose the final values of levels of this parameter for DoE.

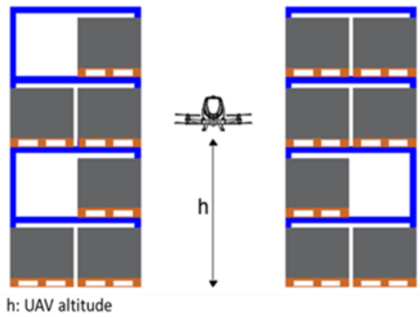


Figure 5.3 Illustration of the UAV Flight Altitude factor for Back-to-Back system

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 et al., 2018).

This test will examine if the position of the RFID tag according to the flight path of the UAV affects its reading by the RFID reader. Specifically, we will check if the RFID tag is read on all four sides of the pallet on a fixed flight path of the UAV.

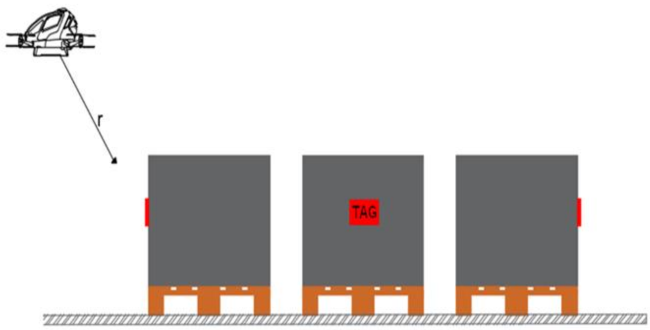


Figure 5.4 Different tag positions for reading

5.8 Summary

This chapter initially described the concept of Design of Experiments as well as a detailed description of the methodology, with all the steps of the process. Subsequently, the experiment was presented and the specific case of the 2k experiment described. In addition, the interpretation of the results was analyzed. Moreover, this chapter initially presented the two storage systems that we will examine in our experiments and the equipment that will be used to perform them. Finally, the parameters to be investigated and initial experiments to examine the values of levels in the design of Experiments that will be taken into consideration for each parameter was described.

6 Experimental results

6.1 Introduction

This chapter presents the evaluation results of the proposed stock count system in terms of stock count efficiency and accuracy. Initially, this chapter presents the results of the first set of laboratory tests followed by the selected factors and their levels that have been chosen for assessing the performance of the proposed system on the second set of laboratory tests. Subsequently, this chapter presents the experimental design used for testing the proposed system, including the methods adopted to execute the experiments and analyze the results. Finally, the chapter presents the statistical analysis of the experimental results.

6.2 Experimental results for the selection of factors to be investigated and values of levels of DoE

The objective of the first set of laboratory tests is to examine the values of levels (DoE) for each parameter that will be investigated via laboratory experiments in terms of RFID tags reading accuracy. The selection of the values of levels of each parameter results from the execution of individual tests for each parameter (factor). Multiple values for each level of each factor are examined so as to define the suitable values that will be adopted during the conduction of the final experiments (second set of laboratory tests).

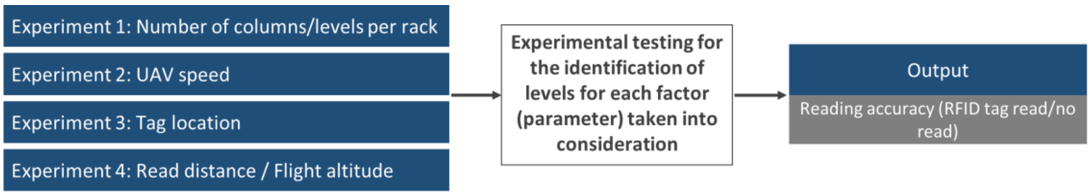
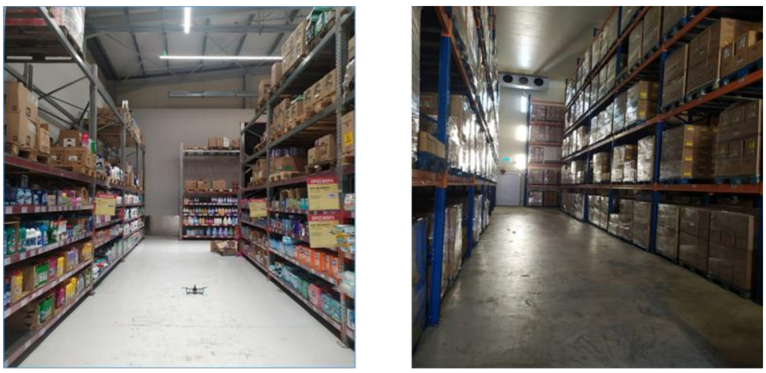


Figure 6.1 1st set of Laboratory tests

For this purpose, the first set of tests was carried out in two different warehouses. The first case refers to a warehouse with dry products stored in an ambient environment and the second one to a warehouse with liquid products stored in a chilled environment. The warehouse with ambient temperature has a height of 8m, consists of shelves with 7 levels and the storage units include items, boxes, and pallets. The warehouse with chilled temperature has a height of 10.9m, consists of shelves with 5 levels and the storage unit used is the pallet.



a) Ambient warehouse b) Chilled warehouse

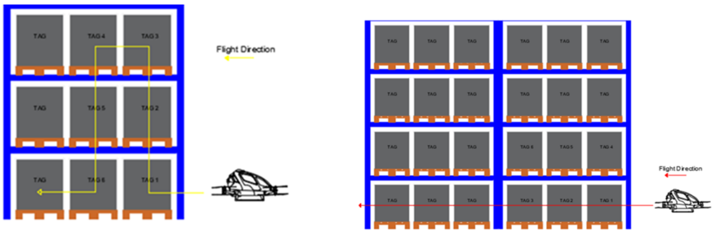
Figure 6.2 Types of warehouses

For both experimental setups, the experiments were carried out by taking into consideration of two different positions of the RFID reader. The RFID reader in one case is positioned on the upper side of the UAV, whereas on the other case underneath the UAV.

a) Upper side b) Underside

Figure 6.3 Positions of RFID reader

Furthermore, the experiments conducted for each parameter were performed for two different ways of flight of the UAV within the warehouse. In the first case the UAV follows an S-shape direction and in the second case the UAV follows a straight direction within the aisles of the warehouse.



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

Figure 6.4 Different ways of UAV's flight

For both experimental set-ups, independent experiments were performed for each factor (Number of columns/levels per rack, UAV speed, Tag location, Read distance/Flight altitude) separately in order to test the reading accuracy of the RFID tags. The aforementioned experiments are presented in Figure 6.5.

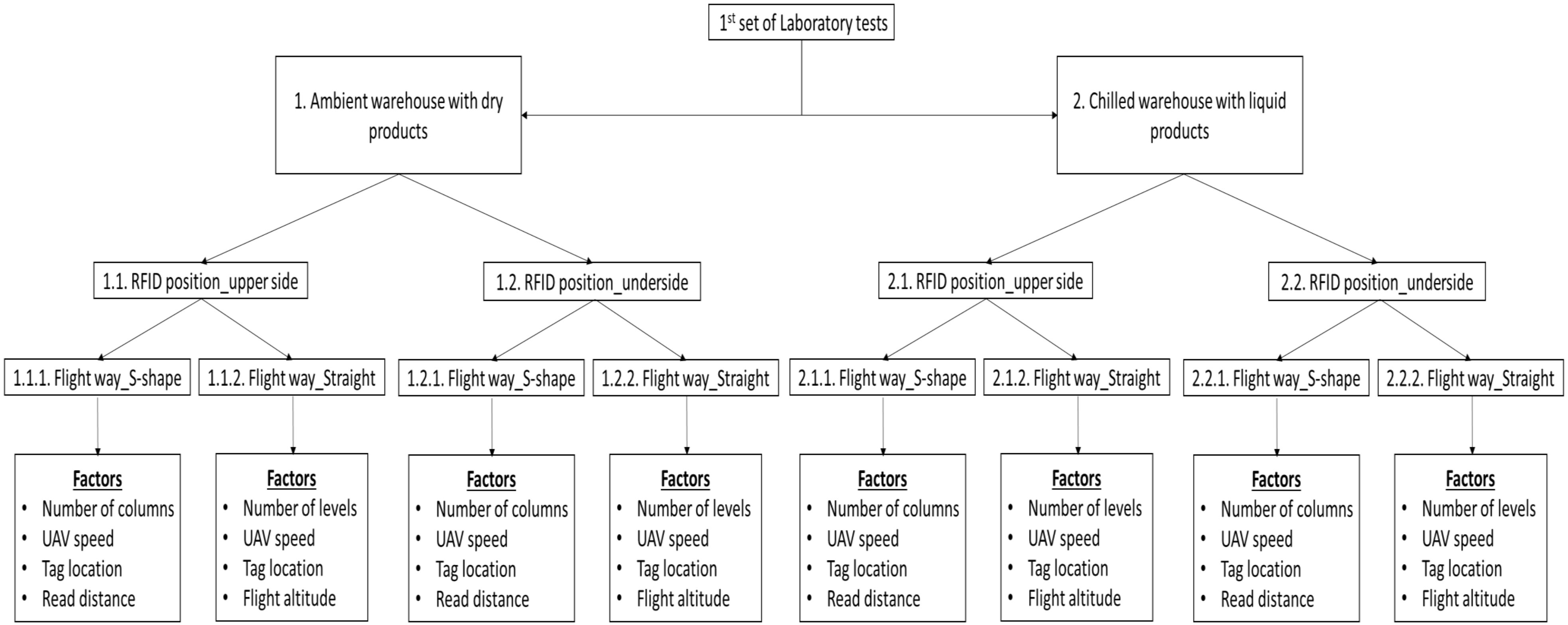


Figure 6.5 Experiments for the first set of laboratory tests

6.2.1 Case study 1: Ambient warehouse with dry products

This subsection presents the results obtained for each factor tested in the first set of laboratory tests. The tables below show in detail the results obtained for each of the individual experiments in the first case study. The first case study concerns an ambient warehouse with dry products, where for each factor 3 replicates were performed to verify if the RFID tag is readable.

RFID position_upper side & Flight way_S-shape

The first case involves examining the four factors (Number of columns per rack, UAV speed, Tag location, Read distance) with the RFID reader positioned on the upper side of the UAV and performing the flight of the UAV in the S-shape flight way. Experiment 1 examines the parameter of Number of column per rack. This experiment has two subcategories (single/double column). Specifically, the UAV performing its flight in the first subcategory flies per column in each shelf and in the second subcategory the UAV flies in the middle of two columns per rack. In both subcategories of Experiment 1, we observe that in all 3 replicates of the test there was a complete readout of the RFID tags (Figure 6.6 & Figure 6.7)

Experiment 1: UAV flight type (single column)

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

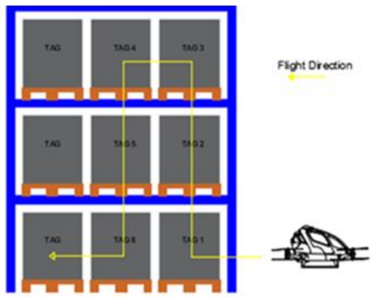


Figure 6.6 Results for factor of UAV flight type (single column)

Experiment 1: UAV flight type (Double column)

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

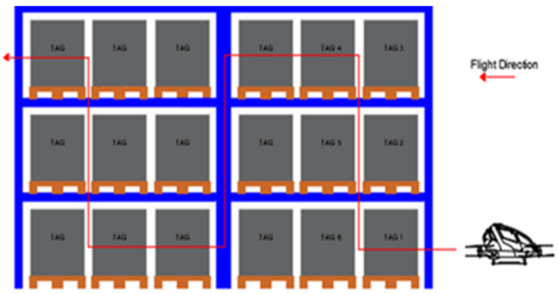


Figure 6.7 Results for factor of UAV flight type (Double column)

Experiment 2 examines the factor of UAV speed. In this experiment, the UAV performs its flight in the S-shape flight way and examines the reading of RFID tags for three different speed values. The specific speed values were set according to the speed limits that could be deployed in the ambient warehouse, so that there is a constant control of the UAV during the flight without accidents. The results of experiment 2 (Figure 6.8) show that there is reading of the RFID tags when the UAV flies at the specified speeds.

Experiment 2: UAV speed

	1st replicate		2nd replicate		3rd replicate	
UAV speed	Read	No read	Read	No read	Read	No read
0,5 m/s	✓		✓		✓	
1 m/s	✓		✓		✓	
1,5 m/s	✓		✓		✓	

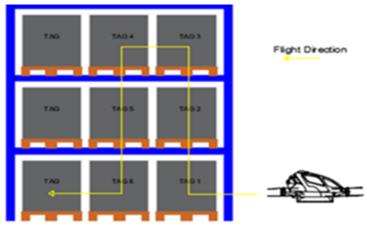


Figure 6.8 Results for factor of UAV speed

Experiment 3 examines the factor of Tag location. The aim of this experiment is to examine whether the position in which the RFID tag is placed affects its reading during the UAV's flight direction. The results of this test showed that whichever side of the pallet the RFID tag is placed on can be read by the RFID reader.

Experiment 3: Tag location

	1st replicate		2nd replicate		3rd replicate	
Tag location	Read	No read	Read	No read	Read	No read
Front side	✓		✓		✓	
Back side	✓		✓		✓	
Right side	✓		✓		✓	
Left side	✓		✓		✓	

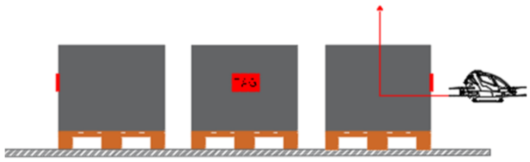


Figure 6.9 Results for factor of Tag location

The last experiment concerns the factor of Read distance. Experiment 4 examines the reading of the RFID tags for specific distances of the UAV from the rack of the aisle. Specifically, the results showed that at 0.7m and 1.25m distance of the UAV from the product RFID tags there was complete reading accuracy in all 3 replicates.

Experiment 4: Read distance

Read distance = 0,7m

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

Read distance = 1,25m

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

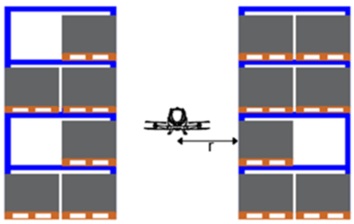


Figure 6.10 Results for factor of Read distance

Based on the above results obtained for the ambient warehouse with the RFID reader positioned on the upper side and the S-shape flight way, we conclude that there is complete reading accuracy for each value of each factor examined.

RFID position_upper side & Flight way_Straight

The second case involves examining the four factors (Number of levels per rack, UAV speed, Tag location, Flight altitude) with the RFID reader positioned on the upper side of the UAV and performing the flight of the UAV in the Straight flight way. Experiment 1 examines the parameter of Number of levels per rack. This experiment has two subcategories (single/double level). Specifically, the UAV performing its flight in the first subcategory flies and scans per level in each rack and in the second subcategory the UAV flies in the middle of two levels and scans the products of them. In both subcategories of Experiment 1, we observe that in all 3 replicates of the test there was a complete readout of the RFID tags (Figure 6.11 & Figure 6.12).

<u>Experiment 1: UAV flight type (single level)</u>

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

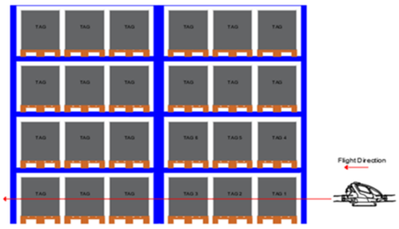


Figure 6.11 Results for factor of UAV flight type (single level)

<u>Experiment 1: UAV flight type (Double level)</u>

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

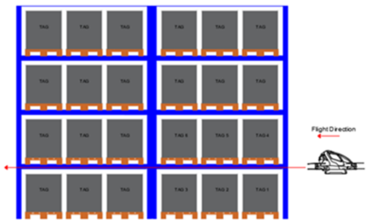


Figure 6.12 Results for factor of UAV flight type (Double level)

Experiment 2 examines the effect of different UAV speeds and found that RFID tags were successfully read at the specified speeds (four different speed values). The specific speed values were set according to the speed limits that could be deployed in the ambient warehouse, so that there is a constant control of the UAV during the flight without accidents.

<u>Experiment 2: UAV speed</u>

	1st replicate		2nd replicate		3rd replicate	
UAV speed	Read	No read	Read	No read	Read	No read
0,5 m/s	✓		✓		✓	
1 m/s	✓		✓		✓	
1,5 m/s	✓		✓		✓	
2 m/s	✓		✓		✓	

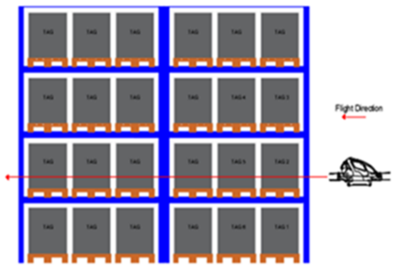


Figure 6.13 Results for factor of UAV speed

Experiment 3 examines the factor of Tag location and specifically whether the position in which the RFID tag is placed affects its reading during the UAV's flight direction. The results of this test showed that whichever side of the pallet the RFID tag is placed on can be read by the RFID reader.

Experiment 3: Tag location

	1st replicate		2nd replicate		3rd replicate	
Tag location	Read	No read	Read	No read	Read	No read
Front side	✓		✓		✓	
Back side	✓		✓		✓	
Right side	✓		✓		✓	
Left side	✓		✓		✓	

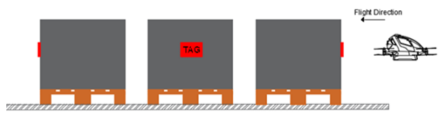


Figure 6.14 Results for factor of Tag location

The last experiment concerns the factor of Flight altitude. Experiment 4 examines the reading of the RFID tags which are placed on the 3 levels (level 0, level 1 and level2) of the rack for specific flight altitudes of the UAV from the ground. Specifically, for each flight altitude of the UAV, different distances are created between the RFID reader and the RFID tags and their reading accuracy is tested. The results showed that for each value of the UAV flight altitude there is full reading accuracy in 2 of the 3 levels.

Experiment 4: Flight altitude

			1st replicate	2nd replicate	3rd replicate
Flight altitude			Read	Read	Read
0,7m	level 0	0,7m	4/4	4/4	4/4
	level 1	2,3m	4/4	4/4	4/4
	level 2	3,9m	1/4	1/4	2/4
2,3m	level 0	0,7m	3/4	4/4	3/4
	level 1	2,3m	4/4	4/4	4/4
	level 2	3,9m	4/4	4/4	4/4
3,2m	level 0	0,7m	0/4	1/4	1/4
	level 1	2,3m	4/4	4/4	4/4
	level 2	3,9m	4/4	4/4	4/4

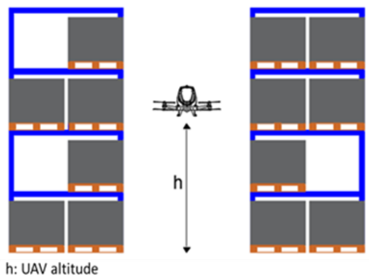


Figure 6.15 Results for factor of Flight altitude

Based on the above results obtained for the ambient warehouse with the RFID reader positioned on the upper side and the Straight flight way, we conclude that there is complete reading accuracy for each value in three of the four factors (Number of levels per rack, UAV speed and Tag location) and a minor fail in read accuracy in the Flight altitude factor.

RFID position_underside & Flight way_S-shape

The third case involves examining the four factors (Number of columns per rack, UAV speed, Tag location, Read distance) with the RFID reader positioned on the underside of the UAV and performing the flight of the UAV in the S-shape flight way. Experiment 1 examines the parameter of Number of column per rack and it has two subcategories (single/double column). Initially, in the first subcategory of single column the UAV flies per column in each shelf and in the second subcategory the UAV flies in the middle of two columns per rack. In both subcategories of Experiment 1, we observe that in all 3 replicates of the test there was a complete readout of the RFID tags (Figure 6.16 & Figure 6.17)

Experiment 1: UAV flight type (single column)

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

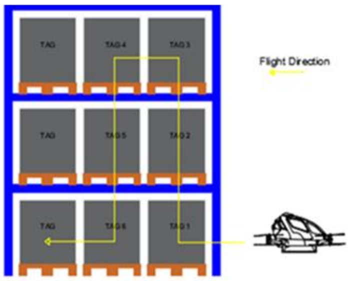


Figure 6.16 Results for factor of UAV flight (single column)

Experiment 1: UAV flight type (Double column)

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

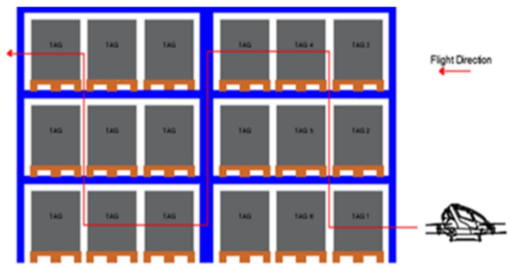


Figure 6.17 Results for factor of UAV flight type (Double column)

Experiment 2 examines the factor of UAV speed. In this experiment, the UAV performs its flight in the S-shape flight way and examines the reading of RFID tags for three different speed values (0,5m/s, 1m/s and 1,5m/s). The specific speed values were set according to the speed limits that could be deployed in the ambient warehouse, so that there is a constant control of the UAV during the flight without accidents. The results of experiment 2 show that there is reading of the RFID tags when the UAV flies at specified speeds.

Experiment 2: UAV speed

	1st replicate		2nd replicate		3rd replicate	
UAV speed	Read	No read	Read	No read	Read	No read
0,5 m/s	✓		✓		✓	
1 m/s	✓		✓		✓	
1,5 m/s	✓		✓		✓	

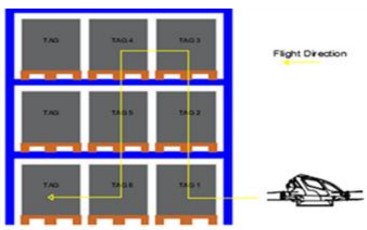


Figure 6.18 Results for factor of UAV speed

Experiment 3 examines the factor of Tag location. The aim of this experiment is to examine whether the position in which the RFID tag is placed affects its reading during the UAV's flight direction. The results of this test showed that whichever side of the pallet the RFID tag is placed on can be read by the RFID reader.

Experiment 3: Tag location

	1st replicate		2nd replicate		3rd replicate	
Tag location	Read	No read	Read	No read	Read	No read
Front side	✓		✓		✓	
Back side	✓		✓		✓	
Right side	✓		✓		✓	
Left side	✓		✓		✓	

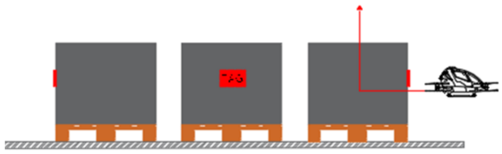


Figure 6.19 Results for factor of Tag location

The last experiment concerns the factor of Read distance. Experiment 4 examines the reading of the RFID tags for specific distances of the UAV from the rack of the aisle. Specifically, the results showed that at 0.7m and 1.25m distance of the UAV from the product RFID tags there was complete reading accuracy in all three replicates.

Experiment 4: Read distance

Read distance = 0,7m

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

Read distance = 1,25m

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

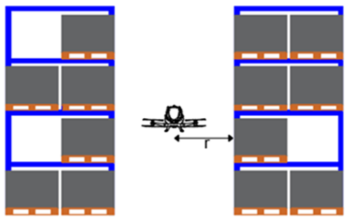


Figure 6.20 Results for factor of Read distance

Based on the above results obtained for the ambient warehouse with the RFID reader positioned on the underside and the S-shape flight way, we conclude that there is complete reading accuracy for each value of each factor examined.

RFID position_underside & Flight way_Straight

The fourth case involves examining the four factors (Number of levels per rack, UAV speed, Tag location, Flight altitude) with the RFID reader positioned on the underside of the UAV and performing the flight of the UAV in the Straight flight way. Experiment 1 examines the parameter of Number of levels per rack. This experiment has two subcategories (single/double level). Specifically, the UAV performing its flight in the first subcategory flies and scans per level in each rack and in the second subcategory the UAV flies in the middle of two levels and scans the products of them. In both subcategories of Experiment 1, we observe that in all three replicates of the test there was a complete readout of the RFID tags (Figure 6.21 & Figure 6.22).

Experiment 1: UAV flight type (single level)

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

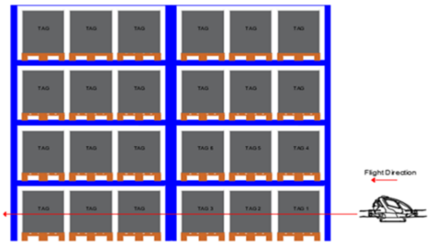


Figure 6.21 Results for factor of UAV flight type (single level)

Experiment 1: UAV flight type (Double level)

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

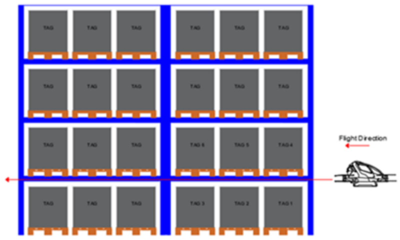


Figure 6.22 Results for factor of UAV flight type (Double level)

Experiment 2 examines the effect of different UAV speeds and found that RFID tags were successfully read at the specified speeds (0,5m/s and 1m/s). The specific speed values were set according to the speed limits that could be deployed in the ambient warehouse, so that there is a constant control of the UAV during the flight without accidents.

Experiment 2: UAV speed

	1st replicate		2nd replicate		3rd replicate	
UAV speed	Read	No read	Read	No read	Read	No read
0,5 m/s	✓		✓		✓	
1 m/s	✓		✓		✓	

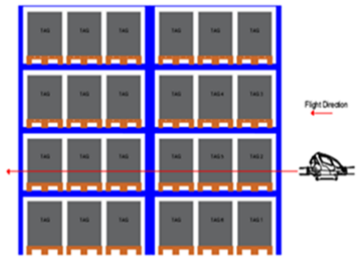


Figure 6.23 Results for factor of UAV speed

Experiment 3 examines the factor of Tag location and specifically whether the position in which the RFID tag is placed affects its reading during the UAV's flight direction. The results of this test showed that whichever side of the pallet the RFID tag is placed on can be read by the RFID reader.

Experiment 3: Tag location

	1st replicate		2nd replicate		3rd replicate	
Tag location	Read	No read	Read	No read	Read	No read
Front side	✓		✓		✓	
Back side	✓		✓		✓	
Right side	✓		✓		✓	
Left side	✓		✓		✓	

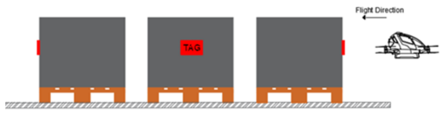


Figure 6.24 Results for factor of Tag location

The last experiment concerns the factor of Flight altitude. Experiment 4 examines the reading of the RFID tags which are placed on the three levels (level 0, level 1 and level2) of the rack for specific flight altitudes of the UAV from the ground. Specifically, for each flight altitude of the UAV, different distances are created between the RFID reader and the RFID tags and their reading accuracy is tested. The results showed that for each value of the UAV flight altitude there is full readout accuracy at 2 of the 3 levels. However, at one of the three levels there are RFID tags that have not been read by the RFID reader, which affects the efficiency of this factor.

Experiment 4: Flight altitude

			1st replicate	2nd replicate	3rd replicate
Flight altitude			Read	Read	Read
0,7m	level 0	0,7m	4/4	4/4	4/4
	level 1	2,3m	4/4	4/4	4/4
	level 2	3,9m	4/4	4/4	3/4
2,3m	level 0	0,7m	4/4	4/4	4/4
	level 1	2,3m	4/4	4/4	4/4
	level 2	3,9m	4/4	4/4	4/4
3,2m	level 0	0,7m	3/4	3/4	4/4
	level 1	2,3m	4/4	4/4	4/4
	level 2	3,9m	4/4	4/4	4/4

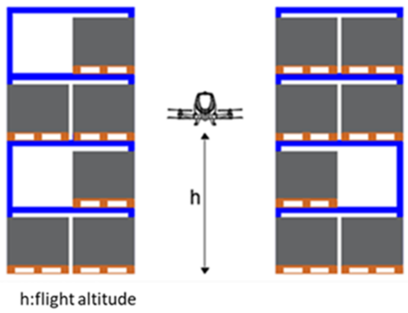


Figure 6.25 Results for factor of Flight altitude

Based on the above results obtained for the ambient warehouse with the RFID reader positioned on the underside and the Straight flight way, we conclude that there is complete reading accuracy for each value in three of the four factors (Number of levels per rack, UAV speed and Tag location) and a minor fail in read accuracy in the Flight altitude factor which affects the efficiency of this factor.

6.2.2 Case study 2: Chilled warehouse with liquid products

This subsection presents the results obtained for each factor tested in the first set of laboratory tests. The same experiments as in case study 1 were carried out and the tables below show in detail the results obtained for each of the individual experiments. The case study 2 concerns a chilled warehouse with liquid products, where for each factor 3 replicates were performed to verify if the RFID tag is readable.

RFID position_upper side & Flight way_S-shape

The first case of case study 2 involves examining the four factors (Number of columns per rack, UAV speed, Tag location, Read distance) with the RFID reader positioned on the upper side of the UAV and performing the flight of the UAV in the S-shape flight way. Experiment 1 examines the parameter of Number of column per rack. This experiment has two subcategories (single/double column). Specifically, the UAV performing its flight in the first subcategory flies per column in each shelf and in the second subcategory the UAV flies in the middle of two columns per rack. In both subcategories of Experiment 1, we observe that in all three replicates of the test there was a complete readout of the RFID tags.

Experiment 1: UAV flight type (single column)

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

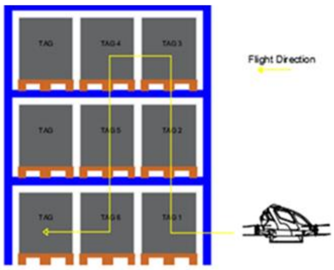


Figure 6.26 Results for factor of UAV flight type (single column)

Experiment 1: UAV flight type (Double column)

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

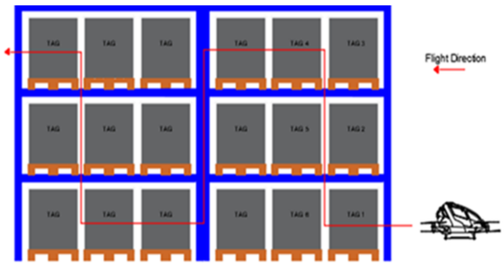


Figure 6.27 Results for factor of UAV flight type (Double column)

Experiment 2 examines the factor of UAV speed. In this experiment, the UAV performs its flight in the S-shape flight way and examines the reading of RFID tags for three different speed values. The specific speed values were set according to the speed limits that could be deployed in the chilled warehouse, so that there is a constant control of the UAV during the flight without accidents. The results of experiment 2 (Figure 6.28) show that there is reading of the RFID tags when the UAV flies at the specified speeds.

Experiment 2: UAV speed

	1st replicate		2nd replicate		3rd replicate	
UAV speed	Read	No read	Read	No read	Read	No read
0,5 m/s	✓		✓		✓	
1 m/s	✓		✓		✓	
1,5 m/s	✓		✓		✓	

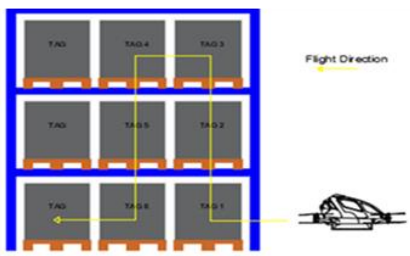


Figure 6.28 Results for factor of UAV speed

Experiment 3 examines the factor of Tag location. The aim of this experiment is to examine whether the position in which the RFID tag is placed affects its reading during the UAV's flight direction. The results of this test showed that only the RFID tags which placed on the front side of the pallet can be read by the RFID reader. The results of the experiment in this case are directly affected by the property of the products (liquid products) that prevent the transmission of radio waves between RFID reader and RFID tags.

Experiment 3: Tag location

	1st replicate		2nd replicate		3rd replicate	
Tag location	Read	No read	Read	No read	Read	No read
Front side	✓		✓		✓	
Back side		✓		✓		✓
Right side		✓		✓		✓
Left side		✓		✓		✓

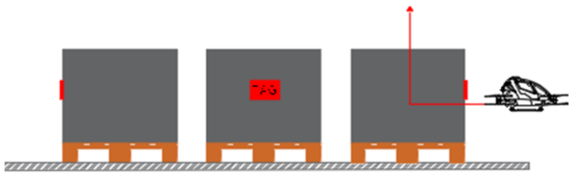


Figure 6.29 Results for factor of Tag location

The last experiment concerns the factor of Read distance. Experiment 4 examines the reading of the RFID tags for specific distances of the UAV from the rack of the aisle. Specifically, the results showed that at 0.7m and 1.25m distance of the UAV from the product RFID tags there was complete reading accuracy in all three replicates.

Experiment 4: Read distance

Read distance = 0,7m

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

Read distance = 1,25m

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

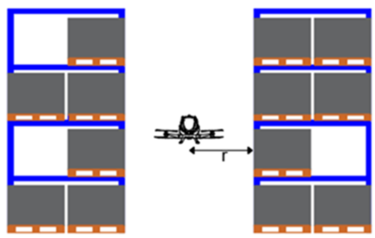


Figure 6.30 Results for factor of Read distance

Based on the above results obtained for the chilled warehouse with the RFID reader positioned on the upper side and the S-shape flight way, we conclude that there is complete reading accuracy for each value in three of the four factors (Number of columns per rack, UAV speed and Read distance). In the tag location factor, RFID tags are read only on the front side of the pallet. The property of the products (liquid products) affect the radio wave transmission between RFID reader and RFID tags and therefore the efficiency of the factor.

RFID position_upper side & Flight way_Straight

The second case involves examining the four factors (Number of levels per rack, UAV speed, Tag location, Flight altitude) with the RFID reader positioned on the upper side of the UAV and performing the flight of the UAV in the Straight flight way. Experiment 1 examines the parameter of Number of levels per rack. This experiment has two subcategories (single/double level). Specifically, the UAV performing its flight in the first subcategory flies and scans per level in each rack and in the second subcategory the UAV flies in the middle of two levels and scans the products of them. In both subcategories of Experiment 1, we observe that in all three replicates of the test there was a complete readout of the RFID tags (Figure 6.31 & Figure 6.32).

Experiment 1: UAV flight type (single level)

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

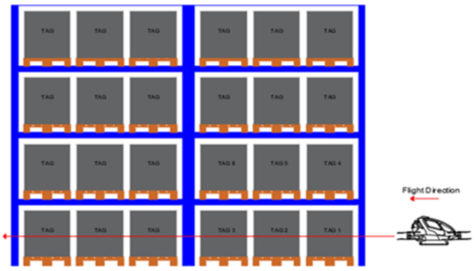


Figure 6.31 Results for factor of UAV flight type (single column)

Experiment 1: UAV flight type (Double level)

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

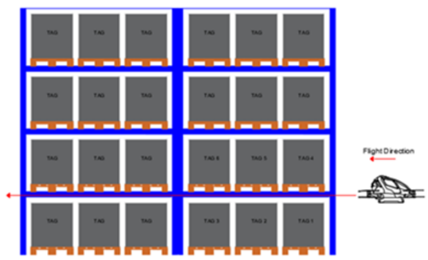


Figure 6.32 Results for factor of UAV flight type (Double level)

Experiment 2 examines the effect of different UAV speeds and found that RFID tags were successfully read at the specified speeds (four different speed values). The specific speed values were set according to the speed limits that could be deployed in the chilled warehouse, so that there is a constant control of the UAV during the flight without accidents.

Experiment 2: UAV speed

	1st replicate		2nd replicate		3rd replicate	
UAV speed	Read	No read	Read	No read	Read	No read
0,5 m/s	✓		✓		✓	
1 m/s	✓		✓		✓	
1,5 m/s	✓		✓		✓	
2 m/s	✓		✓		✓	

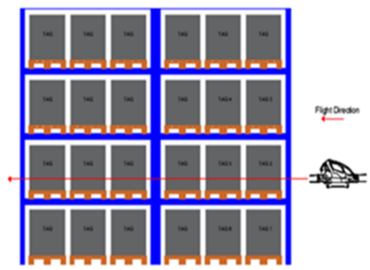


Figure 6.33 Results for factor of UAV speed

Experiment 3 examines the factor of Tag location and specifically whether the position in which the RFID tag is placed affects its reading during the UAV's flight direction. The results show that the RFID tags are read on three sides of the pallet and only the RFID tag on the back side is not read. This happens because between the RFID reader and the RFID tag on the back side of the pallet there are liquid products that prevent the transmission of the radio waves while on the other sides due to the straight flight way there is a gap where there is no material between the RFID reader and the RFID tags and the reading takes place.

Experiment 3: Tag location

	1st replicate		2nd replicate		3rd replicate	
Tag location	Read	No read	Read	No read	Read	No read
Front side	✓		✓		✓	
Back side		✓		✓		✓
Right side	✓		✓		✓	
Left side	✓		✓		✓	

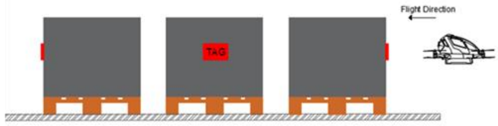


Figure 6.34 Results for factor of Tag location

The last experiment concerns the factor of Flight altitude. Experiment 4 examines the reading of the RFID tags which are placed on the 3 levels (level 0, level 1 and level2) of the rack for specific flight altitudes of the UAV from the ground. Specifically, for each flight altitude of the UAV, different distances are created between the RFID reader and the RFID tags and their reading accuracy is tested. The results show that there is full reading only at level 0 when the UAV is at 0.7m flight altitude and at level 1 when the UAV is at 2.3m while at other levels the reading rates of RFID tags are quite low. At level 3 there is no complete reading at any replicate of the experiment.

Experiment 4: Flight altitude

			1st replicate	2nd replicate	3rd replicate
Flight altitude			Read	Read	Read
0,7m	level 0	0,7m	5/5	5/5	5/5
	level 1	2,3m	2/5	2/5	2/5
	level 2	3,9m	1/5	1/5	1/5
2,3m	level 0	0,7m	3/5	1/5	2/5
	level 1	2,3m	5/5	5/5	5/5
	level 2	3,9m	3/5	3/5	3/5
3,2m	level 0	0,7m	1/5	1/5	1/5
	level 1	2,3m	2/5	3/5	3/5
	level 2	3,9m	3/5	3/5	3/5

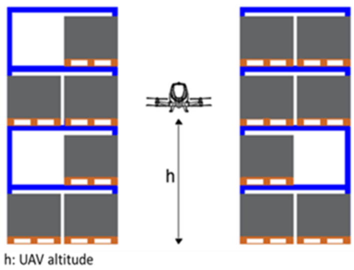


Figure 6.35 Results for factor of Flight altitude

Based on the above results obtained for the chilled warehouse with the RFID reader positioned on the upper side and the Straight flight way, we conclude that there is complete reading accuracy for each value in two of the four factors (Number of levels per rack and UAV speed). A minor failure in reading accuracy exists in the Tag location factor and specifically in reading of the RFID tag located on the back side of the pallet while a low reading rate is observed in the Flight altitude factor.

RFID position_underside & Flight way_S-shape

The third case involves examining the four factors (Number of columns per rack, UAV speed, Tag location, Read distance) with the RFID reader positioned on the underside of the UAV and performing the flight of the UAV in the S-shape flight way. Experiment 1 examines the parameter of Number of column per rack. This experiment has two subcategories (single/double column). Specifically, the UAV performing its flight in the first subcategory flies per column in each shelf and in the second subcategory the UAV flies in the middle of two columns per rack. In both subcategories of Experiment 1, we observe that in all three replicates of the test there was a complete readout of the RFID tags (Figure 6.36 & Figure 6.37)

Experiment 1: UAV flight type (single column)

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

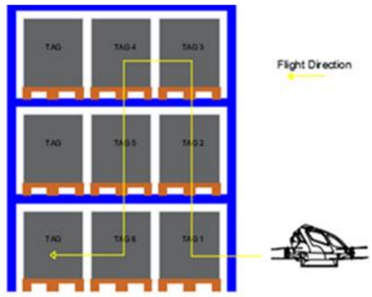


Figure 6.36 Results for factor of UAV flight type (single column)

Experiment 1: UAV flight type (Double column)

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

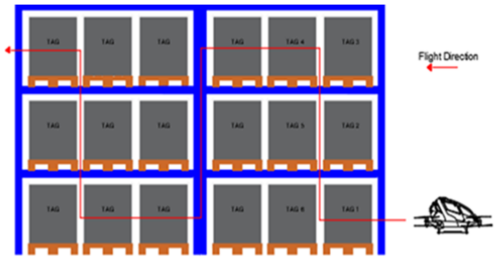


Figure 6.37 Results for factor of UAV flight type (Double column)

Experiment 2 examines the factor of UAV speed. In this experiment, the UAV performs its flight in the S-shape flight way and examines the reading of RFID tags for three different speed values (0,5m/s, 1m/s and 1,5m/s). The specific speed values were set according to the speed limits that could be deployed in the chilled warehouse, so that there is a constant control of the UAV during the flight without accidents. The results of experiment 2 show that there is reading of the RFID tags when the UAV flies at the specified speeds.

Experiment 2: UAV speed

	1st replicate		2nd replicate		3rd replicate	
UAV speed	Read	No read	Read	No read	Read	No read
0,5 m/s	✓		✓		✓	
1 m/s	✓		✓		✓	
1,5 m/s	✓		✓		✓	

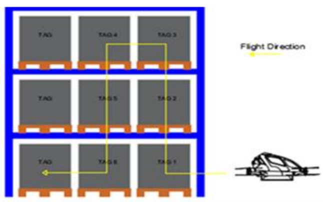


Figure 6.38 Results for factor of UAV speed UAV speed

Experiment 3 examines the factor of Tag location. The aim of this experiment is to examine whether the position in which the RFID tag is placed affects its reading during the UAV's flight direction. The results of this experiment showed that on the front side and the back side the RFID tags are read which is not possible on the other two sides of the pallet.

Experiment 3: Tag location

	1st replicate		2nd replicate		3rd replicate	
Tag location	Read	No read	Read	No read	Read	No read
Front side	✓		✓		✓	
Back side	✓		✓		✓	
Right side		✓		✓		✓
Left side		✓		✓		✓

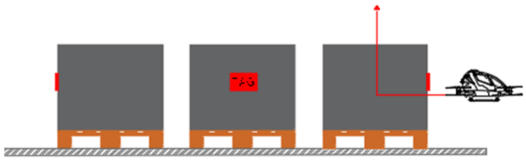


Figure 6.39 Results for factor of Tag location

The last experiment concerns the factor of Read distance. Experiment 4 examines the reading of the RFID tags for specific distances of the UAV from the rack of the aisle. Specifically, the results showed that at 0.7m and 1.25m distance of the UAV from the product RFID tags there was complete reading accuracy in all three replicates.

Experiment 4: Read distance

Read distance = 0,7m

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

Read distance = 1,25m

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

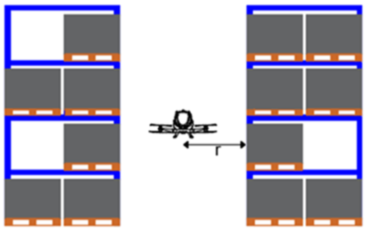


Figure 6.40 Results for factor of read distance

Based on the above results obtained for the chilled warehouse with the RFID reader positioned on the underside and the S-shape flight way, we conclude that there is complete reading accuracy for each value of three of the four factors. The Tag location factor has full readout at two of the four values considered, specifically when the RFID tag is placed on the front side and the back side of the pallet.

RFID position_underside & Flight way_Straight

The fourth case involves examining the four factors (Number of levels per rack, UAV speed, Tag location, Flight altitude) with the RFID reader positioned on the underside of the UAV and performing the flight of the UAV in the Straight flight way. Experiment 1 examines the parameter of Number of levels per rack. This experiment has two subcategories (single/double level). Specifically, the UAV performing its flight in the first subcategory flies and scans per level in each rack and in the second subcategory the UAV flies in the middle of two levels and scans the products of them. In both subcategories of Experiment 1, we observe that in all three replicates of the test there was a complete readout of the RFID tags.

Experiment 1: UAV flight type (single level)

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

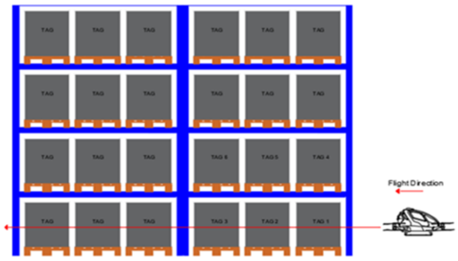


Figure 6.41 Results for factor of UAV flight type (single level)

Experiment 1: UAV flight type (Double level)

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

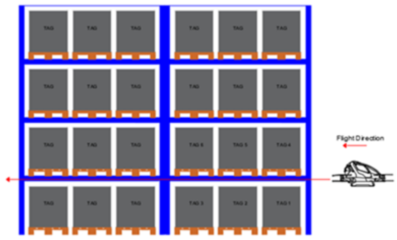


Figure 6.42 Results for factor of UAV flight type (Double level)

Experiment 2 examines the effect of different UAV speeds and found that RFID tags were successfully read at the specified speeds (three different speed values). The specific speed values were set according to the speed limits that could be deployed in the chilled warehouse, so that there is a constant control of the UAV during the flight without accidents.

Experiment 2: UAV speed

	1st replicate		2nd replicate		3rd replicate	
UAV speed	Read	No read	Read	No read	Read	No read
0,5 m/s	✓		✓		✓	
1 m/s	✓		✓		✓	
1,5 m/s	✓		✓		✓	

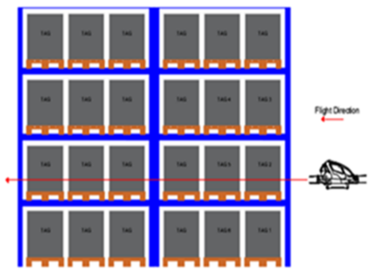


Figure 6.43 Results for factor of UAV speed

Experiment 3 examines the factor of Tag location and specifically whether the position in which the RFID tag is placed affects its reading during the UAV's flight direction. The results of this experiment showed that only on the front side of the pallet was the RFID tag fully readable. On the back side of the pallet there was no RFID tag reading in all three replicates, which does not create confidence in the specific value of the factor, while on the other two sides there was no RFID tag reading.

Experiment 3: Tag location

	1st replicate		2nd replicate		3rd replicate	
Tag location	Read	No read	Read	No read	Read	No read
Front side	✓		✓		✓	
Back side		✓	✓		✓	
Right side		✓		✓		✓
Left side		✓		✓		✓

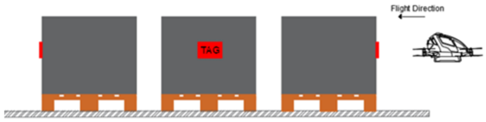


Figure 6.44 Results for factor of Tag location

The last experiment concerns the factor of Flight altitude. Experiment 4 examines the reading of the RFID tags which are placed on the 3 levels (level 0, level 1 and level2) of the rack for specific flight altitudes of the UAV from the ground. Specifically, for each flight altitude of the UAV, different distances are created between the RFID reader and the RFID tags and their reading accuracy is tested. The results showed that complete reading of RFID tags is mainly performed at the level that is at the same altitude as the flight altitude of the UAV.

Experiment 4: Flight altitude

			1st replicate	2nd replicate	3rd replicate
Flight altitude			Read	Read	Read
0,7m	level 0	0,7m	5/5	5/5	5/5
	level 1	2,3m	5/5	5/5	5/5
	level 2	3,9m	3/5	3/5	2/5
2,3m	level 0	0,7m	4/5	4/5	4/5
	level 1	2,3m	5/5	5/5	5/5
	level 2	3,9m	3/5	3/5	3/5
3,2m	level 0	0,7m	1/5	1/5	2/5
	level 1	2,3m	5/5	5/5	5/5
	level 2	3,9m	4/5	4/5	4/5

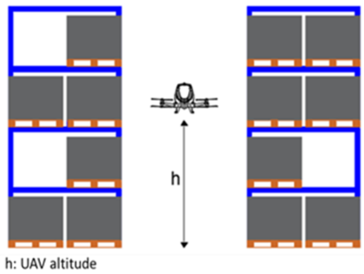


Figure 6.45 Results for factor of Flight altitude

Based on the above results obtained for the chilled warehouse with the RFID reader positioned on the underside and the Straight flight way, we conclude that there is complete reading accuracy for each value in two of the four factors (Number of levels per rack and UAV speed). For the other two factors there is a full reading only for certain of the values considered.

6.2.3 Extra experiment for 1st set of laboratory tests

During the execution of the first set of laboratory tests, an additional experiment was created because of some useful observations that emerged. Initially, from the results obtained from the Read distance and Flight altitude factors, we concluded that when the UAV is in the middle of the aisle width, it can successfully read all RFID tags placed on the front side of the pallets along a rack. Due to the specific results and the specifications of the RFID reader (Circular Polarized Antenna), the hypothesis for simultaneous reading of RFID tags across racks was created, in order to significantly reduce the stock count time.

Furthermore, during the execution of the experiments in both case studies it was observed that the Straight flight way is faster than the S-shape flight way in terms of total stock count time. For this reason, the additional experiment for simultaneous stock count across racks in both case studies performed only for the Straight flight way. The experiment was examined for both positions of the RFID reader (upper side and underside) in both warehouses. The results are very encouraging and show that there is complete reading of the RFID tags in all four cases (Figure 6.46 & Figure 6.47 for ambient warehouse and Figure 6.48 & Figure 6.49 for chilled warehouse).

RFID position_upper side & Flight way_Straight

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	
Tag 7	✓		✓		✓	
Tag 8	✓		✓		✓	
Tag 9	✓		✓		✓	
Tag 10	✓		✓		✓	

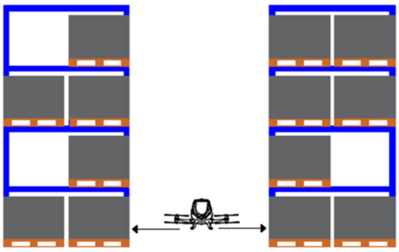


Figure 6.46 Results for simultaneous stock count-Ambient warehouse

RFID position_underside & Flight way_Straight

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	
Tag 7	✓		✓		✓	
Tag 8	✓		✓		✓	
Tag 9	✓		✓		✓	
Tag 10	✓		✓		✓	

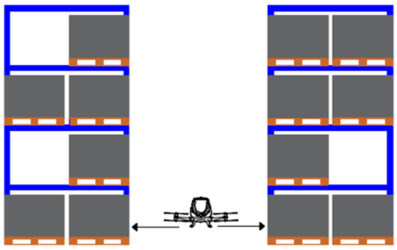


Figure 6.47 Results for simultaneous stock count-Ambient warehouse

RFID position_upper side & Flight way_Straight

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	
Tag 7	✓		✓		✓	
Tag 8	✓		✓		✓	
Tag 9	✓		✓		✓	
Tag 10	✓		✓		✓	

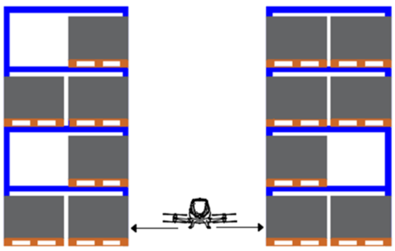


Figure 6.48 Results for simultaneous stock count-Chilled warehouse

RFID position_underside & Flight way_Straight

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	
Tag 7	✓		✓		✓	
Tag 8	✓		✓		✓	
Tag 9	✓		✓		✓	
Tag 10	✓		✓		✓	

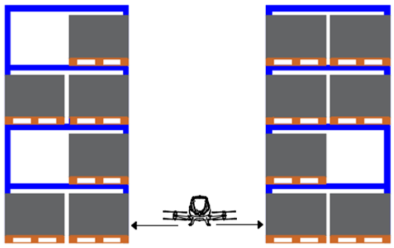


Figure 6.49 Results for simultaneous stock count-Chilled warehouse

Summarizing the results from the first set of laboratory tests and the extra experiment examined, the parameters and values of their levels that will be examined in the second set of laboratory tests were derived based on the efficiency and accuracy of reading. Specifically, the first parameter to be tested is the Number of levels (1 level/2 levels) which is obtained by selecting the straight flight way as the fastest flight way for stock count process. The second parameter is the UAV speed, specifically the values of levels of parameter are 0.5m/s and 1.5m/s which were obtained due to the absolute reading accuracy present in the first set of experiments. The third parameter with the same selection criterion is the Tag location on the pallet and specifically the values of levels for the design of the second set of experiments are the Front side and Back side of the pallet. Finally, the fourth parameter that results from the extra experiment of the first set of laboratory tests is the UAV tag reading method and the values of the two levels considered are Along a rack and Across racks as there is a significant reduction in total stock count time.

6.3 Experimental results from UAV operation in stock count process

6.3.1 Selection of experiment and parameters

The purpose of this experiment (second set of laboratory tests) is to investigate whether the 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 in warehouses. To carry out the experiment under investigation, the Design of Experiments (DoE) method is used, in particular the general factorial design, which is suitable for experiments involving several factors where it is necessary to study their common effect on a response as mentioned in previous chapter.

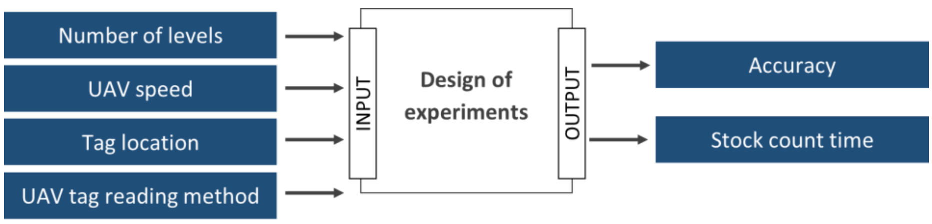


Figure 6.50 Model for accuracy and stock count prediction

Table 6.1 presents the selected factors as well as their corresponding levels which will be used for the experiments.

Table 6.1 Selected factors and their levels

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

The first factor is the Number of levels. This factor refers to the number of levels on the racks in the warehouse that are scanned during the UAV's flight (Figure 6.51).

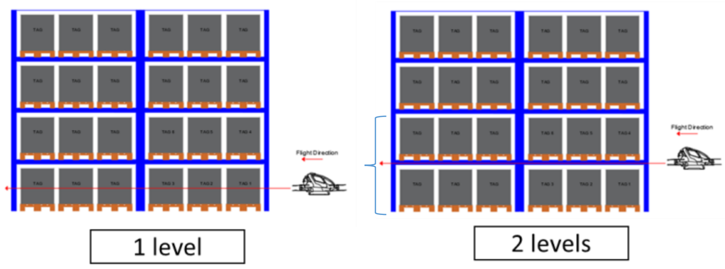


Figure 6.51 Two levels of Number of levels

The second factor is the UAV speed and refers to the speed at which the UAV is flying (Figure 6.52).

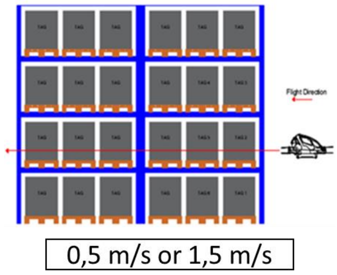


Figure 6.52 Two levels of UAV speed

The third factor is the Tag location. This factor refers to the position where the RFID tag is placed, specifically on one of the four sides of the pallet (Figure 6.53).

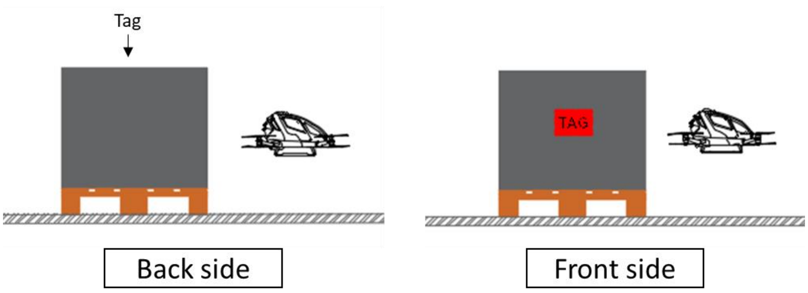


Figure 6.53 Two levels of Tag location

Finally, the fourth factor is the UAV tag reading method. This factor refers to the reading method followed by the UAV during its flight within the aisle of warehouse (Figure 6.54)

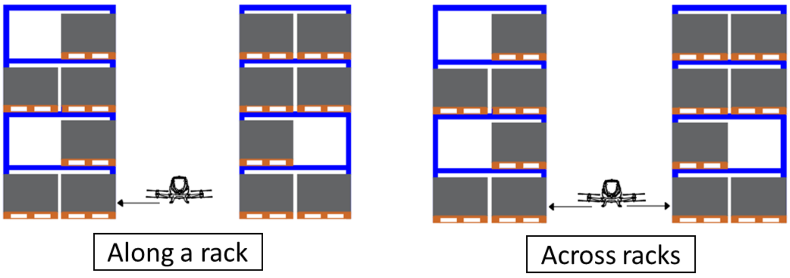


Figure 6.54 Two levels of UAV tag reading method

At the end of the first set of laboratory tests, in addition to defining the factors and their levels, useful conclusions were gained that determined the design and study environment for the second set of laboratory tests. Specifically, the experiments were carried out respectively in both case studies as in the first set of laboratory tests. The first case study refers to an ambient warehouse with dry products and the second case study refers to a chilled warehouse with liquid products. The difference in the second set of laboratory tests is that only the case where the drone is flying in a straight direction was tested and not the case of the S-shape flight way as it saves a lot of stock count time as there is 100% reading accuracy in both cases. Furthermore, the tests were carried out with the RFID reader positioned only on the underside of the UAV device as there were better results in reading of the RFID tags. With the reader positioned on the upper side of the UAV device, there was a decrease in the read signal due to the UAV's propellers. Finally, a specificity of the liquid products that block the radio waves transmission was observed and they do not allow the RFID tags to be read when they are between the RFID reader and the RFID tags. For this reason in case study with chilled warehouse and liquid products we did not take into account the factor of tag location and the RFID tags were placed only on the front side of the pallet.

Applying a full factorial design to the factors of second set of laboratory tests results in 16 possible combinations that affect the stock count time in Case study 1(Ambient warehouse with dry products) and 8 possible combinations that affect the stock count time in Case study 2 (Chilled warehouse with liquid products). These combinations are presented in detail in Table 6.2 and Table 6.3.

Table 6.2 Combinations of factors (Case study 1)

Run	UAV tag reading method	Tag Location	UAV speed	Number of levels
1	Along a rack	Back side	0,5 m/s	1 level
2	Along a rack	Back side	0,5 m/s	2 levels
3	Along a rack	Back side	1 ,5 m/s	1 level
4	Along a rack	Back side	1 ,5 m/s	2 levels
5	Along a rack	Front side	0,5 m/s	1 level
6	Along a rack	Front side	0,5 m/s	2 levels
7	Along a rack	Front side	1 ,5 m/s	1 level
8	Along a rack	Front side	1 ,5 m/s	2 levels
9	Across racks	Back side	0,5 m/s	1 level

Run	UAV tag reading method	Tag Location	UAV speed	Number of levels
10	Across racks	Back side	0,5 m/s	2 levels
11	Across racks	Back side	1 ,5 m/s	1 level
12	Across racks	Back side	1 ,5 m/s	2 levels
13	Across racks	Front side	0,5 m/s	1 level
14	Across racks	Front side	0,5 m/s	2 levels
15	Across racks	Front side	1 ,5 m/s	1 level
16	Across racks	Front side	1 ,5 m/s	2 levels

Table 6.3 Combinations of factors (Case study 2)

Run	UAV tag reading method	UAV speed	Number of levels
1	Along a rack	0,5 m/s	1 level
2	Along a rack	0,5 m/s	2 levels
3	Along a rack	1 ,5 m/s	1 level
4	Along a rack	1 ,5 m/s	2 levels
5	Across racks	0,5 m/s	1 level
6	Across racks	0,5 m/s	2 levels
7	Across racks	1 ,5 m/s	1 level
8	Across racks	1 ,5 m/s	2 levels

In the Design of Experiments, during the statistical analysis, each parameter of the experiment is examined separately (1-way interactions). At the same time, the correlations concerning the combination of the parameters are also taken into account. The statistical analysis also includes the examination of the combination of the parameters in pairs (2-way interactions), in triads (3-way interactions) as well as the combination of all four parameters of the experiment (4-way interactions).

Considering the 4 factors of Case study 1 as well as the corresponding levels, there are fifteen degrees of freedom among sixteen (2^4) different configurations. Specifically, 4 degrees of freedom were associated with the main effects of Number of levels, UAV speed, Tag location and UAV tag reading method (1-way interactions). Also, 6 degrees of freedom were associated with 2-way interactions, one each with Number of levels*UAV speed, Number of levels*Tag location, Number of levels*UAV tag reading method, UAV speed*Tag location, UAV speed*UAV tag reading method and Tag location*UAV tag reading method. Additionally, 4 degrees of freedom were associated with 3-way interactions, one each with Number of levels*UAV speed*Tag location, Number of levels*UAV speed*UAV tag reading method, UAV speed*Tag location*UAV tag reading method. Finally, 1 degree of freedom was associated with 4-way interactions, one each with Number of levels*UAV speed*Tag location*UAV tag reading method.

Similarly, considering the 3 factors of Case study 2 as well as the corresponding levels, there are seven degrees of freedom among eight (2^3) different configurations. Specifically, 3 degrees of freedom were associated with the main effects of Number of levels, UAV speed and UAV tag reading method (1-way interactions). Also, 3 degrees of freedom were associated with 2-way interactions, one each with Number of levels*UAV speed, Number of levels*UAV tag reading method and UAV speed*UAV tag reading method. Finally, 1 degree of freedom were associated with 3-way interactions, one each with Number of levels*UAV speed*UAV tag reading method.

Furthermore, the design of experiment that was developed included 3 replicates per run, so the total number of sample was n = 48 for Case study 1 and n= 24 for Case study 2. It is also worth mentioning that the runs were performed in random order. In our case, the randomization has been ensured through our Design of Experiments and the statistical processing of data in Minitab software tool.

The aim of the experiments in both case studies is to read the 32 RFID tags placed on the first two levels (level 0 and level 1) of warehouse's aisle. The total distance travelled by the UAV from the take-off point to the landing point is in both cases 13m. In each experiment, the total stock count time of the 32 products was measured, with a common stopwatch. The results of the Case study 1 are shown in Table 6.4 (in more detail, see laboratory tests results in Appendix D(A)) and it is observed that the "best" configuration is the combination of across racks*front side*1,5 m/s*2 levels. Respectively, the results of the Case study 2 are shown in Table 6.5 (in more detail, see laboratory tests results in Appendix D(B)) and it is observed that the "best" configuration is the combination of across racks*1,5 m/s*across racks.

Table 6.4 Results of Case study 1

					1st replicate	2nd replicate	3rd replicate
A/A	UAV tag reading method	Tag Location	UAV speed	Number of levels	Time (sec)	Time (sec)	Time (sec)
1	Along a rack	Back side	0,5 m/s	1 level	104,38	109,24	109,68
2	Along a rack	Back side	0,5 m/s	2 levels	48,76	49,38	49,28
3	Along a rack	Back side	1 ,5 m/s	1 level	61,48	62,14	62,28
4	Along a rack	Back side	1 ,5 m/s	2 levels	28,34	28,48	28,72
5	Along a rack	Front side	0,5 m/s	1 level	103,36	110,20	108,74
6	Along a rack	Front side	0,5 m/s	2 levels	47,26	47,44	47,36
7	Along a rack	Front side	1 ,5 m/s	1 level	59,12	64,54	62,86
8	Along a rack	Front side	1 ,5 m/s	2 levels	27,38	28,34	27,86
9	Across racks	Back side	0,5 m/s	1 level	51,69	54,12	54,34
10	Across racks	Back side	0,5 m/s	2 levels	23,53	23,84	23,79
11	Across racks	Back side	1 ,5 m/s	1 level	30,24	30,57	30,64
12	Across racks	Back side	1 ,5 m/s	2 levels	13,32	13,39	13,51
13	Across racks	Front side	0,5 m/s	1 level	51,18	54,60	53,87
14	Across racks	Front side	0,5 m/s	2 levels	22,78	22,87	22,83
15	Across racks	Front side	1 ,5 m/s	1 level	29,06	31,77	30,93
16	**Across racks**	**Front side**	**1 ,5 m/s**	**2 levels**	**12,84**	**13,32**	**13,08**

Table 6.5 Results for Case study 2

A/A	UAV tag reading method	UAV speed	Number of levels	1st replicate Time (sec)	2nd replicate Time (sec)	3rd replicate Time (sec)
1	Along a rack	0,5 m/s	1 level	125,60	125,84	126,40
2	Along a rack	0,5 m/s	2 levels	50,70	51,70	52,50
3	Along a rack	1 ,5 m/s	1 level	84,60	74,16	77,98
4	Along a rack	1 ,5 m/s	2 levels	30,08	30,44	32,54
5	Across racks	0,5 m/s	1 level	62,30	62,42	62,70
6	Across racks	0,5 m/s	2 levels	24,50	25,00	25,40
7	Across racks	1 ,5 m/s	1 level	41,80	36,58	38,49
8	**Across racks**	**1 ,5 m/s**	**2 levels**	**14,19**	**14,37**	**15,42**

6.3.2 Performing the experiment and analyzing the results

The aim of this section is to assess whether and how the selected parameters of the experiment affect the time of stock count according to the results obtained from the statistical analysis carried out with the help of the statistical software Minitab. The statistical analysis was performed separately for the two cases of the study. Specifically, the aim of experiment was to evaluate if and how the selected factors affect the stock count time as well as the accuracy of stock count process.

Case study 1: Ambient warehouse with dry products

Formulation of Research Hypothesis

For the evaluation of stock count system two parameters 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. The stock count time was measured with a common stopwatch, while the accuracy was calculated by taking into consideration the read rate during the reading of RFID tags. The read rate was counted manually after the completion of stock count process.

For the parameter of accuracy only cases where we had 100% RFID tag reading accuracy were considered. For the parameter of stock count time as well for the four factors that have been taken into account for the evaluation of stock count system, certain hypotheses were introduced.

In the first stage of the analysis the statistical ANOVA test is performed, where hypothesis testing as defined below must be carried out:

H_0: All variances are equal

H_1: Not all variances are equal

In detail, there were four null hypotheses for the stock count time:

The first null hypothesis (H0,1) 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 (H0,2) states that the stock count time was equal when either the UAV speed was 0,5m/s or 1,5m/s:

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

The third null hypothesis (H0,3) states that the stock count time was equal either when the tag location was back side or front side:

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

The fourth null hypothesis (H0,4) states that the stock count time was equal either when the UAV tag reading method was along a rack or across the racks:

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

Similarly, the alternative hypotheses H_1 state that:

The first alternative hypothesis (H1,1) states that the stock count time was the different when either the number of levels was 1 level or 2 levels:

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

The second alternative hypothesis (H1,2) states that the stock count time was different when either the UAV speed was 0,5m/s or 1,5m/s:

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

The third alternative hypothesis (H1,3) states that the stock count time was different either when the tag location was back side or front side:

$$H_{1,3}: t_{back\ side} \neq t_{front\ side}$$

The fourth alternative hypothesis (H1,4) states that the stock count time was different either when the UAV tag reading method was along a rack or across the racks:

$$H_{1,4}: t_{along\ a\ rack} \neq t_{across\ the\ racks}$$

In order to evaluate the four parameters of the experiment and their interactions, P-value was used. According to Montgomery (2012), P-value is defined as the lowest level of significance that leads to rejection of the null hypothesis. If the P-value is less than or equal to a predefined significance level (in our case the significance level is α=0.05), then the null hypothesis is rejected and we cannot assume that all samples have the same mean, so at significance level α we accept the alternative hypothesis. On the other hand, if the P-value is greater than α, then at significance level α we cannot reject the null hypothesis.

The Table 6.6 presents the results obtained from the ANOVA analysis and showed that the cases of Number of levels, UAV speed, UAV tag reading method, Number of levels*UAV speed, Number of levels*UAV tag reading method, UAV speed*UAV tag reading method and Number of levels*UAV speed*UAV tag reading method were statistically significant as P-value < 0.05. On the other hand for all other cases, the results showed that there were no statistically significant differences (p-values are greater than 0.05). Therefore, it was shown that for cases: H0.1, H0.2 and H0.4, the null hypothesis was rejected at the significance level α = 0.05, while for case H0.3, at the significance level α = 0.05, the null hypothesis cannot be rejected. This means that the use of the parameters of Number of levels, UAV speed and UAV tag reading method significantly affects the stock count time.

Table 6.6 Results of statistical analysis in terms of stock count time

Source	F-Value	P-Value
Model	1071,82	0,000
Linear	3633,04	0,000
Number of levels	6344,24	0,000
UAV speed	3108,46	0,000
Tag Location	1,19	0,283
UAV tag reading method	5078,26	0,000
2-Way Interactions	248,81	0,000
Number of levels*UAV speed	468,74	0,000
Number of levels*Tag Location	0,97	0,333
Number of levels*UAV tag reading method	677,11	0,000
UAV speed*Tag Location	0,51	0,482
UAV speed*UAV tag reading method	345,38	0,000
Tag Location*UAV tag reading method	0,13	0,719
3-Way Interactions	13,08	0,000
Number of levels*UAV speed*Tag Location	0,06	0,803
Number of levels*UAV speed*UAV tag reading method	52,08	0,000
Number of levels*Tag Location*UAV tag reading method	0,11	0,745
UAV speed*Tag Location*UAV tag reading method	0,06	0,814
4-Way Interactions	0,01	0,934
Number of levels*UAV speed*Tag Location*UAV tag reading method	0,01	0,934
Error		
Total		

The results of the above ANOVA statistical analysis can be confirmed by the Pareto chart. The Pareto chart uses the same level of significance as the normal plot to determine the significance of effects. Therefore from Figure 6.55 the parameters Number of levels, UAV speed, UAV tag reading method, Number of levels*UAV speed, Number of levels*UAV tag reading method, UAV speed*UAV tag reading method and Number of levels*UAV speed*UAV tag reading method which are on the right of the red line are statistically significant. The red line is the reference line which depends on the significance level α=0.05 and indicates which results are statistically significant.

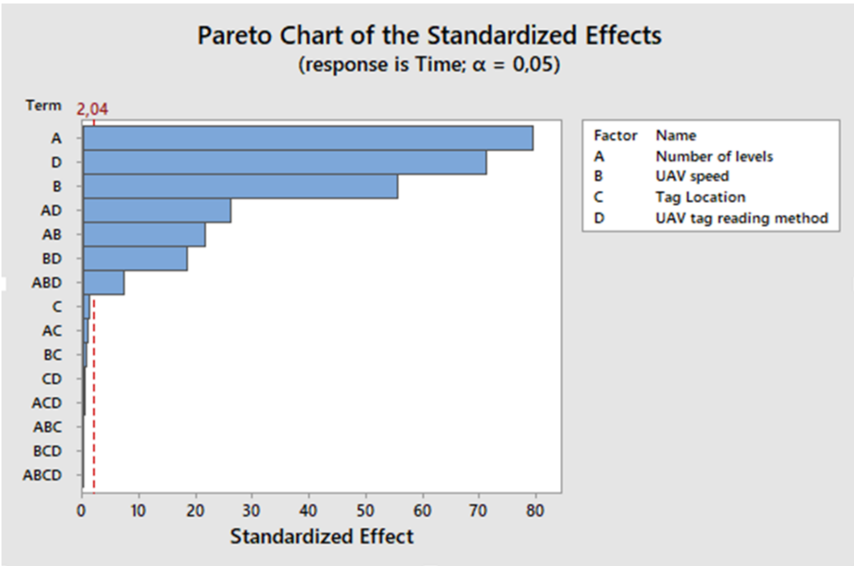


Figure 6.55 Pareto chart in terms of stock count system

In addition, in order to consider correctly the results of the statistical analysis, specifically that the parameters of Number of levels, UAV speed, UAV tag reading method, Number of levels*UAV speed, Number of levels*UAV tag reading method, UAV speed*UAV tag reading method and Number of levels*UAV speed*UAV tag reading method significantly affect the stock count time, we should check whether the normal distribution for stock count time as well as the constant variance and independence of residuals hold true from Figure 6.56. Initially one way of checking the normal distribution is the Normal probability plot which should approximately follow a straight line when the residuals are normally distributed. The normal distribution, although not fully symmetric, is also approximately confirmed by the histogram. Also the test for constant variation of the residuals is carried out by the residuals versus fits plot. This hypothesis is confirmed by the random distribution of residuals on either side of 0 with no stable patterns. Also as observed there are no outliers and the spread between the residuals does not continuously widen, criteria which would indicate the violation of the constant variance. Finally, residuals versus order confirms the hypothesis that the residuals are independent of each other. The residuals in the corresponding plot show no trends or patterns and are randomly distributed around the centerline. From all of the above we conclude that the results of the stock count time are correct.

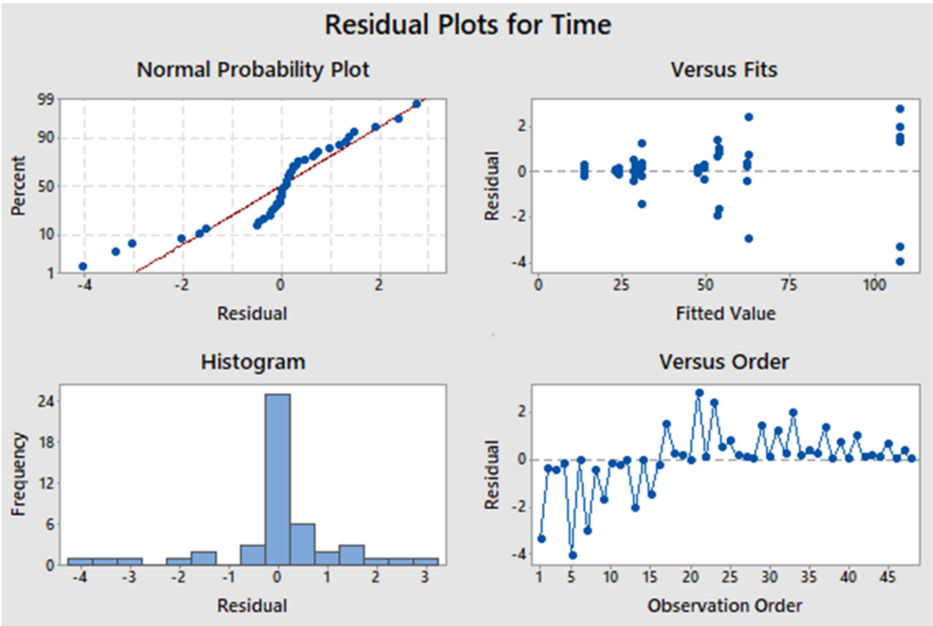


Figure 6.56 Residuals Plot for stock count time

Since we have concluded that the stock count time results are correct we will investigate the levels of statistically significant factors and system configurations that lead to the shorter stock count time. This will be done using boxplots which help to identify possible outliers and visualize the distribution of the data. More specifically, according to Figure 6.57, it can be observed that the stock count time is shorter when the number of levels of stock counting is 2 levels and the RFID tag is placed in front side of the pallet. Furthermore, when the speed of the UAV is 1.5m/s and finally when the tag reading method of the UAV is across the racks.

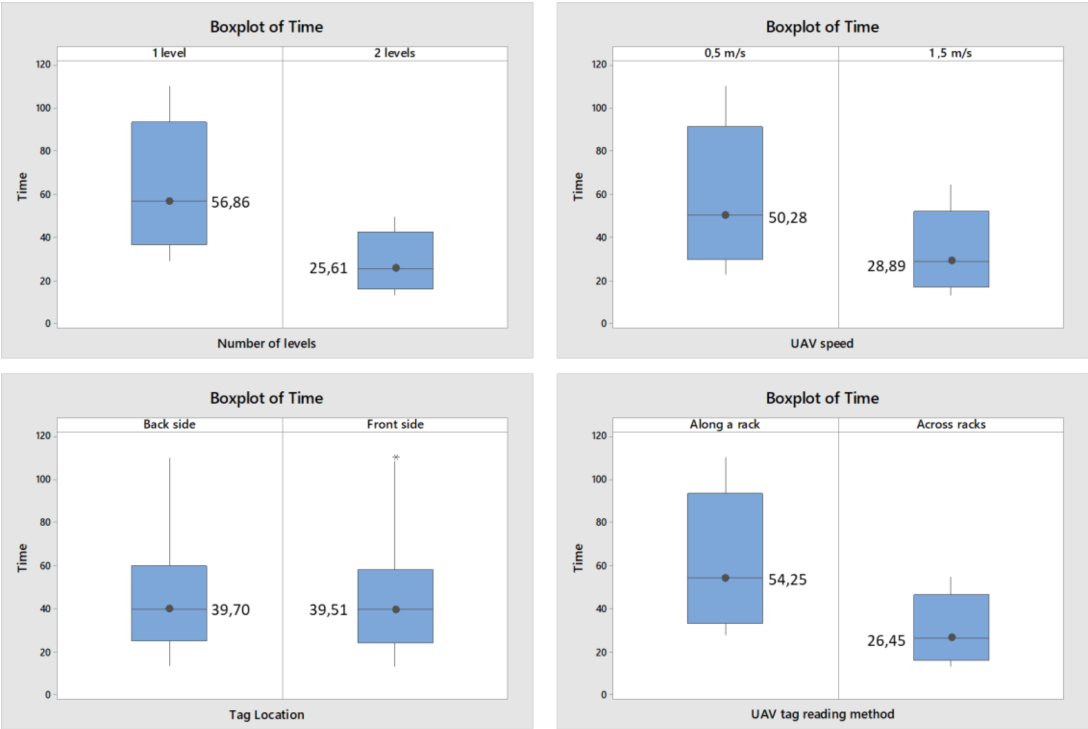


Figure 6.57 Boxplots for stock count time for statistically significant factors

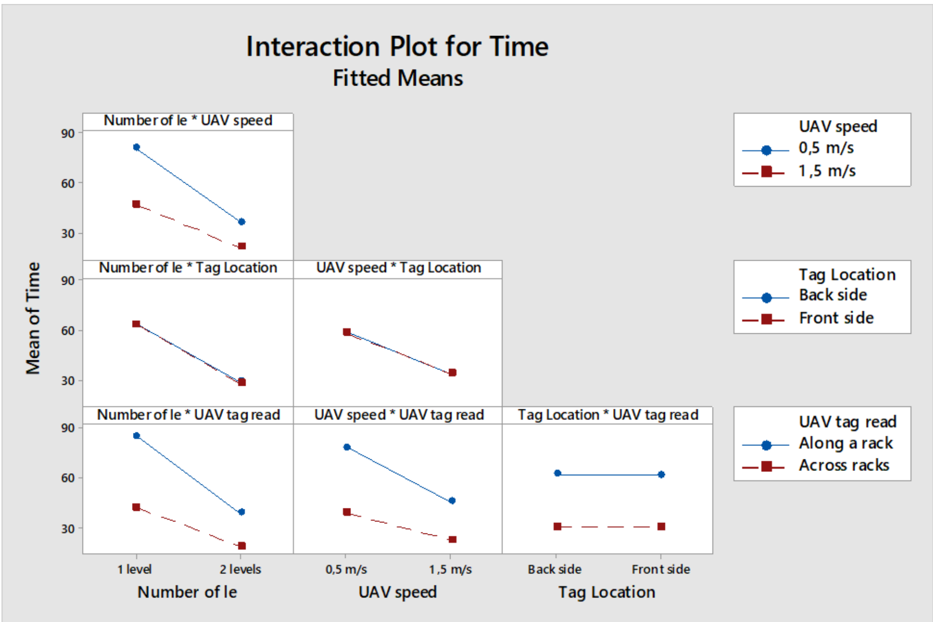


Figure 6.58 Interaction plots

The analysis of the results will also consider the interaction plots as shown in Figure 6.58.

Initially in the plot examining the relationship between Number of levels and UAV speed it can be seen that the best combination in terms of stock count time is the 2 levels and 1,5m/s UAV speed. This conclusion can be drawn from the points on the red and blue lines in the Number of levels*UAV speed plot.

Similarly, in the Number of levels and Tag location plot examining the relationship between Number of levels and Tag location, it can be seen that the best combination in terms of stock count time is the 2 levels and front side tag location.

Furthermore, in the Number of levels*UAV tag reading method plot examining the relationship between Number of levels and UAV tag reading method, it is shown that the best combination in terms of stock count time is the 2 levels and across the racks reading method

Similarly, in the UAV speed*Tag location plot examining the relationship between UAV speed and Tag location it appears that the best combination in terms of stock count time is 1,5 m/s UAV speed and front side tag location.

In addition, in the UAV speed*UAV tag reading method plot examining the relationship between UAV speed*UAV tag reading method, it appears that the best combination in terms of stock count time 1,5m/s UAV speed and across the racks reading method.

Finally, in the Tag location*UAV tag reading method plot examining the relationship between Tag location and UAV tag reading method, it appears that the best combination in terms of stock count time is front side tag location and across the racks reading method.

According to the above analysis of the interaction plots, we conclude that the best combination of stock count parameters that emerges is 2 levels-1,5m/s UAV speed-Front side tag location-Across the racks reading method. This confirms the best combination of the parameters of the first case and is the optimal solution in Case study 1 because it primarily minimizes to a large extent the travel distance of the UAV.

Case study 2: Chilled warehouse with liquid products

Formulation of Research Hypothesis

Similarly with Case Study 1, for the evaluation of stock count system the parameter of stock count time and parameter of accuracy of stock count process were measured. For the parameter of accuracy only cases where we had 100% RFID tag reading accuracy were considered and for the parameter of stock count time as well for the three factors that have been taken into account for the evaluation of stock count system, certain hypotheses were introduced.

Following exactly the same procedure with Case Study 1, the following hypotheses were initially defined

In detail, there were three null hypotheses for the stock count time:

The first null hypothesis (H0,1) 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 (H0,2) states that the stock count time was equal when either the UAV speed was 0,5m/s or 1,5m/s:

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

The third null hypothesis (H0,3) states that the stock count time was equal either when the UAV tag reading method was along a rack or across the racks:

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

Similarly, the alternative hypotheses H_1 state that:

The first alternative hypothesis (H1,1) states that the stock count time was the different when either the number of levels was 1 level or 2 levels:

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

The alternative null hypothesis (H1,2) states that the stock count time was different when either the UAV speed was 0,5m/s or 1,5m/s:

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

The third alternative hypothesis (H1,3) states that the stock count time was different either when the UAV tag reading method was along a rack or across the racks:

$$H_{1,3}: t_{along\ a\ rack} \neq t_{across\ the\ racks}$$

Identical, the P-value is defined as the lowest level of significance that leads to rejection of the null hypothesis. If the P-value is less than or equal to a predefined significance level (in our case the significance level is α=0.05), then the null hypothesis is rejected and we cannot assume that all samples have the same mean, so at significance level α we accept the alternative hypothesis. On the other hand, if the P-value is greater than α, then at significance level α we cannot reject the null hypothesis.

The Table 6.7 presents the results obtained from the ANOVA analysis and showed that all cases (Number of levels, UAV speed, UAV tag reading method, Number of levels*UAV speed, Number of levels*UAV tag reading method, UAV speed*UAV tag reading method and Number of levels*UAV speed*UAV tag reading method) were statistically significant as P-value < 0.05. Therefore, it was shown that for cases: H0.1, H0.2 and H0.3, the null hypothesis was rejected at the significance level α = 0.05. This means that the use of the parameters of Number of levels, UAV speed and UAV tag reading method significantly affects the stock count time.

Table 6.7 Results of statistical analysis in terms of stock count time

Analysis of Variance

Source	F-Value	P-Value
Model	807,04	0,000
Linear	1712,44	0,000
Number of levels	2651,43	0,000
UAV speed	806,26	0,000
UAV tag reading method	1679,64	0,000
2-Way Interactions	166,09	0,000
Number of levels*UAV speed	122,98	0,000
Number of levels*UAV tag reading method	285,71	0,000
UAV speed*UAV tag reading method	89,58	0,000
3-Way Interactions	13,66	0,002
Number of levels*UAV speed*UAV tag reading method	13,66	0,002
Error		
Total		

The results of the above ANOVA statistical analysis can be confirmed by the Pareto chart. The Pareto chart uses the same level of significance as the normal plot to determine the significance of effects. Therefore from Figure 6.59 the parameters Number of levels, UAV speed, UAV tag reading method, Number of levels*UAV speed, Number of levels*UAV tag reading method, UAV speed*UAV tag reading method and Number of levels*UAV speed*UAV tag reading method which are on the right of the red line are statistically significant. The red line is the reference line which depends on the significance level α=0.05 and indicates which results are statistically significant.

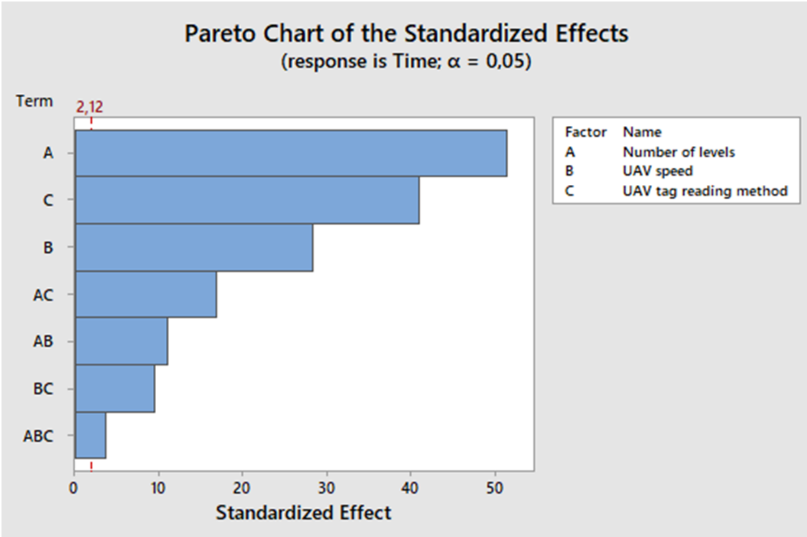


Figure 6.59 Pareto chart in terms of stock count system

Furthermore, based on the Residual Plots (Figure 6.60) which is similar to Case Study 1 we will check whether the normal distribution for stock count time, the constant variance and the independence of the residuals are valid. Initially the Normal probability plot approximately follow a straight line when the residuals are normally distributed. The normal distribution, also confirmed by the histogram. Also the test for constant variation of the residuals is carried out by the residuals versus fits plot. This hypothesis is confirmed by the random distribution of residuals on either side of 0 with no stable patterns. Also as observed there are no outliers and the spread between the residuals does not continuously widen, criteria which would indicate the violation of the constant variance. Finally, residuals versus order confirms the hypothesis that the residuals are independent of each other. The residuals in the corresponding plot show no trends or patterns and are randomly distributed around the centerline. From all of the above we conclude that the results of the stock count time are correct in Case Study 2.

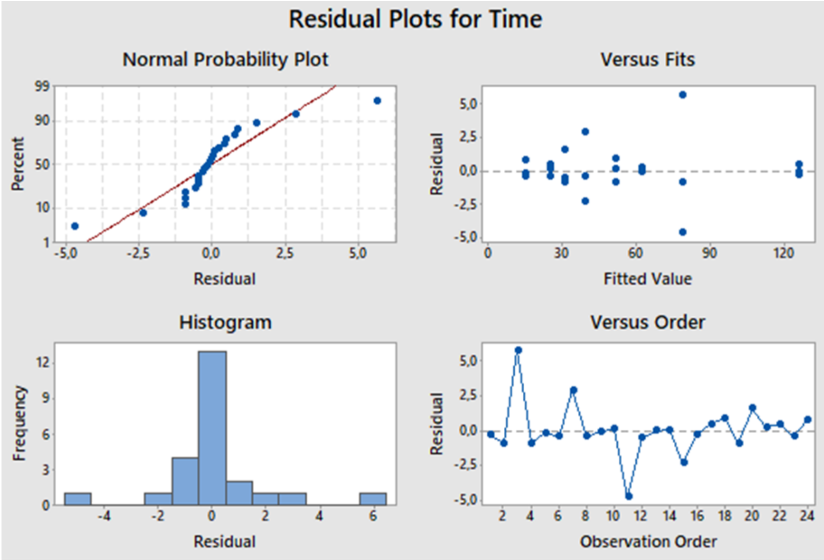


Figure 6.60 Residuals Plot for stock count time

Since we have concluded that the stock count time results are correct we will investigate the levels of statistically significant factors and system configurations that lead to the shorter stock count time. This will be done using boxplots which help to identify possible outliers and visualize the distribution of the data. More specifically, according to Figure 6.61, it can be observed that the stock count time is shorter when the number of levels of stock counting is 2 levels. Furthermore, when the speed of the UAV is 1.5m/s and finally when the tag reading method of the UAV is across the racks.

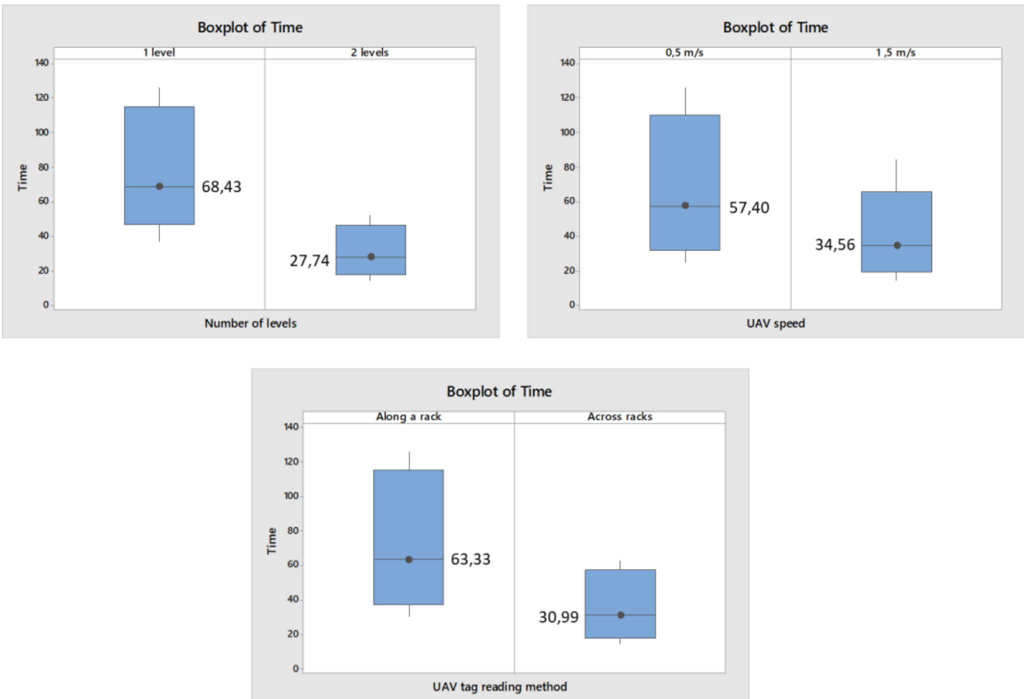


Figure 6.61 Boxplots for stock count time for statistically significant factors

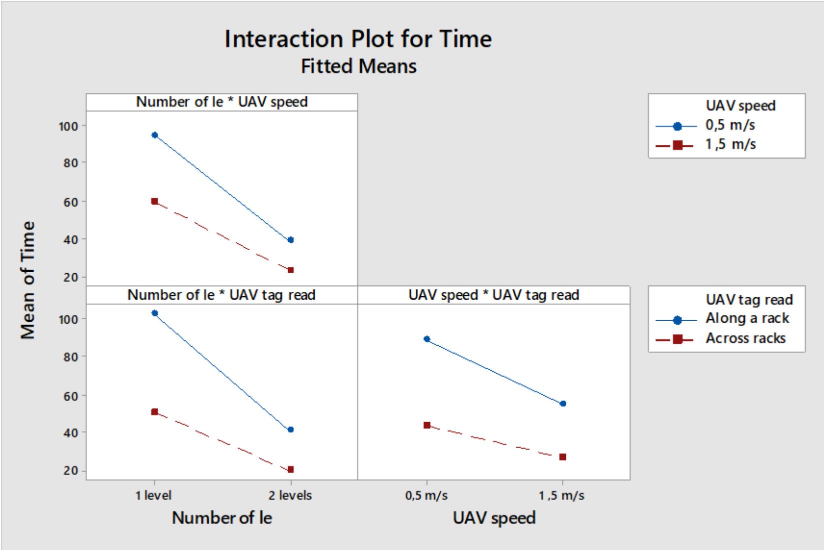


Figure 6.62 Interaction plots

The analysis of the results will also consider the interaction plots as shown in Figure 6.62.

Initially in the plot examining the relationship between Number of levels and UAV speed it can be seen that the best combination in terms of stock count time is the 2 levels and 1,5m/s UAV speed. This conclusion can be drawn from the points on the red and blue lines in the Number of levels*UAV speed plot.

Similarly, in the Number of levels*UAV tag reading method plot examining the relationship between Number of levels and UAV tag reading method, it is shown that the best combination in terms of stock count time is the 2 levels and across the racks reading method

Finally, in the UAV speed*UAV tag reading method plot examining the relationship between UAV speed*UAV tag reading method, it appears that the best combination in terms of stock count time 1,5m/s UAV speed and across the racks reading method.

According to the above analysis of the interaction plots, we conclude that the best combination of stock count parameters that emerges is 2 levels-1,5m/s UAV speed-Across the racks reading method. This confirms the best combination of the parameters of the second case and is the optimal solution in Case study 2 because it primarily minimizes to a large extent the travel distance of the UAV.

6.4 Discussion of the findings

The objective of this study was to investigate the operational and technical parameters that affect the performance of a stock count system using unmanned aerial vehicles (UAVs) in warehouses, through a series of laboratory tests. The findings of this study are important as they reveal the parameters that affect the performance of the automatic stock count system, which may result in increased accuracy and reduced stock count time. After analyzing the results, it was found that there were a number of factors and combinations of factors that significantly impacted the efficiency of the stock count system under investigation. The results showed that the number of levels inventoried at the same time affects the performance of the stock count system, as it saves 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 higher reading accuracy as it 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 in one flight.

According to the results of the statistical analysis, the configuration of the stock count system that provided the most encouraging results in terms of stock count efficiency (i.e., stock count time per warehouse aisle) incorporated the following levels per parameter in case study 1: (a) Number of levels- 2 levels, (b) UAV speed-1.5 m/s, (c) Tag location- Front side, and (d) UAV tag reading method- Across racks. In case study 2, the configuration that provided the most encouraging results incorporated the following levels per parameter: (a) Number of levels- 2 levels, (b) UAV speed-1.5 m/s, and (c) UAV tag reading method- Across racks.

6.4.1 Research implications

The use of RFID reader technology in conjunction with unmanned aerial vehicles (UAVs) has the potential to radically transform the stock count process in a range of sectors. The employment of UAVs equipped with RFID readers can considerably increase the efficiency and accuracy of the stock count operation.

UAVs give precise and up-to-date information on the location and condition of objects in real-time, allowing for an efficient stock count. The employment of RFID reader technology with UAVs reduces the danger of human mistake in manual stock count operations, enhancing stock counting accuracy.

The stock count process is accelerated, and quick data collecting in big warehouses or storage facilities enables efficient stock count integration. Furthermore, automating the stock count process lowers the labor expenses associated with manual stock counting procedures. This, in turn, may result in considerable cost savings for enterprises employing this technology, as well as the elimination of the need for workers to manually count goods in hazardous areas, boosting safety and lowering the chance of accident.

Finally, the combination of RFID reader technology with UAVs has the potential to revolutionize the stock count process in a variety of businesses. The real-time data collection and automation capabilities of UAVs outfitted with RFID readers provide various advantages, including higher accuracy, faster processing, lower costs, and increased safety. More research and development in this area is required to fully exploit the potential of RFID reader technology in conjunction with UAVs for stock counting.

6.4.2 Managerial implications

The use of RFID reader technology in conjunction with Unmanned Aerial Vehicles (UAVs) for stock count has important management ramifications that may considerably help enterprises in a variety of sectors. These consequences may be examined from inventory management, efficiency, cost savings, safety, and resource allocation viewpoints.

In terms of inventory management, the real-time data collected by RFID-equipped UAVs gives accurate and up-to-date information on the position and status of RFID-tagged products. This data may be utilized to improve inventory management by helping managers to make more informed decisions and better prepare for future requirements. This technology's greater visibility improves inventory management by giving managers with a full picture of the inventory.

The employment 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.

The deployment of UAVs outfitted with RFID scanners has significant cost-saving implications for businesses. The removal of manual stock counting saves labour expenses, saving the organization money. Furthermore, the real-time data collected by UAVs outfitted with RFID readers allows managers to more efficiently allocate resources, enhancing overall efficiency and performance.

In terms of safety, the use of UAVs for automated stock counting removes the need for workers in dangerous areas 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.

In conclusion, the administrative implications of integrating RFID reader technology with UAVs for stock count are vast and diversified. This technology's better inventory management, efficiency, cost savings, safety, and resource allocation benefits present considerable opportunity for enterprises to improve their operations and performance. More research and development in this area is required to fully exploit the potential of RFID reader technology in conjunction with UAVs for stock counting.

7 Conclusions and future research agenda

This chapter presents initially a summary of this thesis followed by the main findings from laboratory experiments in order to evaluate the efficiency and accuracy of stock count system. Next steps and directions for future research are also described.

7.1 Dissertation summary and main conclusions

The main objective of this dissertation was the design of an innovative stock count system that adopts the use of a UAV in combination with RFID technology. The methodology followed for the development and testing of this stock count system included 3 main steps. The first step was embraced the identification of the technical characteristics and applications of UAVs, their operational characteristics and the parameters that affect their operational performance in the stock count process (through a literature review). The second step focused on the evaluation, ranking and final selection of the parameters considered which were taken into consideration during the testing of stock count system with the use of UAVs while the third step was related to the laboratory tests conducted to evaluate and optimize the use of UAVs in the stock counting process.

The review of the parameters was conducted through the methodology of a systematic literature review (SLR), in which certain criteria were taken into consideration to identify relevant articles. Following this methodology, 46 articles were initially identified in the literature, of which 25 were relevant to the final corpus. The limited number of published articles related to the research area under study suggests that this field is still at an early stage, understudied, and promising for further research.

Focusing on the results obtained from the systematic literature review and specifically on the investigation for identifying technical and operational parameters that affect the stock count process via the use of UAVs, eight categories of technical characteristics and four categories of operational characteristics (missions, flight zone, operational environment, and applications) were identified. In addition, five indoor warehouse applications in which UAVs can be used were presented and analyzed.

After the completion of the systematic literature review, the next step was to map the user requirements related to the automation of the inventory process through the use of UAVs. Two research methods were adopted to capture these requirements. The first method involved the use of a structured questionnaire distributed to a specific sample of companies and the second method involved personal interviews with logistics company executives through a set of open-end questions in order to evaluate and confirm the survey research findings.

The next step involved the evaluation of the stock count system under consideration, through two different phases of laboratory testing. The first phase of laboratory tests aimed to determine the factors and levels to be used in the second phase of laboratory tests, through independent experiments for each parameter. The second phase of experiments evaluated the selected parameters in terms of reading efficiency and accuracy. The factorial design that was used to set-up the experimental design included four factors in the first experiment with two levels (24 full factorial design) and three factors in the second experiment with two levels (23 full factorial design) per factor. The aim of the test was to determine the optimal combinations between the selected parameters and their levels and to determine the optimal combination of these parameters in order to succeed in having high reading efficiency and accuracy.

Upon completion of the experiments, a statistical analysis was conducted using ANOVA. The results showed that the performance of the system is significantly affected by certain parameters. Regarding the total stock count time, based on the ANOVA results in both experiments, the parameters "number of levels," "UAV speed," and "UAV tag reading method" were statistically significant. The results of the experiments were encouraging showing that UAVs can be used for stock count process with positive impact on cut-costing, staff safety and working performance.

7.2 Future research agenda

Based on the findings of this thesis, 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 aluminum) 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 show 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: Most of the research conducted on the inventory system using UAVs and RFID readers, and the results published, 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 inventory system via the use of UAVs in a real 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 technologies.

References

Antony, J. (1999), “Ten useful and practical tips for making your industrial experiments successful”, *The TQM Magazine*,

Antony, J. (2014), *Design of Experiments for Engineers and Scientists: Second Edition*, *Design of Experiments for Engineers and Scientists: Second Edition*,

Arjomandi, M., Agostino, S., Mammone, M., Nelson, M. and Zhou, T., (2006) ‘Classification of unmanned aerial vehicles’, Mechanical Research Papers – Academia, pp. 1-50

Bae, S.,M, Han, K.,H.,Cha, C., N., and Lee H.,Y., (2016), ‘Development of inventory checking system based on UAV and RFID in open storage yard’, International Conference on Information Science and Security, pp. 1-2

Beul , M., Droeschel, D., Nieuwenhuisen, M., Quenzel, J., Houben, S., and Behnke, S., (2018), ‘Fast autonomous flight in warehouses for inventory applications’, IEEE Robotics and Automation Letters, 3(4), pp. 3121-3128

Björklund, M. and Johansson, H. (2018), “Urban consolidation centre – a literature review, categorisation, and a future research agenda”, Proceedings - International Symposium on Wearable Computers, 48(8), pp. 745-764

Campbell, J., Golden, B. and Pesch, E., (2018) ‘Optimization approaches for civil applications of unmanned aerial vehicles (UAVs) or aerial drones: A survey’, 72, pp. 411-458

Collis, J. and Hussey, R. (2003), “A Practical Guide for Undergraduate and Postgraduate Students”

Chowdhurya, S., Emelogu, A., Marufuzzaman, M., Nurre, S., and Bian, L.,(2017), Drones for disaster response and relief operations: A continuous approximation model. Int. J. Production Economics, pp. 167-184.

Crowther, M.A. and Cook, D.J. (2007), “Trials and tribulations of systematic reviews and meta-analyses.”, Hematology / the Education Program of the American Society of Hematology, pp.493-497

De Falco, A., Narducci, F., and Petrosino, A., (2019), ‘An UAV autonomous warehouse inventorying by deep learning’, International Conference on Image Analysis and Processing, pp. 443-453

Delavarpour, N., Koparan, C., Nowatzki, N., Bajwa, S. and Sun, X., (2021) ‘A Technical Study on UAV Characteristics for Precision Agriculture Applications and Associated Practical Challenges, 13(6), pp. 1-25

De Koster, R., Le-Duc, T and Roodbergen, K., (2007) ‘Design and control of warehouse order picking: A literature review’, European Journal of Operational Research, 182(2), pp.482-501

Denyer, D. and Tranfield, D. (2009), “Producing a Systematic Review”, The Sage Handbook of Organizational Research Methods

Denzin, N.K. (1978), “Sociological Methods: A Sourcebook”

Derpich, I., Miranda, D., and Sepulveda, J., (2018), 'Using drones in a warehouse with minimum energy consumption', International Conference on Computers Communications and Control, pp. 1-6

Durić, J., S., Jovanović, S., Z., and Sibalija, T., (2018), 'IMPROVING THE EFFICIENCY OF THE WAREHOUSE STORAGE PROCESS WITH THE USE OF DRONES', International Journal ''Advanced Quality", 46(3-4), pp. 1-6

Dynamiki, 2022. *Dynamiki.* [Online]
Available at: https://www.dynamiki-sa.gr/el/our-company
[Accessed 28th January 2022].

Fernández-Caramés, T., M., Novoa, O., B., Míguez, I., F., and Lamas P.F. (2019) 'Towards an autonomous industry 4.0 warehouse: A UAV and blockchain-based system for inventory and traceability applications in big data-driven supply chain', 19(10), pp. 3-31

Ghelichi, Z., Gentili, M. and Mirchandani, P. B., (2021) 'Logistics for a fleet of drones for medical item delivery: A case study for Louisville, KY', Computers & Operations Research, 135, pp. 1-20

Gimenez, C. and Tachizawa, E.M. (2012), "Extending sustainability to suppliers: A systematic literature review", Supply Chain Management, 17(5), pp. 531-543

Gligor, D.M. and Holcomb, M.C. (2012), "Understanding the role of logistics capabilities in achieving supply chain agility: A systematic literature review", 17(4), pp. 438-453

Harik, H., C., Guérin, F., Guinand, F., Brethé, J.F., and Pelvillain, H., (2016), 'Towards an autonomous warehouse inventory scheme', IEEE Symposium Series on Computational Intelligence,

Hassanalian, M. and Abdelkefi, A., (2017) 'Classifications, applications, and design challenges of drones: A review', Progress in Aerospace Sciences, 91, pp. 99-131

Hell P., M. and Varga, P., J., (2019) 'Drone systems for factory security and surveillance', Interdisciplinary Description of Complex Systems, 17(3), pp. 458-467

Kang, S., Park, M., W., and Suh, M., (2019), 'Feasibility Study of the Unmanned-aerial-vehicle Radio-frequency Identification System for Localizing Construction Materials on Large-scale Open Sites', Sensors and Materials, 31(5), pp. 1449-1465

Khosiawan, Y. and Izabela Nielsen, I., (2016) 'A system of UAV application in indoor environment', Production & Manufacturing Research, 4(1), pp. 2-22

Kloetzer, M., Burlacu, A., Enescu, G., Caraiman, S. and Mahulea, C., (2019) 'Optimal indoor goods delivery using drones', International Conference on Emerging Technologies and Factory Automation, pp. 1579-1582

Koslowski, R. & Schulzke, M., 2018. Drones Along Borders: Border Security UAVs in the United States and the European Union. *International Studies Perspectives*, November, pp. 305-324.

Kyrkou, C.,Timotheou, S., Kolios, P., Theocharides, T., and Panayiotou, C., (2019) 'Drones: Augmenting Our Quality of Life', IEEE Potentials, 38(1), pp. 30-36

Lagorio, A., Pinto, R. and Golini, R. (2016), "Research in urban logistics: a systematic literature review", International Journal of Physical Distribution and Logistics Management, 46(10), pp. 908-931

Lightfoot, H., Baines, T. and Smart, P. (2013), "The servitization of manufacturing: A systematic literature review of interdependent trends", International Journal of Operations and Production Management, pp. 1408-1434

Marchet, G., Melacini, M. and Perotti, S., (2015) 'Investigating order picking system adoption: a case-study-based approach', International Journal of Logistics Research and Applications, 18(1), pp. 82-98

Macrina, G., Pugliese, L., D., P., Guerriero, F. and Laporte G., (2020) 'Drone-aided routing: A literature review', Transportation Research Part C: Emerging Technologies, 120, pp. 1-25

Menouar, H., Güvenç, I., Akkaya, K., Uluagac, A., Kadri, A., and Tuncer A.(2017) 'UAV-Enabled Intelligent Transportation Systems for the Smart City: Applications and Challenges', Enabling Mobile and Wireless Technologies for Smart Cities, pp. 22-28.

Montgomery, D., 2012. Design and Analysis of Experiments. 5th Edition ed. America: s.n.

Moshref, M. and Winkenbach, J.M., (2021) 'Applications and Research avenues for drone-based models in logistics: A classification and review', Expert Systems with Applications, 177, pp. 1-26

Müller, S., Rudolph, C. and Janke C., (2019) 'Drones for last mile logistics: Baloney or part of the solution?', Transportation Research Procedia, 41, pp. 73-87

Näslund, D. (2002), 'Logistics needs qualitative research – especially action research', International Journal of Physical Distribution & Logistics Management, 32(5), pp. 321-338

NIST/SEMATECH. (2012), "e-Handbook of Statistical Methods", *E-Handbook of Statistical Methods*,

Otto, A., Agatz, N., Campbell, J., Golden, B., and Pesch, E., (2018) 'Optimization approaches for civil applications of unmanned aerial vehicles (UAVs) or aerial drones: A survey', Networks, 72, pp. 411-458

Raj, A. and Sah, B., (2019) 'Analyzing critical success factors for implementation of drones in the logistics sector using grey-DEMATEL based approach', Computers & Industrial Engineering, 138, pp. 1-12

Rejeb, A., Rejeb, K., Simske, S. and Treiblmaier, H., (2021), 'Humanitarian Drones: A Review and Research Agenda', Internet of Things, 16, pp. 1-20

Ridolfi, M., Macoir, N., Van Gerwen, J., V., Rossey, J., Hoebeke, J. and De Poorter, E., (2019) 'Testbed for warehouse automation experiments using mobile AGVs and drones', IEEE Conference on Computer Communications Workshops, pp. 1-2

Saenz, M.J. and Koufteros, X. (2015), 'Special issue on literature reviews in supply chain management and logistics', International Journal of Physical Distribution & Logistics Management, 45

Sarmed, 2021. *Sarmed.* [Online]
Available at: https://www.sarmed.gr/web/companygr/
[Accessed 9 February 2022].

Skywalker, 2022. *Skywalker.* [Online]
Available at: https://www.skywalker.gr/elGR/etairia/parousiasi/D42ADF9D-91E0-4AE0-89AE-52FCECF2FE3F
[Accessed 28th January 2022].

Sorbelli, F., B., Coro, F., Pinotti, C., M., and Shende, A., (2019), 'Automated picking system employing a drone', International Conference on Distributed Computing in Sensor Systems, pp. 633-640

Tranfield, D., Denyer, D. and Smart, P. (2003), 'Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review', British Journal of Management

Tian, H., Wang, T., Liu, Y., Qia, X., and Li, Y. (2020), "Computer vision technology in agricultural automation—A review.". Information Processing in Agriculture, 7(1), pp. 1-19.

Van Gils, T., Ramaekers, K., Caris, A. and de Koster, R.B.M., (2018), 'Designing efficient order picking systems by combining planning problems: State-of-the-art classification and review', European Journal of Operational Research, 267(1), pp.1-15

Wawrla, L., Maghazei, O., and Netland, T., (2019), 'Applications of drones in warehouse operations', Eidgenössische Technische Hochschule Zürich., pp. 1-14

Xu, L., Kamat, V.R. and Menassa, C., C., (2017), 'Automatic extraction of 1D barcodes from video scans for drone-assisted inventory management in warehousing applications', International Journal of Logistics Research and Applications, 21(3), pp. 243-258

Yap, K.M., Eu, K.S. and Low J.M., (2016) 'Investigating Wireless Network Interferences of Autonomous Drones with Camera Based Positioning Control System', IEEE, (5), pp. 1-5

Appendix A – Questionnaire

Investigation of the use of drones in warehouses

Part A-Company profile

1. The main activities of your business are related to (you can choose more than one answer):

- ☐ Third-party logistics
- ☐ Manufacturing companies
- ☐ Wholesalers

2. What is the annual turnover of your business (concerns third-party logistics companies)?

- ☐ <€500.000
- ☐ €500.000- €1.000.000
- ☐ €1.000.000-€3.000.000
- ☐ €3.000.000-€5.000.000
- ☐ €5.000.000-€10.000.000
- ☐ €10.000.000-€20.000.000
- ☐ €20.000.000-€50.000.000
- ☐ >€50.000.000

3. What is the annual turnover of your business (concerns manufacturing & wholesale companies);

- ☐ <€2.000.000
- ☐ €2.000.000-€5.000.000
- ☐ €5.000.000-€10.000.000
- ☐ €10.000.000-€20.000.000
- ☐ €20.000.000-€30.000.000
- ☐ €30.000.000-€50.000.000
- ☐ €50.000.000-€100.000.000
- ☐ >€100.000.000

4. What is the number of employees your business employs?

- ☐ <9 people
- ☐ 10-49 people
- ☐ 50-249 people
- ☐ >250 people

Part B - Investigation of the use of drones in the execution of logistics processes in warehouses

1. During the current operation of your warehouses, what problems do you face during the execution of the following logistics procedures?

	Errors	Low productivity	High operating costs	Low accuracy	No real-time information	Risk of accidents involving workers
Receiving of goods	○	○	○	○	○	○
Intra-logistics	○	○	○	○	○	○
Products control prior to dispatching	◉	○	○	○	○	○
Stock control of raw materials and/or final products	○	○	○	○	○	○
Stock control of re-usable products	○	○	○	○	○	○
Control of stock position accuracy	◉	○	○	○	○	○
Stock count	○	○	○	○	○	○
Other process(please mention)......	○	○	○	○	○	○

2. Are you aware that the above processes could be greatly automated with the use of drones?
   ☐ Yes
   ☐ No

3. Would you be interested in automating some of the above processes with the use of drones?
   ☐ Yes I would like to explore it (even at a piloting level)
   ☐ No

4. What processes would you be interested in automating through the use of drones? (you can select multiple options)
   ☐ Receiving of goods (use of drones with QR code reader or RFID tag)
   ☐ Intra-logistics (transport of goods at an item level)

☐ Products control prior to dispatching
☐ Stock control of raw materials and/or final products
☐ Stock control of re-usable products (e.g. beer kegs) or raw materials (e.g. scrap, pipes, timber, etc.).
☐ Control of stock position accuracy of raw materials and/or final products (especially in goods located in open-air warehouses)
☐ Stock count
☐ Other process (please indicate)

5. Why would you automate logistic processes using drones? (you can select multiple options)
☐ Increase of productivity
☐ Reduction of errors
☐ Reduction of operating costs
☐ Increase in reading accuracy
☐ Real-time information
☐ Avoidance of accidents at work

6. Would you be interested in participating in a pilot application for the use of drones in your own logistics processes in collaboration with the team of University of Aegean?
☐ Yes
☐ No

7. If you were satisfied with the piloting, how long would it take you to adopt the use of drones per process?

	In 1 year from now	Within 1-3 years	Within 3-5 years	I would not automate this process
Receiving of goods	○	○	○	○
Intra-logistics	○	○	○	○
Products control prior to dispatching	○	○	○	○
Stock control of raw materials and/or final products	○	○	○	○
Stock control of re-usable products	○	○	○	○
Control of stock position accuracy of raw	○	○	○	○

materials and/or final products				
Stock count	◌	◌	◌	◌
Other process (please mention)......	◌	◌	◌	◌

8. Why would you not choose drones to automate any of the above processes? (you can select multiple options)
   ☐ I find no particular benefit from such automation
   ☐ Drone technology in logistics applications is not mature yet
   ☐ Drone technology in logistics applications is expensive
   ☐ There are still technical issues with the use of drones (e.g. battery life)

9. Generally speaking, do you think that the use of drones in logistics processes will be of interest and will be adopted in the future by companies that manage warehouses?
   ☐ Yes it will certainly be adopted
   ☐ It will probably to be adopted
   ☐ I'm not sure
   ☐ Probably not
   ☐ No, it will not be adopted

Appendix B – Interview questions

Interviews with executives of logistics companies

Company & interviewee details	
Company name	
Full name	
Affiliation	
Email	

Investigate the use of drones in warehouses

Part A – Current situation

1. How do you perform the main logistics processes (e.g. receiving, picking, controlling of goods to be shipped, stock counts, inventory control) in your warehouses?
2. What weaknesses there are at each level:
    i. Functional (productivity, number of employees required, errors, real-time information, etc.)
    ii. Employees' safety (accident risk)
    iii. Costs (operating costs, equipment, information systems)
3. Have you adopted any type of automation to improve productivity? If so, what reduction in operating costs did you ensure in the above logistics processes?
4. Is there still room for improvement in these processes? What has not been achieved with the existing systems and methods you use?
5. What are the main criteria to proceed with the adoption of fully automated systems for the execution of specific logistics processes (piloting phase or full scale implementation)?
6. The cost of employees in warehouses is low in Greece. Could an investment (e.g. use of drones) be justified?

Part B – Use of drones in logistic processes

1. The above processes could potentially be performed using drones. What do you think of that? Do you see it in positive light?
2. What logistic processes would you consider adopting drones for?
3. What benefits would you expect from using drones?
4. Would investment cost and/or Return-on-Investment (ROI) play a role in your decision?
5. What problems do you think would exist when using drones for the above logistic processes?

6. If you were satisfied with the piloting level, how long would it take you to adopt the use of drones per process?
7. Generally speaking, do you think that the use of drones in logistic processes will be adopted by the Greek market in the coming years?

Appendix C – Results of First set of laboratory tests

1. Ambient warehouse with dry products/RFID position_upper side/Flight way_S-shape

Factor 1: Number of Columns

Single column

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

Double column

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

Factor 2: UAV speed

	1st replicate		2nd replicate		3rd replicate	
UAV speed	Read	No read	Read	No read	Read	No read
0,5 m/s	✓		✓		✓	
1 m/s	✓		✓		✓	
1,5 m/s	✓		✓		✓	

Factor 3: Tag location

	1st replicate		2nd replicate		3rd replicate	
Tag location	Read	No read	Read	No read	Read	No read
Front side	✓		✓		✓	
Back side	✓		✓		✓	
Right side	✓		✓		✓	
Left side	✓		✓		✓	

Factor 4: Read distance

Read distance = 0,7m

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

Read distance = 1,25m

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

2. Ambient warehouse with dry products/RFID position_upper side/Flight way_Straight

Factor 1: Number of Levels

Single level

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

Double levels

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

Factor 2: UAV speed

	1st replicate		2nd replicate		3rd replicate	
UAV speed	Read	No read	Read	No read	Read	No read
0,5 m/s	✓		✓		✓	
1 m/s	✓		✓		✓	
1,5 m/s	✓		✓		✓	

Factor 3: Tag location

	1st replicate		2nd replicate		3rd replicate	
Tag location	Read	No read	Read	No read	Read	No read
Front side	✓		✓		✓	
Back side	✓		✓		✓	
Right side	✓		✓		✓	
Left side	✓		✓		✓	

Factor 4: Flight altitude

			1st replicate	2nd replicate	3rd replicate
Flight altitude			Read	Read	Read
0,7m	level 0	0,7m	4/4	4/4	4/4
	level 1	2,3m	4/4	4/4	4/4
	level 2	3,9m	1/4	1/4	2/4
2,3m	level 0	0,7m	3/4	4/4	3/4
	level 1	2,3m	4/4	4/4	4/4
	level 2	3,9m	4/4	4/4	4/4
3,2m	level 0	0,7m	0/4	1/4	1/4
	level 1	2,3m	4/4	4/4	4/4
	level 2	3,9m	4/4	4/4	4/4

3. Ambient warehouse with dry products/RFID position_underside/Flight way_S-shape

Factor 1: Number of Columns

Single column

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

Double column

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

Factor 2: UAV speed

	1st replicate		2nd replicate		3rd replicate	
UAV speed	Read	No read	Read	No read	Read	No read
0,5 m/s	✓		✓		✓	
1 m/s	✓		✓		✓	
1,5 m/s	✓		✓		✓	

Factor 3: Tag location

	1st replicate		2nd replicate		3rd replicate	
Tag location	Read	No read	Read	No read	Read	No read
Front side	✓		✓		✓	
Back side	✓		✓		✓	
Right side	✓		✓		✓	
Left side	✓		✓		✓	

Factor 4: Read distance

Read distance = 0,7m

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

Read distance = 1,25m

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

4. Ambient warehouse with dry products/RFID position_underside/Flight way_Straight

Factor 1: Number of Levels

Single level

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

Double levels

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

Factor 2: UAV speed

	1st replicate		2nd replicate		3rd replicate	
UAV speed	Read	No read	Read	No read	Read	No read
0,5 m/s	✓		✓		✓	
1 m/s	✓		✓		✓	

Factor 3: Tag location

	1st replicate		2nd replicate		3rd replicate	
Tag location	Read	No read	Read	No read	Read	No read
Front side	✓		✓		✓	
Back side	✓		✓		✓	
Right side	✓		✓		✓	
Left side	✓		✓		✓	

Factor 4: Flight altitude

			1st replicate	2nd replicate	3rd replicate
Flight altitude			Read	Read	Read
0,7m	level 0	0,7m	4/4	4/4	4/4
	level 1	2,3m	4/4	4/4	4/4
	level 2	3,9m	4/4	4/4	3/4
2,3m	level 0	0,7m	4/4	4/4	4/4
	level 1	2,3m	4/4	4/4	4/4
	level 2	3,9m	4/4	4/4	4/4
3,2m	level 0	0,7m	3/4	3/4	4/4
	level 1	2,3m	4/4	4/4	4/4
	level 2	3,9m	4/4	4/4	4/4

5. Chilled warehouse with liquid products/RFID position_upper side/Flight way_S-shape

Factor 1: Number of Columns

Single column

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

Double column

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

Factor 2: UAV speed

	1st replicate		2nd replicate		3rd replicate	
UAV speed	Read	No read	Read	No read	Read	No read
0,5 m/s	✓		✓		✓	
1 m/s	✓		✓		✓	
1,5 m/s	✓		✓		✓	

Factor 3: Tag location

	1st replicate		2nd replicate		3rd replicate	
Tag location	Read	No read	Read	No read	Read	No read
Front side	✓		✓		✓	
Back side		✓		✓		✓
Right side		✓		✓		✓
Left side		✓		✓		✓

Factor 4: Read distance

Read distance = 0,7m

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

Read distance = 1,25m

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

6. Chilled warehouse with liquid products/RFID position_upper side/Flight way_Straight

Factor 1: Number of Levels

Single level

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

Double levels

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

Factor 2: UAV speed

	1st replicate		2nd replicate		3rd replicate	
UAV speed	Read	No read	Read	No read	Read	No read
0,5 m/s	✓		✓		✓	
1 m/s	✓		✓		✓	
1,5 m/s	✓		✓		✓	
2 m/s	✓		✓		✓	

Factor 3: Tag location

	1st replicate		2nd replicate		3rd replicate	
Tag location	Read	No read	Read	No read	Read	No read
Front side	✓		✓		✓	
Back side		✓		✓		✓
Right side	✓		✓		✓	
Left side	✓		✓		✓	

Factor 4: Flight altitude

			1st replicate	2nd replicate	3rd replicate
Flight altitude			Read	Read	Read
0,7m	level 0	0,7m	5/5	5/5	5/5
	level 1	2,3m	2/5	2/5	2/5
	level 2	3,9m	1/5	1/5	1/5
2,3m	level 0	0,7m	3/5	1/5	2/5
	level 1	2,3m	5/5	5/5	5/5
	level 2	3,9m	3/5	3/5	3/5
3,2m	level 0	0,7m	1/5	1/5	1/5
	level 1	2,3m	2/5	3/5	3/5
	level 2	3,9m	3/5	3/5	3/5

7. Chilled warehouse with liquid products/RFID position_underside/Flight way_S-shape

Factor 1: Number of Columns

Single column

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

Double column

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

Factor 2: UAV speed

	1st replicate		2nd replicate		3rd replicate	
UAV speed	Read	No read	Read	No read	Read	No read
0,5 m/s	✓		✓		✓	
1 m/s	✓		✓		✓	
1,5 m/s	✓		✓		✓	

Factor 3: Tag location

	1st replicate		2nd replicate		3rd replicate	
Tag location	Read	No read	Read	No read	Read	No read
Front side	✓		✓		✓	
Back side	✓		✓		✓	
Right side		✓		✓		✓
Left side		✓		✓		✓

Factor 4: Read distance

Read distance = 0,7m

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

Read distance = 1,25m

	1st replicate		2nd replicate		3rd replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

8. Chilled warehouse with liquid products/RFID position_underside/Flight way_Straight

Factor 1: Number of Levels

Single level

Tag	1st replicate Read	1st replicate No read	2nd replicate Read	2nd replicate No read	3rd replicate Read	3rd replicate No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	

Double levels

Tag	1st replicate Read	1st replicate No read	2nd replicate Read	2nd replicate No read	3rd replicate Read	3rd replicate No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	

Factor 2: UAV speed

UAV speed	1st replicate Read	1st replicate No read	2nd replicate Read	2nd replicate No read	3rd replicate Read	3rd replicate No read
0,5 m/s	✓		✓		✓	
1 m/s	✓		✓		✓	
1,5 m/s	✓		✓		✓	

Factor 3: Tag location

Tag location	1st replicate Read	1st replicate No read	2nd replicate Read	2nd replicate No read	3rd replicate Read	3rd replicate No read
Front side	✓		✓		✓	
Back side		✓	✓		✓	
Right side		✓		✓		✓
Left side		✓		✓		✓

Factor 4: Flight altitude

Flight altitude		1st replicate Read	2nd replicate Read	3rd replicate Read
0,7m	level 0 0,7m	5/5	5/5	5/5
	level 1 2,3m	5/5	5/5	5/5
	level 2 3,9m	3/5	3/5	2/5
2,3m	level 0 0,7m	4/5	4/5	4/5
	level 1 2,3m	5/5	5/5	5/5
	level 2 3,9m	3/5	3/5	3/5
3,2m	level 0 0,7m	1/5	1/5	2/5
	level 1 2,3m	5/5	5/5	5/5
	level 2 3,9m	4/5	4/5	4/5

Extra tests - Ambient warehouse with dry products

RFID position_upper side & Flight way_Straight

	1st Replicate		2nd Replicate		3rd Replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	
Tag 7	✓		✓		✓	
Tag 8	✓		✓		✓	
Tag 9	✓		✓		✓	
Tag 10	✓		✓		✓	

RFID position_underside & Flight way_Straight

	1st Replicate		2nd Replicate		3rd Replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	
Tag 7	✓		✓		✓	
Tag 8	✓		✓		✓	
Tag 9	✓		✓		✓	
Tag 10	✓		✓		✓	

Extra tests – Chilled warehouse with liquid products

RFID position_upper side & Flight way_Straight

	1st Replicate		2nd Replicate		3rd Replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	
Tag 7	✓		✓		✓	
Tag 8	✓		✓		✓	
Tag 9	✓		✓		✓	
Tag 10	✓		✓		✓	

RFID position_underside & Flight way_Straight

	1st Replicate		2nd Replicate		3rd Replicate	
Tag	Read	No read	Read	No read	Read	No read
Tag 1	✓		✓		✓	
Tag 2	✓		✓		✓	
Tag 3	✓		✓		✓	
Tag 4	✓		✓		✓	
Tag 5	✓		✓		✓	
Tag 6	✓		✓		✓	
Tag 7	✓		✓		✓	
Tag 8	✓		✓		✓	
Tag 9	✓		✓		✓	
Tag 10	✓		✓		✓	

Appendix D – Results of Second set of laboratory tests

A) Case Study 1: Ambient warehouse with dry products

A/A	UAV tag reading method	Tag Location	UAV speed	Number of levels	1st replicate Time (sec)	1st replicate Accurancy	2nd replicate Time (sec)	2nd replicate Accurancy	3rd replicate Time (sec)	3rd replicate Accurancy
1	Along a rack	Back side	0,5 m/s	1 level	104,38	32/32	109,24	32/32	109,68	32/32
2	Along a rack	Back side	0,5 m/s	2 levels	48,76	32/32	49,38	32/32	49,28	32/32
3	Along a rack	Back side	1 ,5 m/s	1 level	61,48	32/32	62,14	32/32	62,28	32/32
4	Along a rack	Back side	1 ,5 m/s	2 levels	28,34	32/32	28,48	32/32	28,72	32/32
5	Along a rack	Front side	0,5 m/s	1 level	103,36	32/32	110,20	32/32	108,74	32/32
6	Along a rack	Front side	0,5 m/s	2 levels	47,26	32/32	47,44	32/32	47,36	32/32
7	Along a rack	Front side	1 ,5 m/s	1 level	59,12	32/32	64,54	32/32	62,86	32/32
8	Along a rack	Front side	1 ,5 m/s	2 levels	27,38	32/32	28,34	32/32	27,86	32/32
9	Across racks	Back side	0,5 m/s	1 level	51,69	32/32	54,12	32/32	54,34	32/32
10	Across racks	Back side	0,5 m/s	2 levels	23,53	32/32	23,84	32/32	23,79	32/32
11	Across racks	Back side	1 ,5 m/s	1 level	30,24	32/32	30,57	32/32	30,64	32/32
12	Across racks	Back side	1 ,5 m/s	2 levels	13,32	32/32	13,39	32/32	13,51	32/32
13	Across racks	Front side	0,5 m/s	1 level	51,18	32/32	54,60	32/32	53,87	32/32
14	Across racks	Front side	0,5 m/s	2 levels	22,78	32/32	22,87	32/32	22,83	32/32
15	Across racks	Front side	1 ,5 m/s	1 level	29,06	32/32	31,77	32/32	30,93	32/32
16	Across racks	Front side	1 ,5 m/s	2 levels	12,84	32/32	13,32	32/32	13,08	32/32

B) Case Study 2: Chilled warehouse with liquid products

A/A	UAV tag reading method	UAV speed	Number of levels	1st replicate		2nd replicate		3rd replicate	
				Time (sec)	Accurancy	Time (sec)	Accurancy	Time (sec)	Accurancy
1	Along a rack	0,5 m/s	1 level	125,60	32/32	125,84	32/32	126,40	32/32
2	Along a rack	0,5 m/s	2 levels	50,70	32/32	51,70	32/32	52,50	32/32
3	Along a rack	1 ,5 m/s	1 level	84,60	32/32	74,16	32/32	77,98	32/32
4	Along a rack	1 ,5 m/s	2 levels	30,08	32/32	30,44	32/32	32,54	32/32
5	Across racks	0,5 m/s	1 level	62,30	32/32	62,42	32/32	62,70	32/32
6	Across racks	0,5 m/s	2 levels	24,50	32/32	25,00	32/32	25,40	32/32
7	Across racks	1 ,5 m/s	1 level	41,80	32/32	36,58	32/32	38,49	32/32
8	Across racks	1 ,5 m/s	2 levels	14,19	32/32	14,37	32/32	15,42	32/32