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Design, development and testing of Vision Picking Technology

MRes. thesis by
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MRes thesis publications

Journal Publications

- Gialos, A. & Zeimpekis, V. (2020) ‘Vision picking technology: Defining design parameters via a systematic literature review’, International Journal of Logistics Systems and Management, Vol. 11, No. 1, pp. xx - xx.

- Gialos, A. & Zeimpekis, V. (2020) ‘Testing vision picking technology in warehouse operations: Evidence from laboratory experiments’, International Journal of Industrial Engineering and Management *(In press)*.

Chapters in Edited volumes

- Gialos, A. & Zeimpekis, V. (2020) 'Defining and testing system parameters for enhancing vision picking technology in warehouse operations', in V. Zeimpekis, E. Aktas, M. Bourlakis, I. Minis (eds.), Supply Chain 4.0: Improving Supply Chains with Analytics and Industry 4.0 Technologies, Kogan Page Publications, UK, ISBN: 978-1789660753

- Gialos, A. & Zeimpekis, V. (2019) 'The role of digital technologies in Logistics operations', in G. Doukidis (ed.), The Digital Future, Sideris Publications, GR, ISBN: 978-9600808346

Conference Publications

- Gialos, A. & Zeimpekis, V. (2019), ‘State-of-the-art and definition of key design parameters for the development and testing of vision picking technology in warehouse operations’, *30th European Conference on Operational Research (EURO)*, Dublin, Ireland, 23 – 26 June.

- Gialos, A. & Zeimpekis, V. (2019), ‘Testing vision picking technology in warehouse operations: Evidence from laboratory experiments’, *25th International Joint Conference on Industrial Engineering and Operations Management (IJCIEOM)*, Novi Sad, Serbia, 15 – 17 July.

Executive Summary

Over the last years the complexity of warehouse operations has increased significantly due to the increase of e-commerce, customer requests for frequent and low volume order fulfillment as well as the need for faster response times. Although all warehouse processes are critical and affect both customer service and the total logistics cost, order picking process contributes highly (55% to 65%) to the total operational warehouse costs and plays a pivotal role in customer service level. The development of information systems during the last decades brought a remarkable number of applications in product picking process such as RF-scanner, voice and light picking. Yet, there is still a need for better productivity and less operational cost and vision picking through smart glasses and augmented reality may be a promising technology. The latter uses wearable technology and vision-guided picking to produce faster, hands-free and accurate picking solution for industrial operations.

The aim of this thesis is to design and a vision picking system that can be used for product picking in a warehouse facility. More specifically, the first objective of this thesis was to review a set of parameters that can be taken into consideration for vision picking system design, development and testing. The second objective focused on the selection of the most appropriate parameters for testing vision picking system, while the third dealt with the conduction of laboratory tests for the evaluation and assessment of vision picking system in terms of order picking time (efficiency), accuracy and workload.

The review of parameters was conducted by using the Systematic Literature Review (SLR) approach. The latter embraces, a three-step review phase and takes into consideration a series of inclusion criteria for the identification of research articles. Overall, 44 articles were reviewed, but the final corpus involved 20 of them. It is worth mentioning that the number of published papers is limited in this research area and this is may be a representative sign that the field is quite promising from a research point of view. Based on the reviewed papers, 20 parameters were identified for vision picking system design, development and testing. Subsequently, these parameters were

classified into three categories, namely: a) system parameterization, b) operational performance and, c) comparative assessment with other picking systems. The first category deals with the device design and development and includes 14 reviewed parameters. The second category comprises 3 parameters which concern the testing of the performance of the vision picking system in the industrial environment and the third category encompasses 3 parameters which are used for the comparison of vision picking system with other picking systems in the industrial environment.

Due to the high number of parameters of the first category (system parameterization), the 14 parameters were classified into three different sub-categories. The first sub-category deals with the ergonomic aspects and involves 4 parameters, the second focuses on visualization aspects and includes 6 parameters, while the third sub-category is associated with technical aspects and encompasses 4 parameters.

In order to select the parameters that would be tested in laboratory environment, the Analytic Hierarchy Process (AHP) was adopted. The latter methodology was applied via a questionnaire that was initially constructed by the research team and subsequently filled in by 15 experts located in Greece who work in logistics service providers, as well as in companies with in-house logistics. The aim of that process was to rank the parameters that would be taken into consideration for system testing. Three parameters (i.e. Display Holder, Field of View, Barcode Type) were initially selected from this process. Furthermore, one more parameter (i.e. existence of confirmation) which deals with the operational performance of vision picking process was considered based on the input received by logistics executives. The latter was included in the set of parameters that were tested in laboratory environment, since it affects both the acceptance of the system, by the end users as well as the performance of the system.

The testing of vision picking system was accomplished via a series of laboratory tests that were conducted by adopting the Design of Experiments (DoE) methodology. A full factorial design has been used that incorporates 4 factors at two levels (2^4 full factorial design). Eighty (80) tests were conducted in order to identify the optimal setup of the proposed vision picking system both in terms of order picking efficiency and accuracy.

Furthermore, the perceived workload of vision picking system was evaluated via NASA TLX survey.

The results of the study revealed that the performance of vision picking system can be affected significantly from certain factors. In terms of order picking time, the results indicated that the only parameter that was statistically significant (based on the ANOVA results) was the “existence of confirmation”. Indeed, vision picking process without confirmation step can improve the order picking time, when compared to the vision picking process with confirmation step. In terms of order picking accuracy, the results showed that a 2-way interaction (i.e. “Field of View*Existence of confirmation”). In this case, the best configuration for high levels of accuracy, is achieved when the display is set to “below of line of sight” and confirmation step exists. In terms of perceived workload, the NASA TLX score showed that the workload was adequate when compared with similar studies. While focusing on the individual subscales of NASA TLX score, the physical demand and frustration level have the highest score, followed by mental demand, temporal demand, effort and performance.

Executive Summary in Greek
(Επιτελική σύνοψη)

Τα τελευταία χρόνια η πολυπλοκότητα κατά τη διάρκεια εκτέλεσης των διαδικασιών εντός των αποθηκευτικών χώρων έχει αυξηθεί σημαντικά, εξαιτίας της ραγδαίας αύξησης του ηλεκτρονικού εμπορίου, των απαιτήσεων των πελατών για συχνές και μικρές παραγγελίες καθώς επίσης και της απαίτησης για πολύ μικρούς χρόνους ανταπόκρισης. Παρά το γεγονός ότι όλες οι διαδικασίες ενός αποθηκευτικού χώρου είναι εξίσου σημαντικές και επηρεάζουν το επίπεδο εξυπηρέτησης των πελατών καθώς επίσης και το λειτουργικό κόστος, είναι σημαντικό να αναφερθεί ότι η διαδικασία της συλλογής παραγγελιών αποτελεί την πιο ακριβή διαδικασία, δεδομένου ότι συμβάλει στο λειτουργικό κόστος σε ποσοστό που αγγίζει το 55% - 65% του συνολικού λειτουργικού κόστους που προκύπτει απ’ όλες τις διαδικασίες μιας εγκατάστασης logistics. Η ανάπτυξη των πληροφοριακών συστημάτων κατά τη διάρκεια των τελευταίων δεκαετιών, συνέβαλε στην εμφάνιση μιας σειράς αξιόλογων τεχνολογιών και συστημάτων για τη συλλογή των παραγγελιών (π.χ. συλλογή παραγγελιών με τη χρήση τερματικών συσκευών, με τη χρήση φωνητικών εντολών και με τη χρήση φωτεινών ενδείξεων). Παρ’ όλα αυτά, υπάρχει ακόμη η ανάγκη για την υιοθέτηση μιας τεχνολογίας/συστήματος που θα έχει τη δυνατότητα να αυξήσει την παραγωγικότητα και να μειώσει το ποσοστό λαθών κατά τη διάρκεια συλλογής των παραγγελιών. Με βάση τη βιβλιογραφία καθώς επίσης λαμβάνοντας υπόψη μια σειρά απο μελέτες, διαφαίνεται ότι η τεχνολογία της συλλογής παραγγελιών με τη χρήση της όρασης (Vision picking) αποτελεί μια πολλά υποσχόμενη τεχνολογία, δεδομένου ότι μπορεί να προσφέρει πιο γρήγορη συλλογή παραγγελιών, με λιγότερα λάθη και με υψηλό βαθμό ελευθερίας των χεριών των εργαζόμενων συλλογής παραγγελιών.

Ο βασικός σκοπός της παρούσης διπλωματικής αφορά στο σχεδιασμό ενός συστήματος συλλογής παραγγελιών, με τη χρήση της όρασης, το οποίο θα μπορεί να χρησιμοποιείται σε εγκαταστάσεις logistics. Για την επίτευξη του αρχικού σκοπού είναι απαραίτητο να επιτευχθεί μια σειρά απο επιμέρους στόχους. Ο πρώτος στόχος αφορά στον εντοπισμό μιας σειράς παραμέτρων (μέσω βιβλιογραφικής επισκόπησης), οι οποίες μπορούν να

χρησιμοποιηθούν κατά τη διάρκεια των σταδίων σχεδιασμού, ανάπτυξης και αξιολόγησης / ελέγχου της εν λόγω τεχνολογίας/συστήματος. Ο δεύτερος στόχος, εστιάζει στην αξιολόγηση και επιλογή μιας σειράς παραμέτρων, προκειμένου να χρησιμοποιηθούν για την αξιολόγηση της εν λόγω τεχνολογίας, ενώ ο τρίτος στόχος σχετίζεται με την αξιολόγηση της τεχνολογίας μέσω μιας σειράς εργαστηριακών δοκιμών στα πλαίσια των οποίων θα μετρηθεί η αποδοτικότητα του συστήματος σε επίπεδο α) χρόνου ολοκλήρωση συλλογής παραγγελιών, β) ακρίβειας παραγγελίας και γ) φόρτου εργασίας.

Η καταγραφή των παραμέτρων πραγματοποιήθηκε μέσω της μεθοδολογίας της συστημικής βιβλιογραφικής επισκόπησης, κατά την εφαρμογή της οποία λαμβάνονται υπόψη μια σειρά απο κριτήρια μέσω των οποίων πραγματοποιείται ο εντοπισμός των σχετικών άρθρων. Με τη εφαρμογή της προαναφερθείσας μεθοδολογίας, εντοπίσηκαν συνολικά 44 άρθρα στη βιβλιογραφία, ωστόσο μόνο τα 20 από αυτά ήταν συναφή με το αντικείμενο της εν λόγω διπλωματικής. Σε αυτό το σημείο είναι σημαντικό να αναφερθεί ότι ο περιορισμένος αριθμός δημοσιευμένων άρθρων σχετικά με το αντικείμενο που μελετάται στην παρούσα διπλωματική, αποτελεί σημάδι ότι το συγκεκριμένο αντικείμενο/πεδίο έρευνας δεν έχει μελετηθεί επαρκώς και είναι αρκετά ενδιαφέρον και πολλά υποσχόμενο για περαιτέρω έρευνα και μελέτη τα επόμενα έτη.

Εστιάζοντας στα αποτελέσματα της βιβλιογραφικής επισκόπησης και εφαρμόζοντας τη μεθοδολογία της συστημικής βιβλιογραφικής επισκόπησης εντοπίστηκαν συνολικά 20 παράμετροι για το σχεδιασμό, ανάπτυξη και αξιολόγηση της τεχνολογία / συστήματος συλλογής παραγγελιών με τη χρήση της όρασης. Στη συνέχεια, οι εν λόγω παράμετροι κατηγοριοποιήθηκαν σε τρεις κατηγορίες. Οι κατηγορίες που χρησιμοποιήθηκαν είναι: α) παραμετροποίηση συστήματος, β) λειτουργική αποδοτικότητα συστήματος και γ) συγκρητική αξιολόγηση συστήματος με άλλα συστήματα συλλογής παραγγελιών. Η πρώτη κατηγορία σχετίζεται με το σχεδιασμό και την ανάπτυξη του συστήματος και περιλαμβάνει 14 παραμέτρους. Η δεύτερη κατηγορία αφορά στη αξιολόγηση του συστήματος σε πραγματικό περιβάλλον εργασίας και περιλαμβάνει 3 παραμέτρους, ενώ η τρίτη κατηγορία περιλαμβάνει 3 παραμέτρους, οι οποίοι χρησιμοποιούνται για τη συγκρητική αξιολόγηση του υπό εξέταση συστήματος με άλλα συστήματα συλλογής παραγγελιών, σε πραγματικό περιβάλλον εργασίας. Εξαιτίας του υψηλού αριθμού παραμέτρων στην πρώτη κατηγορία, οι 14 παράμετροι κατηγοριοποιήθηκαν περαιτέρω σε 3 υποκατηγορίες. Η πρώτη υποκατηγορία σχετίζεται με θέματα εργονομίας και περιλαμβάνει 4 παραμέτρους, η δεύτερη εστιάζει σε θέματα απεικόνισης και περιλαμβάνει 6 παραμέτρους, ενώ η τρίτη υποκατηγορία σχετίζεται με τεχνικά θέματα και περιλαμβάνει 4 παραμέτρους.

Μετά την ολοκλήρωση της συστημικής βιβλιογραφικής επισκόπησης, το επόμενο στάδιο αφορά στη αξιολόγηση των παραμέτρων που εντοπίστηκαν και στην επιλογή των σημαντικότερων παραμέτρων για την αξιολόγηση του συστήματος. Πράγματι, λαμβάνοντας υπόψη τις αρχές της διαδικασίας αναλυτικής ιεράρχησης, όλες οι παράμετροι της πρώτης κατηγορίας αξιολογήθηκαν μέσω συγκεκριμένων ερωτηματολογίων από 15 στελέχη εταιριών που δραστηριοπούνται σε ελληνικές εμπορικές, παραγωγικές και εταιρίες παροχής υπηρεσιών logistics και εξειδικεύονται σε διαδικασίες logistics. Με βάση τα αποτελέσματα της αξιολόγησης, επιλέχθηκαν συνολικά 4 παράμετροι για την αξιολόγηση του συστήματος συλλογής παραγγελιών μέσω όρασης. Οι παράμετροι που επιλέχθηκαν είναι οι εξής: α) τύπος εξοπλισμού συγκράτησης της οθόνης στο κεφάλι του εργαζόμενου, β) θέση οθόνης σε σχέση με το οπτικο πεδίο του εργαζόμενου, γ) τύπος γραμμωτού κώδικα που χρησιμοποείται και δ) δυνατότητα ύπαρξης επιβεβαίωσης της συλλογής των τεμαχίων κατά την τοποθέτηση στο καρότσι συλλογής.

Το επόμενο στάδιο μετά τη αξιολόγηση και επιλογή των παραμέτρων, αφορά στην αξιολόγηση του υπό εξέταση συστήματος συλλογής παραγγελιών, μέσω μιας σειράς εργαστηριακών δοκιμών και υιοθετώντας τη μεθοδολογία και τις αρχές του πειραματικού σχεδιασμού και της στατιστικής ανάλυσης. Για το σχεδιαμό των πειραμάτων χρησιμοποιήθηκε ένας πλήρης παραγοντικός σχεδιασμός (full factorial design). Ο παραγοντικός σχεδιασμός περιελάμβανε 4 παράγοντες / παραμέτρους σε 2 επίπεδα (2^4 πλήρης παραγοντικός σχεδιασμός). Αναλυτικότερα, κατά τη διάρκεια των πειραμάτων αξιολόγησης του συστήματος, πραγματοποιήθηκαν 80 επαναληπτικές δοκιμές προκειμένου να καθοριστούν οι ιδανικοί συνδυασμοί ανάμεσα στις παραμέτρους και στα επίπεδά τους. Για τον καθορισμό των βέλτιστων συνδυασμών το σύστημα αξιολογήθηκε σε επίπεδο α) χρόνου ολοκλήρωση συλλογής παραγγελιών, β) ακρίβειας παραγγελίας και γ) φόρτου εργασίας. Για την αξιολόγηση του φόρτου εργασία χρησιμοποιήθηκε η μεθοδολογία του δείκτη μέτρησης του φόρτους εργασίας (NASA-TLX).

Τα αποτελέσματα τα οποία προέκυψαν από τη στατιστική ανάλυση, μετά την ολοκλήρωση των πειραμάτων, δείχνουν ότι η απόδοση του συστήματος συλλογής παραγγελιών μπορεί να επηρεαστεί (στατιστικά σημαντικά) από ορισμένες παραμέτρους. Όσον αφορά το χρόνο ολοκλήρωσης παραγγελιών, τα αποτελέσματα έδειξαν ότι η μόνη παράμετρος που ήταν στατιστικά σημαντική (βάσει των αποτελεσμάτων της ANOVA) ήταν η *"δυνατότητα ύπαρξης επιβεβαίωσης"*. Πράγματι, στη περίπτωση όπου δεν υπήρχε επιβεβαίωση κατά τη διάρκεια της διαδικασίας συλλογής των τεμαχίων, ο χρόνος ολοκλήρωσης των παραγγελιών ήταν αρκετά συντομότερος σε σχέση με την περίπτωση όπου κατά τη διάρκεια συλλογής των τεμαχίων ο εργαζόμενος έπρεπε να επιβεβαιώνει τη συλλογή κάθε τεμαχίου που τοποθετούσε στο καρότσι συλλογής. Σε επίπεδο ακρίβειας (ρυθμός λαθών) κατά τη διάρκεια συλλογής των παραγγελιών, τα αποτελέσματα έδειξαν ότι υπάρχει αμφίδρομη αλληλεπίδραση ανάμεσα σε δυο παραμέτρους *("θέση οθόνης σε σχέση με το οπτικό πεδίο του εργαζόμενου * δυνατότητα ύπαρξης επιβεβαίωσης")*. Λαμβάνοντας τα αποτελέσματα τα οποία σχετίζονται με τις παραπάνω παραμέτρους καθώς επίσης και με τα αντίστοιχα επίπεδά τους, προκύπτει ότι το υψηλότερο επίπεδο ακρίβειας παραγγελιών επιτεύχθηκε όταν το επίπεδο της παραμέτρου "θέση οθόνης σε σχέση με το οπτικό πεδίο του εργαζόμενου" ήταν κάτω από το οπτικό πεδίο του εργαζόμενου και το επίπεδο της παραμέτρου " δυνατότητα ύπαρξης επιβεβαίωσης" ήταν με ύπαρξη επιβεβαίωσης. Όσον αφορά το εκτιμώμενο φόρτο εργασίας κατά τη διάρκεια συλλογής των παραγγελιών, σύμφωνα με τη βαθμολογία του δείκτη μέτρησης του φόρτους εργασίας (NASA-TLX), προκύπτει ότι ο φόρτος εργασίας ήταν σε ικανοποιητικό επίπεδο σε σύγκριση με την αντίστοιχη βαθμολογία που παρουσιάζεται σε παρόμοιες μελέτες.

Contents

List of Figures

List of Tables

Chapter 1. Introduction

This chapter initially presents the rationale of this research as well as the importance of order picking process in warehouse operations. Subsequently the aim and the objectives, as well as the research methodology of this thesis are described. The chapter concludes with the structure of this thesis.

1.1. Rationale

Warehousing constitutes a critical process of modern logistics and supply chains. Over the last years the complexity and requirements of warehousing have increased due to a series of factors such as an increase in e-commerce sales and international competition, the demand for frequent and low volume order fulfillment and the customers' need for faster response time (Marchet *et al*., 2015; Lu *et al*., 2016). The main objectives of modern warehouses include the ability to tackle the aforementioned challenges in order to increase their productivity and agility, since underperformance may result in high cost and lower customer service levels (van Gils *et al.,* 2018). The optimization of warehouse operations and the reduction of costs is a difficult task for the warehouse managers, because most warehouses are manually operated, resulting in delivering labor-intensive services to their customers (van Gils *et al.,* 2018).

All warehouse processes such as receiving, put-away, order picking, packaging, and shipping affect the logistics cost, but the order picking process has a significant impact on both the overall logistics costs as well as on customer service (Marchet *et al.,* 2015). Order picking is the warehouse activity during which a number of goods are retrieved from a warehouse system in order to fulfill customer orders (Goetschalckx and Ashayeri, 1989). For warehouses with manual systems[1], order picking is the most labor-intensive operation in warehouses and accounts for no less than 55% to 65% of the total operational warehouse costs (Theys *et al.,* 2010), while for warehouses with automated systems[2], order picking is a very capital intensive operation because of the high investment costs (Tompkins *et al.,* 2011; Chen *et al.,* 2016). The main factors for this

[1] Manual order picking systems are based on paper picking lists and/or barcode reading (Marchet *et al.,* 2015)

[2] Automated order picking systems deal with AR/AS systems, robotic mobile fulfillment systems (Azadeh *et al.,* 2017; Calzavara *et al.,* 2019) and Automated Guided Vehicles (Roodbergen and Vis, 2009).

increased cost include travelling time among the aisles, as well as the waiting time in front of the pick faces (Richards, 2014). For these reasons, order picking is characterized by professionals as the highest priority area for productivity improvements (de Koster *et al.,* 2007). Indeed, improvements in the efficiency of order picking could directly lead to time and cost savings, and indirectly improve the customer service level and thus the entire supply chain performance (Chen *et al.,* 2016).

Taking into consideration the significance of order picking, a number of studies have dealt with the optimization of the order picking process, focusing on layout design, storage assignment, zoning, batching and routing methods (de Koster *et al.,* 2007; Chen *et al.,* 2016). Furthermore, according to Dallari *et al.,* (2009), the type and characteristics of products, the number and size of orders, the types of functional areas, the material handling equipment and the operating policies are also important parameters which have been considered for the selection and optimization of a manual order picking system. Apart from the manual order picking systems, during the last years the adoption of automated order picking systems (e.g. AR/AS systems or Automated Guided Vehicles) is another approach for time and cost savings as well as errors reduction (Hou *et al.,* 2009). Nevertheless, the investment cost, the interrupting warehouse operation during the implementation period, the loss of flexibility in the long term and the fulfillment of safety standards are some of the most common barriers for the development of automated or semi-automated technical solutions in order to support picking operations *(Hackman et al.,* 2001).

Focusing on the pickers-to-goods system, which is the most widespread order picking system in Western Europe (van Gils *et al.,* 2018), the development of information technologies during the last decades, has brought a remarkable number of ICT-based applications and systems (e.g. Pick-by-Light Systems, Pick-by-Voice Systems, A-Frame, etc.) which support the picking process. During the last decades, these systems have managed to update the traditional order picking systems which are based on paper picking lists or barcode reading (Marchet *et al.,* 2015). Nevertheless, the recent trend in logistics facilities (e.g. distribution centers) is the acceptance of late orders and the direct delivery within tight time windows. This trend, has brought a series of challenges for logistics companies word-wide, since it led to the reduction of available time for order picking and to an increased possibility for errors in terms of order accuracy and completeness.

To this end, a growing number of companies have turned their interest to digitalization by adopting novel systems and smart applications along their business processes in order to handle the growing challenges of cost efficiency, flexibility, adaptability, stability, customer service, and sustainability (Wang *et al.,* 2016). This emerging trend of automation technologies and the use of advanced Information Technology (IT) systems and smart applications increase the productivity and provide a wide range of opportunities and benefits for the logistics sector which represents an appropriate application area for new technologies and applications (Olivares *et al.,* 2015; Hofmann and Rüsch, 2017). Especially, in order picking process the use of vision picking through smart glasses and augmented reality can support both time efficiency and picking accuracy (Hanson *et al.,* 2017).

Vision Picking with Augmented Reality (AR) which includes picking using wearable technology combines the very best of vision-guided picking so as to produce a faster, hands-free solution for industrial environments. The combination of real-world and virtual information provides speed and accuracy beyond previous warehouse picking systems (Stoltz *et al.,* 2017). Vision picking is a promising order picking technology but is still at an early stage. To this end, it is necessary to identify and investigate the key parameters which will support vision picking system to become an attractive order picking technology for industrial environments.

1.2. Scope and Objectives

The main aim of this thesis is the design, development and testing of vision picking system. The objectives are as follows:

- Conduction of literature review for the identification of parameters which are taken into consideration during the parameterization of the vision picking device, the evaluation of the operational performance of the vision picking system, and the comparative assessment of vision picking system with other order picking systems.

- Evaluation, ranking and final selection of parameters which are taken into consideration during the testing of vision picking system.
- Laboratory tests for the evaluation and optimization of the vision picking device 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 a systematic literature review (SLR) for the parameters elicitation and system design and development. The second method deals with Analytical Hierarchy Process (AHP) for the evaluation and ranking of identified parameters laboratory, while the third method focuses on laboratory (Lab) tests for system testing and evaluation.

The combination of three methods which is followed in this thesis, can overcome the potential bias and sterility of single method approaches and is known as triangulation (Collis and Hussey, 2003). More specifically, in this thesis the methodological triangulation has been considered by taking into consideration the four different types of triangulation (data, investigator, theory and mythological) which Denzin (1978) describes. As it can be seen in Table 1.1, a three-phase methodologically triangulated research is adopted in order to design, develop and testing the vision picking system.

Table 1.1 The three-phased triangulated research methodology

Phase	Method	Output
1	Systematic literature review (SLR) of parameters for System parameterization, Operational performance, Comparative assessment	Parameters identification for system design and development
2	Analytical Hierarchy Process (AHP) for the evaluation and ranking of identified parameters of Phase 1	Parameters Selection for system testing
3	Laboratory (Lab) Tests	Testing, evaluation and optimization of system by using the selected parameters of Phase 2

Phase 1 - Systematic Literature Review (SLR)

In the first phase the systematic literature review (SLR) was selected as a research method, combined with a series of research questions (RQ), which aimed at the identification, review and categorization of parameters in the field of vision picking system design and evaluation. 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. Furthermore, the SLR method provides a significant number of benefits in a field, aiming at identifying research gaps (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 it is implemented in a series of research fields 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.

Phase 2 - Analytical Hierarchy Process (AHP)

In the second phase, the evaluation and ranking of identified parameters was made by adopting the Analytical Hierarchy Process (AHP). AHP is a well-established methodology which was developed by Saaty in the 70's (Saaty, 1987) and supports the decision makers facing a complex problem with multiple conflicting and subjective criteria (Baswaraj *et al.,* 2018). AHP is one of the modern Multiple Criteria Decision Analysis (MCDA) tools which was developed in order to assess, prioritize, rank and evaluate decision choices and depends on the knowledge of experts (Baswaraj *et al.,* 2018). AHP compares alternatives solutions with reference to a criterion, in pair wise mode and resulting priorities may be utilized to compare and rank alternatives. Also, it is important to mention that AHP checks for consistency using consistency index (Kumar *et al.,* 2015). The implementation of AHP in real life scenarios does not require advanced knowledge of either mathematics or decision analysis (Baswaraj et al., 2018), while the simplicity and versatility of AHP accounts for its popularity (Promentilla et al., 2018).

Phase 3 - Design of Experiment (DoE) & Lab tests

In the second phase, a series of tests were designed and executed in laboratory environment. More specifically, the Design of Experiment (DoE) methodology has been adopted for the design of laboratory tests in order to assess the vision picking system's performance. More specifically, a full factorial design has been used for the tests performed that incorporates 4 factors at two levels (2^4 full factorial design). All possible combinations of these factors across their levels have been used in the design (Montgomery, 2012). The main output of this phase was the testing and evaluation of system in terms of order picking time, accuracy and workload.

1.4. Structure of thesis

The structure of this thesis is organized as follows:

Chapter 2 describes the features of the currently available order picking systems. A comparative assessment between conventional and innovative order picking systems is also conducted followed by a description of a series of similar studies which evaluate the performance of vision picking systems in terms of order picking time and accuracy (error rate).

Chapter 3 presents the results of the literature review conducted in vision picking design, development and testing parameters via the adoption of the Systematic Literature Review (SLR) methodology. Based on the results obtained, 20 critical parameters are identified into three categories, namely: a) system parameterization, b) operational performance and, c) comparative assessment with other picking systems.

Chapter 4 presents the ranking and selection of vision picking system design parameters by adopting the Analytical Hierarchy Process (AHP) methodology. The chapter describes the procedure as well as the results which are obtained by the evaluation of the proposed parameters performed by 15 experts who work in logistics service providers, as well as in commercial and manufacturing companies in Greece.

Chapter 5 discusses the evaluation results of the proposed vision picking system in terms of order picking efficiency and accuracy via a series of laboratory tests that were conducted by adopting the Design of Experiments (DoE) methodology. In this chapter, the methodology as well as the intermediate steps of this evaluation are presented followed by the selected factors and their levels that have been chosen for assessing the performance of the proposed system. 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. The remaining sections shows the statistical analysis of the test results.

Chapter 6 presents the assessment of the proposed system in terms of perceived workload. The chapter provides the theoretical background of NASA TLX technique, as well as the proposed implementation steps for the calculation of the total NASA TLX score. The chapter presents also the results obtained for our case and a benchmarking exercise that was made by comparing the results obtained with the results of similar studies.

Chapter 7 describes the managerial implications that stem from the adoption of vision picking system, the gaps that currently exist which are crucial both for further investigation as well as for insights into the needs of practitioners.

Finally, Chapter 8 presents the conclusions of this thesis as well as a future research agenda in this topic.

Chapter 2. Order picking systems: theoretical background

This chapter presents the currently available order picking systems with emphasis on vision picking systems. During the first section the characteristics, the productivity rates, the benefits as well as the inefficiencies of each available order picking technology are presented. Subsequently, the vision picking system is described in detail. More specifically, the importance as well as the operation and the types of vision picking systems are descripted followed by the presentation of the results of a series of studies which evaluate the vision picking system in comparison with other conventional order picking systems.

2.1. Conventional Order Picking systems

Picking is the most time and cost consuming process in a warehouse (Richards, 2014). Focusing on manuals order picking systems, as well as taking into account the Figure 2.1, it can be seen that the manual order picking systems can support pick rates of between 400 to 500 order lines per hour.

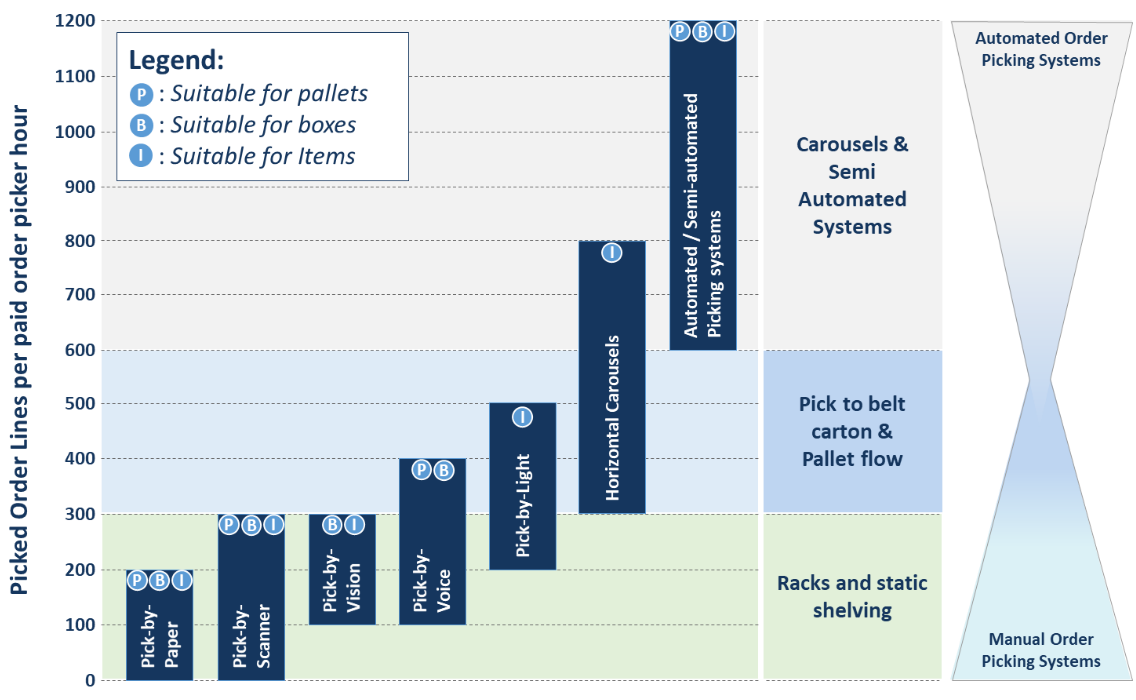


Figure 2.1 Order picking productivity per type of equipment and technology, adapted from (MWPVL, 2018)

For this range of order lines, a remarkable number of order picking systems are available. More specifically, a significant number of companies, continue to use paper picking lists, keeping the complexity as well as the error rate of process in high levels (Gialos and Zeimpekis, 2018). Typically, in a pick-by-paper system the picker uses a paper picking list in order to identify the location of each type of item, the number of items to be picked and the sequence in which the items will be picked (Weaver *et al.,* 2010). By following the guidelines which were described on the paper picking list, the picker collects the items from the shelves (picking shelves) and transports them to specific work stations for further processing (e.g. labelling, packaging, etc.). The use of paper lists is intuitive for human beings but laborious to handle (Reif, 2009; Schwerdtfeger *et al.,* 2009). Furthermore, the use of paper lists does not give the ability to pickers to confirm a correct pick, while the text-only picking lists can be difficult to read from pickers when product numbers are long (Guo *et al.,* 2015). Moreover, it is important to mention that the use of paper lists increased order picking time and does not provide a hands-free operation (Guo *et al.,* 2015), in order to reduce the level of ergonomics. Based on the above, it seems that Pick-by-paper is characterized by high percentage of errors and it is not a time efficient process (Weaver *et al.,* 2010), since 50% of a picker's time is consumed travelling, 20% searching, 15% picking, 10% in set up and 5% performing other tasks (Tompkins *et al.,* 2011). On the other hand, Pick-by-paper is a simple and easy to learn solution, while the implementation cost is low (Guo *et al.,* 2015).

In contrast to conventional systems, the modern systems do not involve any paperwork. Indeed, paperless systems such as pick by RF Scanning, pick by light, and pick by voice have been implemented in warehouses in order to increase the flexibility, efficiency and effectiveness and also to reduce the error rate and the waste from the use of paper (Reif and Günthner, 2009). These modern systems include mobile data entry devices which still have a remarkable handling effort but are usually connected in real-time to a Warehouse Management System (WMS) processing the data (Reif and Günthner, 2009). Focusing on the pickers-to-goods system, which is the most widespread order picking system in Western Europe (van Gils *et al.,* 2018), it is worth taking into consideration the features, as well as the advantages and disadvantages of such systems.

Pick-by-RF Scanner is one of the most widespread order picking technology which can be used in order to improve the traditional Pick-by-paper systems (Battini *et al.,* 2015). Instead of paper picking lists, handheld mobile data terminals (MDT) are used for the accomplishment of order picking. More specifically, the MDTs are equipped with barcode scanners and in most cases they are used to display the next pick and confirm a correct pick as it occurs (Weaver *et al.,* 2010), nevertheless there are some cases where this technology can be combined with a paper picking list. The only prerequisite in order to be apply this technology in a logistics facility is that all the stock keeping units (SKU) are necessary to be tagged with a barcode that is scanned by the operator during the order picking process (Battini *et al.,* 2015). To this point, it is important to mention that according to Battini *et al.,* (2015), handheld radio frequency identification (RFID) scanners are also available for more order picking time savings but in this case RFID tags should be placed in each SKU. To this end, it seems that this technology provides a shorter order picking time and reduced number of errors when compared with Pick-by-paper systems.

Alternatively, a Pick-by-voice system is a voice directed device that uses speech recognition to allow pickers to communicate with the WMS and execute the order picking process (Battini *et al.,* 2015). In this technology, the pickers are equipped with a headset and a microphone in order to receive and sent instructions which deal with the intermediate steps of order picking process as well as their actions for confirmation. This technology gives the necessary direction to the pickers in order to move from the previous to the next pick, and provides usable information to pickers (e.g. type of item, amount of items, etc.) (Starner, 2002). Furthermore, the primary advantages of this order picking technology are that pickers are hands-free and a worth mentioning rise in productivity (i.e. 10% - 15%) may be achieved when this system is compared with traditional systems (Marchet *et al.,* 2015). Unfortunately, picking by voice has low training ability and addresses difficulties in noisy industrial environments (medium ergonomics), as well as its implementation causes nagging by workers because they claim that they have to listen to a monotonous voice during their shift (Reif and Günthner, 2009).

Compared to voice support systems, pickers that use Pick-by-light systems are guided by lights that are installed on each storage compartment (Battini *et al.,* 2015). In addition, there are some cases where the lights are installed on the pick bins, which in most cases are mounted on carts (pick-to-cart) or are located, parametrically of a workstation (Guo *et al.,* 2015). Most Pick-by-light systems require that pickers have to press a button in order to confirm the picked quantity which is shown on small displays installed on the warehouse shelves or on the pick bins. Furthermore, in some more advanced systems, proximity or weight sensors sense a picker's actions and automatically proceed to the next pick or give a warn of an incorrect pick (Weaver *et al.,* 2010). The light picking approach is a costly solution (when compared to other methods), since there is a need for installation of displays into the shelf construction (Reif and Günthner, 2009). However light picking decreases picking errors, provides high levels of productivity and has a low training curve (Richards, 2014; Marchet *et al.,* 2015), thus pikers are getting familiarized with the system very quickly.

Despite the benefits of current systems, the development and the optimization of the information systems is a critical factor for the improvement of order picking process (Brynzér and Johansson, 1995). To this end, the emergence of the Internet of Things (IoT) as a result of the Fourth Industrial Revolution (Industry 4.0) has urged a significant number of industries to adopt smart systems and novel applications in order to digitalize and integrate their business processes (Gialos and Zeimpekis, 2018). Focusing on order picking process, the Vision picking (or Pick-by-Vision) technology is an innovative solution which may produce improved performance and perceive workload as compared to current order picking systems (Kim *et al.,* 2019).

2.2. Vision Picking and Augmented Reality (AR) Technology

Augmented Reality (AR) is a technology which can support the human visual sense and has a substantial potential for industrial applications (Reif *et al.,* 2010). Indeed, companies like Knapp, Picavi, Ittelligence and SAP, DHL, Generix and UBiMAX have initiated the development of AR solutions (Stoltz *et al.,* 2017; Kim *et al.,* 2019). Logistics is one of the most appropriate sector for the implementation of this technology (Cirulis and Ginters, 2013), while order picking is the most widespread warehouse operation wherein head-worn display (HWD) use has received growing attention during the last years (Friedrich, 2002; Kim *et al.,* 2019).

The Pick-by-Vision system, which uses wearable technology combines the very best of vision-guided picking to produce a faster, hands-free solution for industrial environments (Schwerdtfeger *et al.,* 2009). This order picking system uses smart glasses to merge virtual images and information with an operator's surrounding environment. The operator wears the glasses, follows the commands given, and scans product barcodes all within the glasses' display (Figure 2.2).

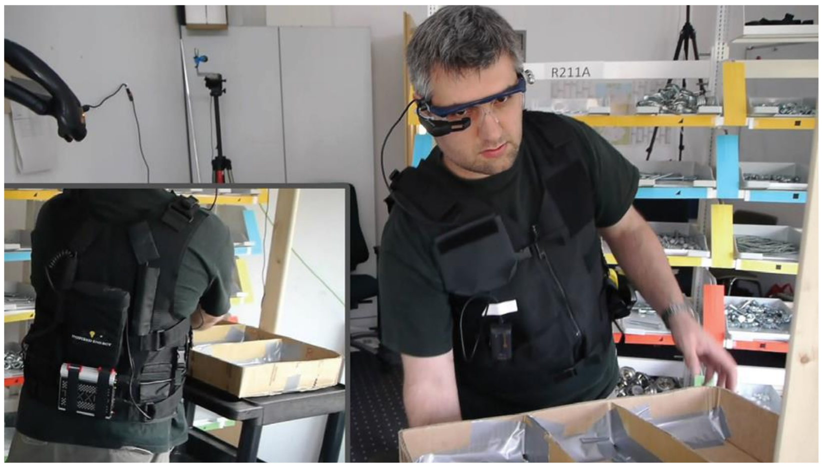


Figure 2.2 Pick-by-Vision by using Smart glasses, (Baumann et al., 2011)

Furthermore, it is worth mentioning that Pick-by-Vision systems can be supported with wearable AR or non-AR hardware platform such as Head Mounted Displays (HMDs) and Smart Glasses (Schwerdtfeger *et al.,* 2009; Weaver *et al.,* 2010). In the case of AR existence, the system can provide better guidance to pickers by using 3D arrows in order to show the way to the storage location and point at the picking unit (Reif and Walch, 2008). On the other hand, the existence of AR in these systems poses a series of problems, mainly due to the lack of adequate hardware, but also due to not yet resolved usability issues (Livingston *et al.,* 2005). Nevertheless, it is widespread that the combination of real-world and virtual information provides speed and accuracy beyond previous warehouse picking systems (Stoltz *et al.,* 2017).

The importance as well as the potential benefits of this innovative order picking technology, has led a significant number of researchers to conduct tests in order to compare the conventional order picking systems with the Pick-by-Vision technology in terms of order picking time, accuracy and workload. An indicative example are Reif and

Günthner, (2009) who evaluate a Pick-by-Vision system in a real storage environment. The results show that Pick-by-Vision was 4% faster than a paper based picking system, while the error rate for the paper list was seven times higher when compared to Pick-by-Vision. Also Schwerdtfeger *et al.,* (2009) mentions that Pick-by-Vision can increase the performance of a picker in terms of time and error rate, but the discomfort questionnaire shows that improvements of the display devices are necessary to reduce potential for headaches. Furthermore, the study shows that about 20% of subjects had serious problems using the HMD, an issue that was also observed in earlier studies. Recently, Wu *et al.,* (2015) have compared pick-by-light with pick-by-HUD (Head-Up Display). The results of the comparison show that pick-by-HUD was significantly faster and more accurate than pick-by-light. Apart from the lower time and error rate, pick-by-HUD had a lower workload than pick-by-light, as a result the participants tended to prefer it.

Taking into consideration the above, it seems that Pick-by-Vision is an emerging technology which has the potential to improve the order picking process with fewer errors and faster picking speed. However, based on current studies and evaluations of these systems it seems that the type of displays, as well as the User Interface (UI) design affect the perceived workload, usability, visual discomfort and job performance (Kim *et al.,* 2019), while it often causes concerns which deal with visual discomfort, eye-strain, headaches, dizziness, nausea, etc. (Patterson *et al.,* 2006).

To this end, it is critical for the improvement and optimization of this innovative technology to identify the parameters that can be taken into account by the researchers or other stakeholders during the phases of Pick-by-Vision system design and development. Also it will be useful to identify the parameters that could be used, in cases of comparative assessments with other order picking systems. This parameter identification (via a literature review process) will also contribute positively to the available literature which is quite limited in the field of Vision Picking and Augmented Reality (AR) Technology (Stoltz *et al.,* 2017).

2.3. Summary

This chapter presented various available order picking systems such as pick by RF-scanning, pick by voice, pick by light, etc. Subsequently, it was argued that despite the benefits of current picking systems, the development and the optimization of information systems for product picking is critical for the improvement of order picking process. It this thus concluded that there is a need for smart technologies and novel applications in order to improve the productivity and accuracy of the product picking process. By taking into consideration the current literature, vision picking (or Pick-by-Vision) systems seem to be an innovative solution which may produce improved performance and perceive workload as compared to current order picking systems.

Chapter 3. Literature review in vision picking design and development parameters

This chapter presents the results of the literature review conducted in vision picking design, development and testing parameters. For the review the Systematic Literature Review (SLR) methodology was adopted. Initially, the methodology for the selection of the most appropriate literature review approach is presented. Subsequently, the implementation steps as well as the procedure for implementing the SLR methodology are presented. Then, the descriptive analysis of the reviewed articles is made, while the chapter concludes with the presentation of the 20 critical parameters revealed by the review that are classified into three categories, namely: a) system parameterization, b) operational performance and, c) comparative assessment with other picking systems.

3.1. Selection of Literature Review method

In the current literature, not many articles are available regarding vision picking, especially when the aim is to identify system design parameters. It was important thus to adopt a specific literature review approach so as certain system design parameters to be identified and reviewed. Different types of literature review techniques are available, such as: systematic review, semi-systematic review, integrative review, etc (Snyder, 2019; Maditati et al., 2018). Depending on the purpose of the review, all types of available literature review techniques are helpful and suitable to reach a specific goal (Snyder, 2019). Table 3.1, presents the main criteria that can be taken into consideration for the selection of the most appropriate literature review approach.

Systematic literature review approach is used to synthesize research findings in a systematic, transparent, and robust way (Davis et al., 2014). Also this approach can be adopted for identifying and critically appraising relevant research, as well as for collecting and analyzing data from similar studies (Snyder, 2019).

Table 3.1 Main features of literature review approaches, (Snyder, 2019)

Approach	**Systematic**	**Semi-systematic**	**Integrative**
Typical purpose	Synthesize and compare evidence	Overview research area and track development over time	Critique and synthesize
Research questions	Specific	Broad	Narrow or broad
Search strategy	Systematic	May or may not be systematic	Usually not systematic
Sample characteristics	Quantitative articles	Research articles	Research articles, books, and other published texts
Analysis and evaluation	Quantitative	Qualitative/quantitative	Qualitative

On the other hand, the semi-systematic review approach is designed for topics that have been conceptualized differently and studied by various groups of researchers within diverse disciplines and that hinder a full systematic review process (Wong et al., 2013). Last but not least, the integrative review approach used to assess, critique, and synthesize the literature on a research topic in a way that enables new theoretical frameworks and perspectives to emerge (Torraco, 2005).

By taking into account the features of the most common literature review approaches, as well as by considering the objective of this research (i.e. Identification of relevant studies in order to collect data which deal with the system design parameters), the systematic literature review (SLR) was selected as the most suitable research method, coupled with a series of research questions (RQ), which aim at the identification, detection and categorization of parameters in the current scientific literature.

3.2. Implementation of Systematic Literature Review (SLR) method

The identification, detection and categorization of parameters for system design, development and testing is accomplished by using the systematic literature review (SLR) method. 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. To this end, taking into consideration the basic principles of the systematic literature review (SLR), as well as, the lack of available systematic analyses of the topic which this study deals with, the objective of the first step was to define the basic Research Questions (RQ).

The RQ1 addressed in this phase deals with the main parameters which are taken into consideration during the design of a device that is used for vision picking in a logistics facility. The RQ1 is presented below:

RQ1. *Which are the main parameters which are taken into consideration for a vision picking device parameterization?*

Another important element is the evaluation of efficiency as well as the optimization of the operation of this device. To this end, the RQ2 focuses on the parameters which are used by practitioners in order to run operations performance and thus to evaluate and optimize the vision picking system. Consequently, the RQ2 is described as following:

RQ2. *Which are the main parameters which are taken into consideration for the evaluation and optimization of vision picking systems in terms of operational performance?*

Finally, given the variety of order picking systems, the last objective of this phase is the identification of parameters for the evaluation and comparative assessment of vision picking system with alternative order picking systems in terms of the industrial environment. Thus the RQ3 is:

RQ3. *Which are the main parameters which are taken into consideration for the evaluation and comparative assessment of vision picking system in terms of the industrial environment?*

In order to answer the above RQs we use the systematic literature review (SLR) method. More specifically, we follow a three-step protocol based on previews prominent articles (Tranfield *et al.,* 2003; Touboulic and Walker, 2015; Lagorio *et al.,* 2016), in order to come up with a reliable and proven work. In particular, Figure 3.1 shows the steps of selecting a protocol, as well as the results of the systematic literature review.

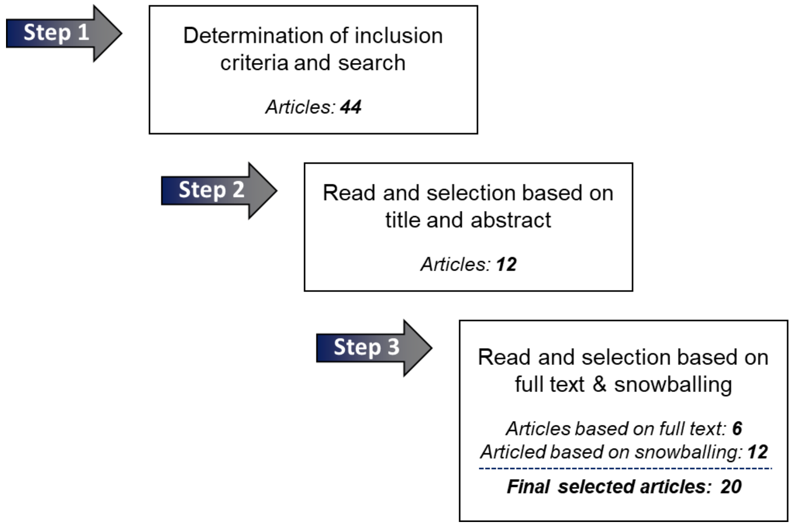


Figure 3.1 The steps of selecting protocol and the results of SLR

The steps of selecting protocol are described below:

Step 1: Determination of inclusion criteria and search

In order to achieve a comprehensive research, a series of search terms / keywords and induction criteria were determined during the first phase of this step. In this phase the concept of vision picking system is described with a series of synonyms. Also, in this step our research has focused on papers published in peer reviewed journals as well as in international conferences in the field of logistics. The main reason for the inclusion of articles from international conferences in this work is that the number of papers in peer reviewed journals which deal with the objective of this work is limited. Furthermore, it is worth mentioning that literature such as PhD dissertations, technical reports, etc. have been excluded from this work. All the above inclusion criteria that have been used for our search are presented in Table 3.2.

Table 3.2 Inclusion criteria for articles selection

Inclusion criteria	Description
Search terms / Keywords	Vision picking, Pick-by-vision, Wearable technology, Wearable computers. Order picking, Augmented reality, Head-mounted displays, Smart glasses, User interface
Document types	Articles
Source types	a) Peer-reviewed journals, b) International conferences
Language	English

Step 2: Read and selection based on title and abstract

In this step a review of selected papers (from step 1) has taken place based on the titles and abstracts of papers. During this review a series of papers out of the research scope were excluded from our list. More specifically, 32 papers focus on other issues than vision picking system (i.e. resource dimensions, storage assignment, batching, routing, etc.) and fields (i.e. vision picking for manufacturing, vision picking for health, etc.). After the completion of this step, the remaining number of articles was 12.

Step 3: Read and selection based on full text and snowballing

During the last step of the protocol, the reading of full versions of available papers as well the refining of our list took place. After the reading of full versions of candidate papers, 6 papers were excluded, because they were not in the scope of our research. In this phase, by taking into consideration the remaining papers, we checked the references of the selected papers and we added to our list the papers which met our inclusion criteria which were identified during the first step of protocol. To this end, our final corpus involved 20 papers.

Considering the corpus of 20 papers some descriptive statistics were first applied and then an analysis of papers took place, in order to classify the most important key parameters for vision picking system design, development and testing, on three categories: a) system parameterization, b) operational performance and, c) comparative assessment with other picking systems.

3.3. Descriptive analysis of the reviewed articles

Table 3.3 presents the results in terms of the number of papers resulting from the selection protocol in the systematic literature review (SLR). Based on this Table, 60% (12 papers) of the reviewed papers are conference papers, while only 40% (8 papers) account for journal papers. The low number of published papers and therefore the limited number of journal articles are representative signs, that the field is quite new from a research point of view. This seems to be confirmed by taking into consideration the time distribution of the reviewed studies.

Table 3.3 Overview of the reviewed articles

	Type of article	
	Journal	Conference
(Schwerdtfeger *et al.,* 2006)		●
(Reif and Walch, 2008)	●	
(Tumler *et al.,* 2008)		●
(Schwerdtfeger and Klinker, 2008)		●
(Reif and Günthner, 2009)	●	
(Schwerdtfeger *et al.,* 2009)		●
(Iben *et al.,* 2009)		●
(Reif *et al.,* 2010)	●	
(Weaver *et al.,* 2010)		●
(Grubert *et al.,* 2010)		●
(Schwerdtfeger *et al.,* 2011)	●	
(Baumann *et al.,* 2011)		●
(Baumann *et al.,* 2012)		●
(Krajcovic *et al.,* 2014)	●	
(Guo *et al.,* 2015)	●	
(Wu *et al.,* 2015)		●
(Hanson *et al.,* 2017)	●	
(Renner and Pfeiffer, 2017)		●
(Bräuer and Mazarakis, 2018)		●
(Kim *et al.,* 2019)	●	
Total:	**8**	**12**

Figure 3.2, illustrates graphically the time distribution by year of the selected articles. Based on the results of the figure below, it is evident that the years of publication among the identified publications vary from 2006 to 2019. The number of articles considering the design, development and testing of vision picking system has grown rapidly during the last years. Half of the considered articles are published in the last eight (8) years, indicating that the area is significantly expanding over the last few years. The peak in the number of papers is observed during the three-year period from 2008 to 2010, where 9 papers (3 journal papers and 6 conference papers) were published.

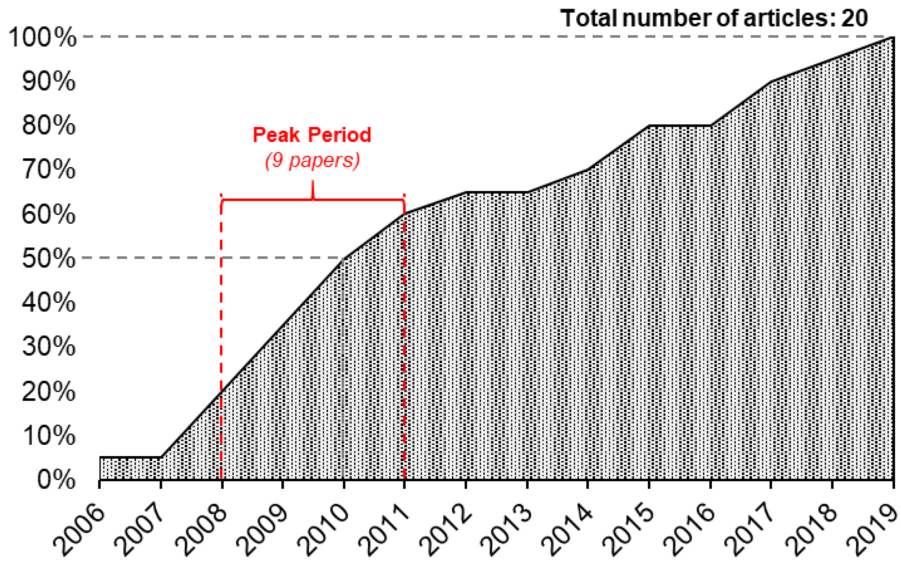


Figure 3.2 Time distribution of the review articles

Focusing on articles that have been published on peer-reviewed journals and by taking into consideration Table 3.4, it can be concluded that only seven journals have been used for the publication of eight (8) scientific articles. Also, it is worth mentioning that there is only one journal with more than one publication, while all the other journals have less than one publication.

Table 3.4 Number of papers per journal

Journal	No.
The visual Computer	2
Applied Ergonomics	1
Communications	1
Computer	1
Computer Graphics forum	1
Computer & Industrial Engineering	1
Virtual Reality	1

3.4. Parameters for vision picking design, development and testing

This section introduces a classification scheme in order to categorize the content of the selected articles. Figure 3.3 presents the three categories which are used in this overview chapter to categorize the reviewed parameters.

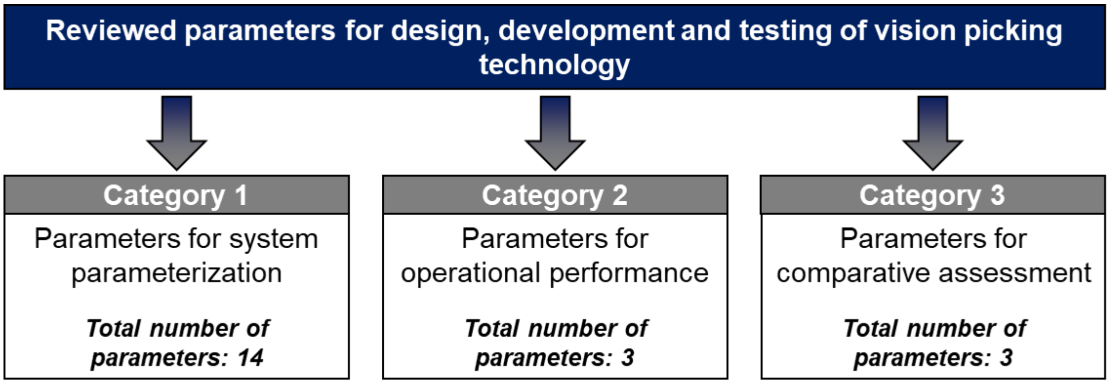


Figure 3.3 Classification scheme

The first category deals with the device design and development (*Category 1: Parameters for devise parameterization*) and includes fourteen (14) reviewed parameters. The second category comprises three (3) parameters which concern the testing of the performance of the vision picking system in the industrial environment (*Category 2: Parameters for operational performance*). Last but not least, the third category has to do with three (3) parameters which are used for the comparison of vision picking system with other picking systems in the industrial environment (*Category 3: Parameters for comparative assessment*). All the reviewed parameters are described and analyzed in the sections below.

3.4.1. Parameters for device parameterization

This section aims at identifying and classifying the parameters that are used for the design and development of a vision picking system. According to the literature review, it is observed that during the design and development of vision picking systems it is critical to take into consideration a series of parameters which affect the performance of the system. As it can be seen in Figure 3.4, these parameters can be classified in three different sub-categories. The first sub-category deals with the ergonomic aspects and involves four parameters (display type, interaction device, display holder and weight of equipment). The second focuses on visualization aspects and includes seven parameters (field of view, mounting option, information mode, information availability, display view, existence of Augmented Reality and display settings) while the third sub-category is associated with technical aspects and encompasses four parameters (barcode type, scanning distance, battery life and existence of tracking system).

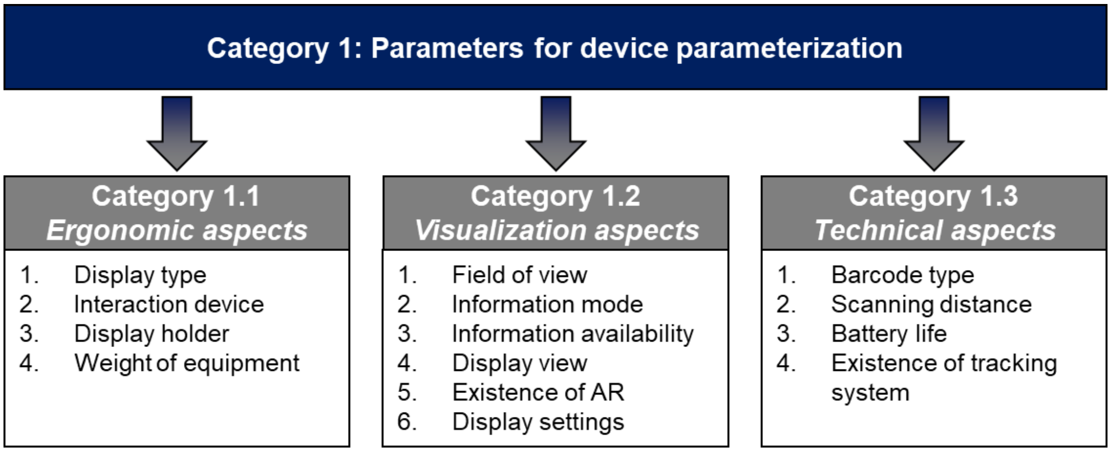


Figure 3.4 Classification of parameters for devise parameterization

Ergonomic aspects

The ergonomic aspects of device parameterization play a critical role during the design and development of the system because they deal with parameters which define how comfortable a worker would feel while using the system. The most crucial requirement is that the worker has to wear the equipment of vision picking during one shift. To this end, the vision picking equipment is necessary to be light, ergonomically designed, safe and with an eight-hour battery operation (Reif and Günthner, 2009).

The first parameter which affects the ergonomic aspects is the display type. According to Kim *et al.,* (2019), there are two different available display types. The first type contains binocular displays (Figure 3.5a) and the second type involves monocular displays (Figure 3.5b). By taking into consideration the results of Table 3.5, it can be concluded that monocular displays are more preferable, because they are less intrusive and lighter. On the other hand, some participants in tests support that the binocular displays are more comfortable and easier to focus (Kim *et al.,* 2019) but have a limited field of view.

(a) (b)

Figure 3.5 a) Binocular head-worn display, b) Monocular head-worn display, (Kim *et al.,* 2019)

Apart from the display type, one more important parameter is the interaction device, which is necessary for the picks confirmation, as well as for the input of zero crossing (pick area with out-of-stock). Considering the results of Table 3.5, there are two different devices that could be used for the vision picking. The first alternative is an adjusting knob or gesture control and the second one is speech input. An adjusting knob can be transferred easily to the user interface and is more suitable for industrial environments. On the other hand speech input provides a hands free interaction and is the most intuitive form of interaction for humans, but this technical solution faces a series of implementation difficulties in noisy environments (Reif and Günthner, 2009; Reif *et al.,* 2010).

One more parameter that has been mentioned is the type of display holder which depends on the design of the equipment. According to investigated studies, as well as by taking into consideration the available equipment that can be used for vision picking (Syberfeldt *et al.,* 2017), there are two different types of display holders. The first type is the glasses (smart glasses), while the second type is the headbands, which are worn on the head, using the suitable equipment (Stoltz *et al.,* 2017). Some of the most well-known glasses and headbands for vision picking are the followings: Google glasses, Vuzix M300, Epson Moverio BT-300, Microsoft HoloLens, RealWear HMT-1, etc. (Bräuer and Mazarakis, 2018). According to the results that are presented in Table 3.5, both types of display holders have been evaluated in a series of tests and according to Stoltz *et al.,* (2017), they provide a hands-free solution for the execution of the order picking process. The type of holder together with the total weight of equipment can affect the performance of pickers and are responsible for a series of problems that pose various restrictions for pickers when wearing the equipment. Indeed, some studies mention that heavy glasses pushed too hard on the nose and as a result are uncomfortable to wear (Velamkayala *et al.,* 2017;

Bräuer and Mazarakis, 2018) while some others support that the use of headbands are not comfortable and cause headaches (Schwerdtfeger *et al.,* 2009).

Table 3.5 Overview of parameters which deal with ergonomic aspects

	Display Type		Interaction Device		Display Holder		Weigh of Equipment
	Binocular	Monocular	Speech input	Knob / Gesture	Glasses	Headbands	
(Schwerdtfeger *et al.,* 2006)		●				●	
(Reif and Walch, 2008)			●	○	●		○
(Tumler et al., 2008)						●	
(Schwerdtfeger and Klinker, 2008)				●		●	
(Reif and Günthner, 2009)			●	●		●	○
(Schwerdtfeger *et al.,* 2009)				●		●	○
(Iben *et al.,* 2009)		●				●	
(Reif *et al.,* 2010)			●			●	○
(Weaver *et al.,* 2010)		●	●				
(Grubert *et al.,* 2010)				●		●	
(Schwerdtfeger *et al.,* 2011)			●	●		●	
(Baumann *et al.,* 2011)		●		●	●		
(Baumann *et al.,* 2012)					●		
(Krajcovic *et al.,* 2014)				●	●		
(Guo *et al.,* 2015)	○	○			●		○
(Wu *et al.,* 2015)					●		
(Hanson *et al.,* 2017)			●			●	
(Renner and Pfeiffer, 2017)					●	●	
(Bräuer and Mazarakis, 2018)							○
(Kim *et al.,* 2019)	●	●	●		●		
Total tested parameters:	**1**	**5**	**7**	**7**	**8**	**11**	**0**
Total Non-tested parameters:	**1**	**1**	**0**	**1**	**0**	**0**	**6**

● : Tested parameter
○ : Non-tested parameter

Focusing on the weight of equipment, it can be seen that the weight range of the used glasses and headbands is big. Indeed, according to Syberfeldt *et al.,* (2017), the weight range of conventional equipment is between 70gr – 350gr, while some other studies mention that the weight of some common AR glasses can reach up to 580gr (Bräuer and Mazarakis, 2018). Based on the available results (Schwerdtfeger *et al.,* 2009; Syberfeldt *et al.,* 2017) the heavy equipment cause physical fatigue and headaches and do not allow their use by pickers for extended periods. Thus, it is important to mention that the equipment should be light and ergonomically designed in order to be used by pickers over of a shift of eight hours (Reif and Günthner, 2009). Despite the fact that the weight constitutes a critical factor for the acceptance of vision picking equipment, the reviewed studies have not conducted a direct assessment in terms of weight.

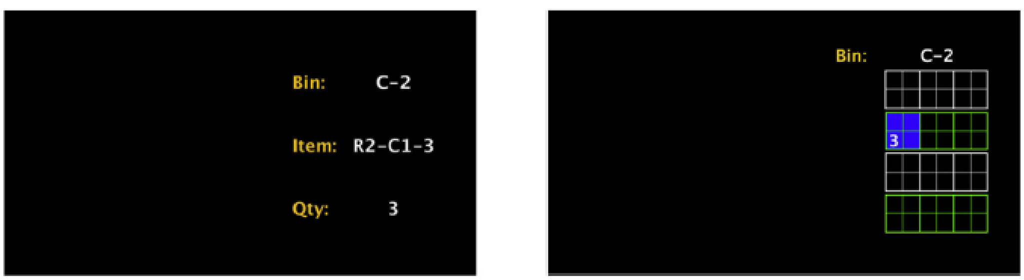
Visualization aspects

According to the reviewed studies, the visualization aspects during the design and development of vision picking system deal with the Graphical User Interface (GUI) of the device. Indeed, one of the most important things of a vision picking system is the GUI, because the virtual information must be displayed at the right time and at the right position (Reif and Walch, 2008; Reif *et al.,* 2010). Nevertheless, the display of necessary information (i.e. stock location, article number, goods description, required quantities, etc.) on pickers glasses or headbands is not always appeared efficiently, due to various problems, such as eye strain, difficulties seeing the display image, eye pain, eye concentration problems, and headaches, which are observed during the testing of vision picking system (Baumann *et al.,* 2012). Based on the results that are presented in Table 3.6, there are six key parameters that can be used by researchers in order to increase the performance and improve the GUI of this emerging technology.

More specifically, the first parameter which affects the visualization aspects is the field of view, as it defines the area in which the pickers can see the content while wearing their glasses or headbands. According to Renner and Pfeiffer, (2017), the full field of view of a human is 180°, however the use of vision picking equipment for the execution of order picking process reduces the field of view of pickers. Indeed the display area of available glasses or headbands covers a field of view of 20° to 90° (Renner and Pfeiffer, 2017; Bräuer and Mazarakis, 2018). To this point it is worth mentioning that a significant number of vision picking devices has a really small field of view (Syberfeldt *et al.,* 2017), and this fact creates multiple problems that deal with the performance and the safety of pickers when vision picking is adopted in industrial environments (Reif *et al.,* 2010; Kim *et al.,* 2019). On the other hand, the larger fields of view, increase the satisfaction level of pickers (Ok *et al.,* 2015) as well as task performance (Kishishita *et al.,* 2014).

Another factor that affects the field of view is the mounting options of equipment. When an adjustable device is used the picker has two options. According to Guo *et al.,* (2015), the first option is the placement of display above of line of sight, while the second option is below the line of sight. This is a factor that depends on the preferences of each picker, but it is worth mentioning that it has not yet been evaluated yet. Furthermore, one more interesting factor that can be taken into account is the location of field of view when a vision picking system is supported by AR. According to Renner and Pfeiffer, (2017), there are two different options. In the first option, the AR field of view can be located in the center of field of view of picker, while in the second option it may be located towards the periphery.

The second parameter that affiliates with the visualization aspects is the information mode. According to Kim *et al.* (2019), there are two different information modes. The first is the text based (Figure 3.6a) and the second is the graphical-based user interface design (Figure 3.6b). As it can be observed in Table 3.6, the most reviewed studies use the graphical-based user interface design, because this mode reduces the task completion time (Schwerdtfeger *et al.,* 2006), the errors and the perceived workload (Kim *et al.,* 2019). This is justified, because it is easier and faster to read and understand the tasks to be accomplished when a picker uses a graphical-based interface design (Kim *et al.,* 2019).



(a) (b)

Figure 3.6 a) Text-based user interface design, b) Graphical-based user interface design, (Kim *et al.,* 2019)

The third parameter focuses on the information availability on the display of pickers. This parameter is evaluated only in one study, yet it seems to influence the system performance. According to Kim *et al.,* (2019), there are two levels of information availability. In the first level, the information is constantly visible (always-on), while in the second level the information appears only for a few seconds on the picker’s display and then disappears. Also, it is important to mention that in the second case the picker has the ability to request to view the information again. So, taking into account these two different levels of information availability, it can be assumed that the first level (always-on) is more preferable (Kim *et al.,* 2019). This happens because the first level of information availability provides reduced order picking performance and also does not force the pickers to memorize information (Kim *et al.,* 2019).

The display view is one more parameter which affects the visualization aspects. According to Guo *et al.,* (2015), two different types of display views are identified. The first type is the transparent display (Figure 3.7a), and the second type is the opaque display (Figure 3.7b). As it can be seen in Table 3.6, in most cases opaque displays have been used, since the authors argue that the opaque display is more efficient for the execution of the order picking process. Indeed, by taking into consideration a direct comparison between the transparent and the opaque display (Guo *et al.,* 2015), it is proven that the opaque display has reduced the order picking time (~2.7%) and the error rate per pick (~2.3%) than the transparent display

(a) (b)

Figure 3.7 a) Transparent display, b) Opaque display, (Guo *et al.,* 2015)

The fifth parameter deals with the existence of AR in a vision picking system. Based on Table 3.6, most authors have recognized the benefits of AR and they have used it in order to support the vision picking system. According to Reif *et al.* (2010), the use of AR may lead to reduced order picking times because, the dead time as well as the time for information search during the order picking process is reduced. On the other hand, some other studies support that the existence of AR in a vision picking system has not yet shown an improvement which is worth mentioning in either accuracy or speed over traditional order picking systems (Guo *et al.,* 2015).

Table 3.6 Overview of parameters which deal with visualization aspects

	Field of view	Information mode		Information availability		Display view		Existence of AR		Display Settings
		Text	Graphics	On demand	Always on	Transparent	Opaque	Yes	No	
(Schwerdtfeger *et al.,* 2006)		●	●					●	●	
(Reif and Walch, 2008)		●						●		
(Tumler et al., 2008)								●		
(Schwerdtfeger and Klinker, 2008)								●		
(Reif and Günthner, 2009)	○							●		
(Schwerdtfeger *et al.,* 2009)				●				●	●	
(Iben *et al.,* 2009)		●							●	
(Reif *et al.,* 2010)								●	●	
(Weaver *et al.,* 2010)			●				●			
(Grubert *et al.,* 2010)								●		
(Schwerdtfeger *et al.,* 2011)	●		●					●		
(Baumann *et al.,* 2011)			●				●	●		
(Baumann *et al.,* 2012)		●					●	●		
(Krajcovic *et al.,* 2014)								●		
(Guo *et al.,* 2015)	○		●			●	●		●	○
(Wu *et al.,* 2015)			●				●		●	
(Hanson *et al.,* 2017)			●					●		
(Renner and Pfeiffer, 2017)	●							●		
(Bräuer and Mazarakis, 2018)	○							●		
(Kim *et al.,* 2019)		●	●	●	●					
Total tested parameters:	**2**	**5**	**8**	**2**	**1**	**1**	**5**	**15**	**6**	**0**
Total Non-tested parameters:	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**

● : Tested parameter
○ : Non-tested parameter

In addition, Schwerdtfeger *et al.,* (2009) argue that there are enough obstacles when somebody tries to support a vision picking system with AR in an industrial environment, while mention that most of the AR systems remain laboratory prototypes. Some of the most common obstacles are the lack of adequate hardware, as well as some not yet resolved usability issues (Livingston *et al.,* 2005). Moreover, Schwerdtfeger *et al.,* (2006) argue that the AR vision picking systems display an increased number of errors, when compared with traditional order picking systems. Last but not least, according to Stoltz *et al.,* (2017), the cost of AR solutions is one more obstacle and it is necessary to be reduced in order to be adopted. To this end, it can be concluded that the existence of AR in a vision picking system is not yet a mature option for real life scenarios, as a result further improvements and tests are required.

The last parameter which is related to the visualization aspects is the display setting. This parameter is not yet tested but according to Guo *et al.* (2015) it can contribute to the optimization of displays. The resolution, as well as a series of others characteristics of displays such as brightness, contrast and color depth can be evaluated in order to improve the GUI of available displays.

Technical aspects

Based on the results which are illustrated in Table 3.7, the technical aspects of the device parameterization consist of four parameters. An initial finding is that this category of parameters is not yet evaluated adequate when compared to the parameters that deal with ergonomic and visualization aspects.

The first parameter which deals with the technical aspects is the barcode type. By taking into consideration the results of Table 3.7, it can be seen that the barcode type is mentioned in only one article. In the latter article, QR code labels are attached to items and the pickers confirm their picks by scanning the QR codes of items (Baumann *et al.,* 2012). According to Stoltz *et al.,* (2017) in most cases the use of barcodes and QR codes has dominated the logistics sector, but further research is required. Furthermore, some other studies highlight the need for linking the order picking systems with automatic identification systems, such as RFID tags (Krajcovic *et al.,* 2014).

Apart from the type of barcode, another important parameter is the scanning distance (the distance between the label of item/box and the reader). The scanning distance depends on the camera resolution, the size of printed code (label) (Stoltz *et al.,* 2017), as well as the ability of head mounted display for autofocus (Schwerdtfeger *et al.,* 2009).

The third parameter of technical aspects is related to the battery life. Four studies mention that the battery life of equipment plays an important role for the adoption of vision picking in industrial environment. Indeed, most studies support that the equipment should be rugged with eight-hour battery operations (Reif and Walch, 2008; Reif and Günthner, 2009; Reif *et al.,* 2010). To this end, it is important to mention that the battery life of available glasses / headbands ranges from 1 hour to 8 hours (Syberfeldt *et al.,* 2017), but the battery life of the most popular glasses / headbands is less than 4 hours (Bräuer and Mazarakis, 2018). Nevertheless, this problem can be dealt with by using external batteries which can extend the duration of the current batteries.

Table 3.7 Overview of parameters which deal with technical aspects

	Barcode type	Scanning distance	Battery life	Existence of tracking system	
				Yes	No
(Schwerdtfeger *et al.,* 2006)				●	
(Reif and Walch, 2008)			○	●	
(Tumler *et al.,* 2008)				●	
(Reif and Günthner, 2009)			○	●	●
(Schwerdtfeger *et al.,* 2009)		○		●	
(Reif *et al.,* 2010)			○	●	●
(Grubert *et al.,* 2010)				●	
(Schwerdtfeger *et al.,* 2011)				●	●
(Krajcovic *et al.,* 2014)				●	
(Bräuer and Mazarakis, 2018)	●		○	●	
Total tested parameters:	**1**	**0**	**0**	**10**	**3**
Total Non-tested parameters:	**0**	**1**	**4**	**0**	**0**

● : Tested parameter
○ : Non-tested parameter

The last parameter which affects the technical aspects is the existence of a tracking system within the vision picking system. A tracking system depends on a series of factors such as resolution, degrees of freedom, range, update rate and accuracy (Rolland *et al.,* 2001; Reif and Günthner, 2009; Reif *et al.,* 2010). According to the literature review, there are a lot of tracking systems available (electromagnetic, inertial, mechanical, optical, radio-based and ultrasonic systems), but the most suitable choice for industrial environments, is the optical tracking system (Reif and Günthner, 2009; Reif *et al.,* 2010). By applying an optical tracking system, the performance of the vision picking process is improved in terms of the number of errors, while the combination of a tunnel with a frame seems to be the best solution for a vision picking system which is supported by a tracking system (Reif *et al.,* 2010). Also, according to Schwerdtfeger *et al.,* (2011), the frame–

based visualization (Figure 3.8b) in a vision picking system with tracking system, works faster and without errors when compared with arrow-based (Figure 3.8a) and tunnel-based visualizations (Figure 3.8c).

(a) (b) (c)

Figure 3.8 a) Arrow-based visualization, b) Frame-based visualization and c) Tunnel-based visualization, (Schwerdtfeger *et al.,* 2011)

3.4.2. Parameters for operational performance measurement

The implementation of the vision picking system in industrial environment requires the evaluation of a series of parameters that affect the operational performance of the system. According to the literature review, there are three critical parameters that must be taken into consideration during the implementation of vision picking system in real life scenarios. Based on the results of Table 3.8, the reviewed parameters are the picking strategy, the handling unit of products and the existence of picks confirmation or not.

Focusing on the first parameter, the literature review shows that multiple order picking is the principal picking strategy for the case of vision picking. Indeed, according to Hanson *et al.,* (2017) multiple order picking can improve the efficiency of order picking process, when compared with the discrete picking. Also, most of the reviewed studies mention that multiple order picking is supported by carts which can used for the picking of multiple orders (four or more), simultaneously. Moreover, it is observed that a significant number of studies use colorful plastic bins which are mounted on carts, in order to execute the order picking process in a more efficient manner.

Another important parameter which has been evaluated from a series of studies, deals with the handling unit of products. As it can be seen in Table 3.8, in the majority of articles the vision picking system is used for item picking, while in a sole study it has also been sued for box picking. Moreover, it is worth mentioning that this technology has not been adopted for the case of pallet picking. To this end, according to the results of the literature review, vision picking is a technology that may improve the total performance of the order picking process in terms of speed and accuracy, when implemented in micro-picking operation.

Table 3.8 Overview of parameters for operational performance

	Picking Strategy		Handling Unit		Existence of confirmation	
	Multiple order picking	Discrete picking	Item	Box	Yes	No
(Schwerdtfeger *et al.,* 2006)	●		●		●	
(Reif and Walch, 2008)			●			
(Schwerdtfeger and Klinker, 2008)			●		●	
(Reif and Günthner, 2009)	●		●			
(Schwerdtfeger *et al.,* 2009)		●		●	●	
(Iben *et al.,* 2009)	●		●		●	
(Reif *et al.,* 2010)			●		●	
(Weaver *et al.,* 2010)	●		●		●	
(Schwerdtfeger *et al.,* 2011)	●		●		●	
(Baumann *et al.,* 2011)	●		●		●	
(Krajcovic *et al.,* 2014)		●	●		●	
(Guo *et al.,* 2015)	●		●			●
(Wu *et al.,* 2015)	●		●			●
(Hanson *et al.,* 2017)	●		●		●	
(Bräuer and Mazarakis, 2018)			●		●	
(Kim *et al.,* 2019)			●		●	
Total:	**9**	**2**	**15**	**1**	**12**	**2**

The last parameter deals with the existence of pick confirmation during the order picking process. As it can be seen in Table 3.8, most studies use a confirmation system, in order to increase the accuracy of the process. The confirmation of picks can be done with different ways. According to Bräuer and Mazarakis, (2018), an effective way for the picks confirmation is the scanning of items' QR codes with an external QR code reader, while Weaver *et al.,* (2010) suggest the use of a RF scanner. Also, Reif *et al.,* (2010), Schwerdtfeger *et al.,* (2011) and Hanson *et al.,* (2017) mention that a voice confirmation is a reliable solution, while other studies assess the use of a confirmation button for the picks confirmation (Baumann *et al.,* 2011; Krajcovic *et al.,* 2014).

Last but not least there are two reviewed articles that suggest smart and innovative solutions for the pick confirmation. More specifically, Hanson *et al.,* (2017) argue that RFID technology is an effective alternative solution, while Iben *et al.,* (2009) suggest that RFID tags, accelerometers, proximity sensors, capacitive sensors, etc., could be used in the years to come. On the other hand, there are quite a few studies which support that the existence of a confirmation system during the order picking process reduces the system performance and it is not necessary for the execution of process.

3.4.3. Parameters for comparative assessment

The last category related to parameters deals with the comparative assessment of vision picking system with other conventional order picking systems in industrial environments. As it can be seen in Table 3.9, there are various studies which compare vision picking system with all the available order picking systems. Nevertheless, the majority of studies focus their comparison between vision picking and Pick-by-vision or Pick-by-paper with or without RF scanners. On the contrary, the number of studies which compare the vision picking with the Pick-by-light and Pick-by-voice is limited.

Based on the results of Table 3.9, there are three key parameters for the comparison assessment of vision picking with other order picking systems. More specifically, the number of orders, the lines per order, as well as the items per order line are the key parameters that are usually taken into consideration.

With regards to the first parameter, based on Table 3.9 the number of orders which is executed for the evaluation and comparison of system ranges from 3 orders to 14 orders. The second parameter deals with the lines per order and according to Table 3.9, the number of lines per order ranges from 2 to 5 lines. Finally, the last parameter of this category deals with the count of items per order line. As for the last parameter, according to Table 3.9 the number of items per order line ranges from 1 item to 7 items.

Table 3.9 Overview of investigated order picking systems and parameters for comparative assessment

	Investigated order picking systems				Parameters		
	Pick-by-Vision (Parameters comparison)	Pick-by-Vision VS Pick-by-Paper	Pick-by-Vision VS Pick-by-Light	Pick-by-Vision VS Pick-by-Voice	Number of orders	Lines per order	Items per order line
(Schwerdtfeger *et al.*, 2006)	●						
(Reif and Walch, 2008)		●	●	●	5		
(Tumler *et al.*, 2008)		●					
(Schwerdtfeger and Klinker, 2008)	●				3		
(Reif and Günthner, 2009)		●			14	2 - 6	1 - 6
(Schwerdtfeger *et al.*, 2009)	●				6	5	2.03
(Iben *et al.*, 2009)		●					
(Reif *et al.*, 2010)		●			14	3.7	2.3
(Weaver *et al.*, 2010)		●		●			
(Grubert *et al.*, 2010)		●					
(Schwerdtfeger *et al.*, 2011)	●	●					
(Baumann *et al.*, 2011)	●				3		1 - 5
(Baumann *et al.*, 2012)	●						
(Krajcovic *et al.*, 2014)	●						
(Guo *et al.*, 2015)		●	●		3		1 - 7
(Wu *et al.*, 2015)			●				
(Hanson *et al.*, 2017)		●					
(Renner and Pfeiffer, 2017)	●						
(Bräuer and Mazarakis, 2018)	●						
(Kim *et al.*, 2019)	●						
Total:	**10**	**10**	**3**	**2**			

3.5. Summary

In this chapter the review of various design, development and testing parameters for vision picking system took place via the use of Systematic Literature Review (SLR) approach. Based on the reviewed papers, 20 parameters were identified that were classified into three categories, namely: a) system parameterization, b) operational performance and, c) comparative assessment with other picking systems. The first category deals with the device design and development and includes 14 reviewed parameters. The second category comprises 3 parameters which concern the testing of the performance of the vision picking system in the industrial environment and the third category encompasses 3 parameters which are used for the comparison of vision picking system with other picking systems in the industrial environment. Due to the high number of parameters of the first category (system parameterization), the 14 parameters were classified into three different sub-categories. The first sub-category deals with the ergonomic aspects and involves 4 parameters, the second focuses on visualization aspects and includes 6 parameters, while the third sub-category is associated with technical aspects and encompasses 4 parameters.

Chapter 4. Ranking and selection of vision picking design and development parameters

This chapter presents the ranking and selection of vision picking system design parameters by adopting the Analytical Hierarchy Process (AHP) methodology. Initially, the theoretical background, as well as the implementation steps of AHP methodology are presented. Subsequently, the procedure and the corresponding steps for the adoption of AHP in the ranking process of proposed are described. The chapter concludes with the presentation of the final results.

4.1. Analytical Hierarchy Process: Implementation steps

The AHP methodology is a decision support tool which compares criteria or alternatives with reference to specified criterion in pair wise-mode. In order to achieve this comparison, it is necessary to use a fundamental scale of numbers which has been proven in practice and validated. By using this fundamental scale of numbers, the individual preferences can be converted into a linear additive weight for each alternative (Luthra *et al.,* 2013). The results of this methodology can be taken into account by decision makers in order to evaluate and rank the alternatives and make a proven choice. AHP methodology includes the following three steps (Saaty, 2008):

Step 1: Establish the hierarchy structure

In this step the construction of hierarchy structure takes place. The first level of hierarchy deals with the goal of the analysis. The second level includes the criteria or dimensions of analysis while the last level focus on alternatives.

Step 2: Constructing the pair wise comparison matrix

During the second step, a set of pairwise comparison matrices is constructed. Each element in an upper level is used to compare the elements in the level immediately below with respect to it. In order to make comparisons, it is necessary to be used a scale of numbers (see Table 4.1) that indicates how many times more important or dominant one element is over another element with respect to the criterion or property with respect to which they are compared. The standard numeric scale used for AHP is from 1 to 9 scale which lies between “equal importance” to “extreme importance”, the value 9 indicates that one factor is extremely less important than the other, while value 1 indicates equal importance.

Table 4.1 The fundamental scale of absolute numbers, (Saaty, 2008)

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption
1.1 – 1.9	If the activities are very Close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

Step 3: Calculate the consistency

In the last step of the AHP methodology, the calculation of consistency takes place. More specifically, in order to confirm that the priority of elements is consistent, the consistency index (CI) for each matrix, as well as the Random Consistency index (RI) can be calculated by using equations 4.1 and 4.2. According to Saaty (2000), the CI and CR are defined as follows:

$$CI = (\lambda max - n)/ (n - 1) \tag{4.1}$$

$$CR = CI/RI \tag{4.2}$$

The value of RI varies depending upon the order of matrix. Table 4.2 shows the value of the RI for matrices of order (n) 1 to 10.

Table 4.2 Random index, (Saaty, 2008)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

The acceptable Consistency Ratio (CR) range varies as per the matrix size (Thomas L. Saaty, 2000; Cheng and li, 2001; Luthra *et al.,* 2013):

- Matrix size (3 x 3): Acceptable CR value <= 0.05
- Matrix size (4 x 4): Acceptable CR value <= 0.08
- Matrix size (n x n), n>=5: Acceptable CR value <= 0.1

If the value of CR is equal to, or less than that value, it means that the ranking is acceptable (good level of consistency). On the other hand, if CR is more than the acceptable CR value, the ranking process needs to be reviewed, re-evaluated and improved. To this point, it is worth mentioning that an acceptable CR value can help the decision makers to take a more reliable decision, during the evaluation process (Kumar *et al.,* 2009; Luthra *et al.,* 2013).

4.2. Implementing AHP methodology for selecting and ranking vision picking system design and development parameters

By taking into consideration the results of the SLR, 20 parameters have been identified in total. From these parameters, only 14 of them dealt with vision picking system design. The other 6 parameters focused on a) testing the performance of vision picking system in industrial environment and b) comparing vision picking system with other picking systems (e.g. RF-scanner). The 14 selected parameters were validated from experts' opinions in three dimensions (ergonomic aspects, visualization aspects and technical aspects).

In order to select and rank the aforementioned parameters, it was necessary to follow the steps described in section 4.2. Following the recommended methodology by Saaty (2008), during the first step, the construction of hierarchy structure took place. More specifically, the AHP framework of evaluation of vision picking parameters was structured in three levels (Figure 4.1).

The first level includes the goal (to prioritize vision picking design and development critical parameters), the second level focuses on the dimensions of parameters (ergonomic aspects, visualization aspects, technical aspects), while the third level deals with the constructs of dimensions (14 design and development parameters).

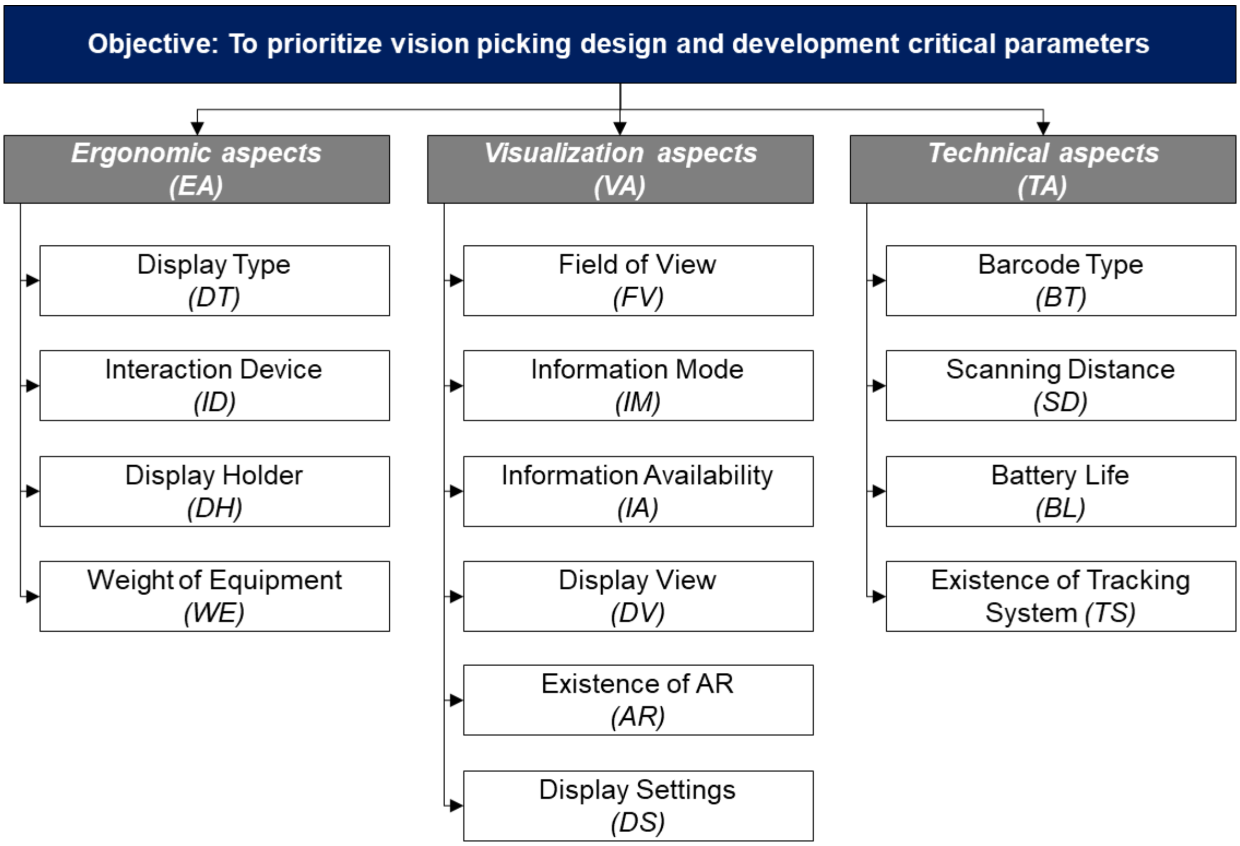


Figure 4.1 AHP based hierarchical model to evaluate vision picking design and development critical parameters

During the second step of recommended methodology the necessary questionnaire with the pair wise comparison matrices (PWCM) was constructed (Appendix A). For the construction of the questionnaire, all dimensions and constructs of AHP based hierarchical model have been taken into consideration, while the suggested by Saaty (2008) scale of numbers (see Table 4.1) was used.

After the construction of the necessary questionnaire, the ranking of the selected parameters was completed by experts. In this phase a series of interviews with logistics / warehouse managers, specialist and executives took place. The questionnaire was filled by 15 experts who work in logistics service providers, as well as in commercial and manufacturing companies (with in house logistics) in Greece.

The steps for filling up the questionnaire, were specific and common for all participants and are presented below.

- **Step 1**: Presentation of the main aim and objective of this research
- **Step 2**: Detailed description of reviewed parameters to the participants (experts)
- **Step 3**: Specific instructions to participant on how to fill the questionnaire
- **Step 4**: Rating of vision picking system design parameters by experts (it was completed via questionnaire).

After the completion of ranking, a short discussion with the participants was taken place in order to give me their feedback about the vision picking system, the challenges and inefficiencies as well as the potential benefits from its implementation in real life scenarios.

After the completion of interviews and data collection (expert's inputs), the data analysis as well as the calculation of consistency were accomplished based on the recommended methodology of Saaty (2008) (see section 4.2). In the last step, the priorities were calculated based on the AHP methodology by taking into consideration the hierarchical model as well as the ratings achieved through the questionnaire. Furthermore, for each pair wise comparison matrix (PWCM), the maximum Eigen values (λmax), CI and CR were calculated and were presented in the tables of section 4.4. To this point, it is important to mention that values of consistency ratio (CR) were in acceptable range for all the Pair wise comparison matrices shown in Tables 4.3 to 4.6, ensuring reliability of decision makers.

4.3. AHP methodology: data analysis and results

Based on the ratings obtained through the questionnaire, matrices were formed and the priorities are synthesized using the methodology of Analytical Hierarchy Process (AHP). All the results of ranking presented in Tables 4.3 to 4.6.

Focused on the second level (2nd level) of hierarchical model, Table 4.3 presents weights given by experts to three dimensions (ergonomic aspects, visualization aspects, technical aspects).

Table 4.3 Pair wise comparison matrix (PWCM) of criteria

Criteria	EA	VA	TA	Priority Weighting	Rank
EA	1.00	2.00	3.00	0.57	1st
VA	0.50	1.00	2.00	0.33	2nd
TA	0.33	0.50	1.00	0.10	3rd

Maximum Eigen Value = 3.009209

CI = 0.004604

CR = 0.007

According to the results of Table 4.3, the “Ergonomic Aspects – (EA)” was ranked as the most important dimension (0.57) during the design and development of vision picking system. The second place occupied by the “Visualization Aspects – (VA)” (0.33), while the less important dimension dealt with the “Technical Aspects – (TA)” (0.10).

Based on the expert’s input the first two dimensions play an important role for the acceptance of vision picking system by the industry users. Also, they support that the third dimension (technical aspects) can be improved by the IT companies, if proven that vision picking system has the potential to bring a series of benefits in order picking process.

In the third level (3rd level) of decision making, a significant number of parameters / constructs have been ranked for each dimension. More specifically, Table 4.4 shows pair wise comparison matrix (PWCM) indicating weights provides by experts to parameters / constructs of “Ergonomic Aspects – (EA)” dimension.

As it can be seen, the “Interaction Devise – (ID)” has been found the most important parameter (0.44) in the first dimension (ergonomic aspects), followed by “Display Holder – (DH)” (0.25), “Display Type – (DT)” (0.22) and “Weight of Equipment – (WE)” (0.09).

Table 4.4 Pair wise comparison matrix (PWCM) of ergonomic aspects dimension

Constructs under EA	DT	ID	DH	WE	Priority Weighting	Rank
DT	1.00	0.60	0.80	2.00	0.22	3rd
ID	1.67	1.00	2.00	5.00	0.44	1st
DH	1.25	0.50	1.00	3.00	0.25	2nd
WE	0.50	0.20	0.33	1.00	0.09	4th
						Maximum Eigen Value = 4.024781
						CI = 0.008260
						CR = 0.009

In Table 4.5, constructs under the second dimension (visualization aspects) had been checked for hierarchy. “Information mode – (IM)” was reported as the most important (0.31) construct, followed by “Field of view – (FV)” (0.23) and Existence of AR” (0.18). Then, follows “Display view – (DV)” (0.12), Display settings – (DS)” (0.08) and “Information availability – (IA)” (0.07).

Table 4.5 Pair wise comparison matrix (PWCM) of visualization aspects dimension

Constructs under VA	FV	IM	IA	DV	AR	DS	Priority Weighting	Rank
FV	1.00	0.80	3.00	2.00	1.30	4.00	0.23	2nd
IM	1.25	1.00	4.00	3.00	2.00	5.00	0.31	1st
IA	0.33	0.25	1.00	0.80	0.50	0.30	0.07	6th
DV	0.50	0.33	1.25	1.00	0.80	3.00	0.12	4th
AR	0.77	0.50	2.00	1.25	1.00	5.00	0.18	3rd
DS	0.25	0.20	3.33	0.33	0.20	1.00	0.08	5th
								Maximum Eigen Value = 6.479866
								CI = 0.095973
								CR = 0.073

Table 4.6 presents pair wise comparison matrix (PWCM) indicating weights provides by experts to parameters / constructs of technical aspects dimension. According to the results of Table 4.6, the “Barcode Type – (BT)” was reported as the most important (0.37) construct of third dimension. The second place occupied by “Scanning Distance – (SD)”

(0.32), followed by “Battery Life – (BL)” (0.16) and “Existence of Tracking System – (TS)” (0.14).

Table 4.6 Pair wise comparison matrix (PWCM) of technical aspects dimension

Constructs under EA	BT	SD	BL	TS	Priority Weighting	Rank
BT	1.00	1.50	2.00	2.50	0.37	1st
SD	0.67	1.00	3.00	2.00	0.32	2nd
BL	0.50	0.33	1.00	1.50	0.16	3rd
TS	0.40	0.50	0.67	1.00	0.14	4th
					Maximum Eigen Value = 4.087733	
					CI = 0.029244	
					CR = 0.032	

Taking into account the results of ranking presented in Tables 4.3 to 4.6, we can conclude that the most important dimensions for the vision picking system design and development are the “Ergonomic Aspects – (EA)” as well as the “Visualization Aspects – (VA)”. In terms of “Ergonomic Aspects – (EA)” the “Interaction Devise – (ID)” and “Display Holder – (DH)” were founded as the most important constructs, while, for the “Visualization Aspects – (VA)” dimension, the “Information mode – (IM)” and “Field of view – (FV)” were ranked as the most important constructs. Finally, it is important to mention that the “Technical Aspects – (TA)” dimension was less important for the experts when compared with the other two dimensions.

The complete ranking of critical constructs / parameters for vision picking system design and development is presented in Table 4.7. More specifically, by considering the overall weight of parameters the following results are revealed: the “Interaction Devise – (ID)”, “Display Holder – (DH)” and “Display Type – (DT)” have been rated as the top three critical parameters. On the other hand, the “Existence of Tracking System – (TS)”, as well as the “Information availability – (IA)” are the last two parameters, based upon overall weight values of parameters.

Table 4.7 Overall weighting and ranking of vision picking design and development critical parameters

Dimension S.N.	Dimension description	Weight of dimensions	Rank	Parameters S.N.	Parameters description	Local weight of parameters	Overall weight of parameters	Overall ranking of parameters
1	Ergonomic aspects **(EA)**	0.54	1st	1.1	DT	0.22	0.116	3rd
				1.2	ID	0.44	0.236	1st
				1.3	DH	0.25	0.137	2nd
				1.4	WE	0.09	0.050	9th
2	Visualization aspects **(VA)**	0.30	2nd	2.1	FV	0.23	0.069	5th
				2.2	IM	0.31	0.093	4th
				2.3	IA	0.07	0.021	14th
				2.4	DV	0.12	0.037	10th
				2.5	AR	0.18	0.054	7th
				2.6	DS	0.08	0.024	12th
3	Technical aspects **(TA)**	0.16	3rd	3.1	BT	0.37	0.061	6th
				3.2	SD	0.32	0.053	8th
				3.3	BL	0.16	0.027	11th
				3.4	TS	0.14	0.022	13th

4.4. Summary

In this chapter the ranking of vision picking system design parameters took place. Based on the ratings obtained through the questionnaire (expert's input), Pair wise comparison matrices (PWCM) were formed and the priorities were synthesized using the methodology of Analytical Hierarchy Process (AHP). The ranking of parameters was performed by 15 experts who work in logistics service providers, as well as in commercial and manufacturing companies (with in house logistics) in Greece. The results showed that the most important dimensions for the vision picking system are the "Ergonomic Aspects – (EA)" as well as the "Visualization Aspects – (VA)", while the "Technical Aspects – (TA)" dimension was less important for the experts when compared with the other two dimensions. In terms of parameters, the five most important parameters were the "Interaction Devise – (ID)", "Display Holder – (DH)", "Display Type – (DT)" "Information mode – (IM)" and "Field of view – (FV)" respectively.

Chapter 5. Design of Experiments for Vision Picking system evaluation

This chapter presents the evaluation of vision picking system in terms of order picking efficiency and accuracy via a series of laboratory tests that were conducted by adopting the Design of Experiments (DoE) methodology. Initially the methodology as well as the intermediate steps of this evaluation are presented followed by the selected factors and their levels that have been chosen for assessing the performance of proposed system. Then, the experimental design that has been used for the design and testing of 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.

5.1. Design of Experiments: Implementation steps

In order to investigate a particular process or system, the investigators usually perform experiments (Montgomery, 2012). An experiment can be defined as a test or a series of tests in which determined changes are performed to the input variables of a process, thus we may observe and identify the reasons for changes that may be observed in the output response (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. In engineering, during the development / evaluation of a process or system, it is important to adopt a robust procedure with specific steps for planning and conducting experiments, data collection and analyzing the resulting data in order to be achieved reliable, valid and objective conclusions (NIST/SEMATECH, 2012).

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

Step 1: Recognition of and statement of the problem

The first step of methodology is to understand the problem, to realize the need for experimentation and to develop all ideas about the objectives of the experiment. Also, to this point, it is important a clear statement of the problem, since it contributes significantly to better understanding of the process or system being considered and the final solution of the problem.

Step 2: Choice of factors, levels and ranges

For the evaluation of a process or system is important to take into account a series of factors. These factors can be classified as either potential design factors or nuisance factors. The potential design factors are those factors that the experimenters may wish to vary in the experiment and can affect the output response. The nuisance factors may have effects that must be accounted for, but usually not taken into account during the execution of an experiment.

Step 3: Choice of experimental design

Choice of design involves the selection of experimental design technique (e.g. classical experimental design, orthogonal array designs, etc.), the consideration of sample size (number of replicates), the selection of a suitable run order from the 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 formulation of research hypothesis as well as the final check of process take 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 not errors. Also, in 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 experiment and data collection, it is necessary to analyze the data through statistical methods in order to export the results and conclusions. Moreover, it is important to mention that graphical methods can be effective in data analysis and interpretation. Furthermore, 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 in this stage, particularly in presenting the experimental results.

5.2. Statement of the problem and choice of factors & levels

The objective of this research is to evaluate the performance of vision picking system via laboratory experiments in terms of order picking efficiency and accuracy. To this end, a series of experiments were performed by varying a number of factors in order to be identified the most important factors / effects which affect the performance of the vision picking system in terms of order picking time and accuracy.

For the selection of factors, the results from the Systematic Literature Review (SLR), and the Analytical Hierarchy Process (AHP) were considered. However, the final selection of parameters to be investigated was made by taking into consideration a series of technical limitation we had in the laboratory. The latter deal with the available technical equipment, the limited space for conducting tests (i.e. product picking), no available budget for further development of multiple graphical user interphases (GUI) and limited time for performing the tests.

To this end, the three (out of the 14 in total) factors which were selected, were: the display holder, the field of view (mounting options) and the barcode type. The selected factors are presented in Table 5.1 (highlighted in blue color).

Table 5.1 Overall weighting and ranking of vision picking design and development critical parameters

Dimension S.N.	Dimension description	Weight of dimensions	Rank	Parameters S.N.	Parameters description	Local weight of parameters	Overall weight of parameters	Overall ranking of parameters
1	Ergonomic aspects **(EA)**	0.54	1st	1.1	DT	0.22	0.116	3rd
				1.2	ID	0.44	0.236	1st
				1.3	**DH**	**0.25**	**0.137**	**2nd**
				1.4	WE	0.09	0.050	9th
2	Visualization aspects **(VA)**	0.30	2nd	**2.1**	**FV**	**0.23**	**0.069**	**5th**
				2.2	IM	0.31	0.093	4th
				2.3	IA	0.07	0.021	14th
				2.4	DV	0.12	0.037	10th
				2.5	AR	0.18	0.054	7th
				2.6	DS	0.08	0.024	12th
3	Technical aspects **(TA)**	0.16	3rd	**3.1**	**BT**	**0.37**	**0.061**	**6th**
				3.2	SD	0.32	0.053	8th
				3.3	BL	0.16	0.027	11th
				3.4	TS	0.14	0.022	13th

Furthermore, it is important to mention that apart from these factors, we decided to include in our experiments, one more factor which deals with the operational performance of vision picking process. This factor deals with the existence of confirmation during the order picking process and according to the literature review conducted, it affects both the order picking time as well as the accuracy of vision picking process. This factor was also suggested by logistics experts, (during the filling of questionnaire for the ranking of vision picking system design parameters) to be included in the Laboratory tests, since this parameter apart from the critical effects on operational performance, affects the acceptance of system by the end users. To this point, it is important to mention that this factor was not ranked via the AHP which is presented in chapter 4.

According to Figure 5.1, the input of the experiment included 4 factors, while the outputs were: a) the order picking efficiency (i.e. order picking time) as well as b) the accuracy of the picker (i.e. number of picking mistakes). In literature, similar studies (Schwerdtfeger *et al.,* 2006; Reif and Walch, 2008; Tumler *et al.,* 2008; Schwerdtfeger and Klinker, 2008; Reif and Günthner, 2009; Schwerdtfeger *et al.,* 2009; Iben *et al.,* 2009; Weaver *et al.,* 2010; Reif *et al.,* 2010; Grubert *et al.,* 2010; Schwerdtfeger *et al.,* 2011; Baumann *et al.,* 2011; Baumann *et al.,* 2012; Krajcovic *et al.,* 2014; Guo *et al.,* 2015; Wu *et al.,* 2015; Hanson *et al.,* 2017; Renner and Pfeiffer, 2017; Bräuer and Mazarakis, 2018; Kim *et al.,* 2019), use these outputs in order to assess the performance of vision picking systems during the execution of laboratory and field tests, that is why we have also selected them.

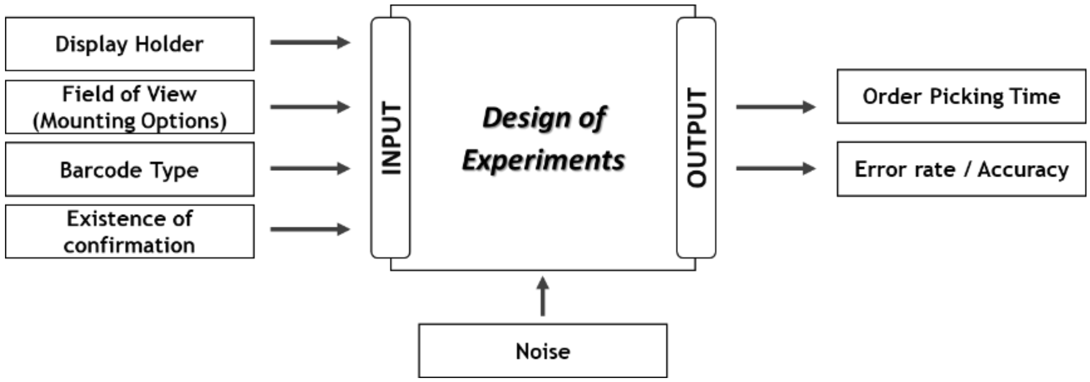


Figure 5.1 Model for order picking time and accuracy prediction

Moreover, a series of nuisance (noise) factors, that are taken into account include intra-logistics noise, lighting of the room, etc. Since the experimental procedure took place in a laboratory environment, the nuisance factors effects were not taken into consideration.

Table 5.2, presents the selected factors as well as their corresponding levels which were used for the experiments.

Table 5.2 Selected factor and their levels

Factor	Level 1	Level 2
Display Holder	Glasses	Headbands
Field of View (Mounting Options)	Above of line of sight	Below of line of sight
Barcode Type	1D	2D
Existence of confirmation	Yes	No

The first factor was the display holder. For this factor both glasses (level 1) and headbands (level 2) were evaluated during the laboratory tests. According to the available equipment that can be used for vision picking (Syberfeldt *et al.,* 2017), there are two different types of display holders. The first type is the glasses, while the second type is the headbands, which are worn on the head, using the suitable equipment (Stoltz *et al.,* 2017). Some of the most well-known glasses and headbands for vision picking are the followings: Google glasses, Vuzix M300, Epson Moverio BT-300, Microsoft HoloLens, RealWear HMT-1, etc. (Bräuer and Mazarakis, 2018). Both types of display holders have been evaluated in a series of tests and according to Stoltz *et al.,* (2017), they provide a hands-free solution for the execution of the order picking process. The type of holder together with the total weight of equipment can affect the performance of pickers and are responsible for a series of problems that pose various restrictions for pickers when wearing the equipment.

The second factor was the field of view and can be affected from the mounting options of the display (above of line of sight or below of line of sight), significantly. During the laboratory tests both above of line of sight (level 1) and below of line of sight (level 2) mounting options were concerned. More specifically, the field of view is the area in which the pickers can see the working space while wearing their glasses or headbands. According to Renner and Pfeiffer, (2017), the full field of view of a human is 180°, however the use of vision picking equipment for the execution of order picking process reduces the field of view of pickers. Indeed, the display area of available glasses or headbands covers a field of view of 20° to 90° (Renner and Pfeiffer, 2017; Bräuer and Mazarakis, 2018). To this point, it is worth mentioning that a significant number of vision picking devices has a really small field of view (Syberfeldt *et al.,* 2017), and this fact creates multiple problems that deal with the performance and the safety of pickers when vision picking is adopted in industrial environments (Reif *et al.,* 2010; Kim *et al.,* 2019). On the other hand, larger fields of view, increase the satisfaction level of pickers (Ok *et al.,* 2015) as well as their task performance (Kishishita *et al.,* 2014).

The third factor was the barcode type. For this factor both 1D barcode type (level 1) and 1D 2D barcode type (level 2) were evaluated during the laboratory tests. Based on the results of our literature review, there are two different types of barcodes types. The first type is the 1D barcode while the second one is the 2D barcode (QR code). More specifically, barcode labels are attached to items and the pickers confirm their picks by scanning the barcodes of items (Baumann *et al.,* 2012). According to Stoltz *et al.,* (2017) in most cases the use of barcodes and QR codes has dominated the logistics sector, but some other studies highlight the need for linking the order picking systems with automatic identification systems, such as RFID tags (Krajcovic *et al.,* 2014).

The last factor was the existence of pick confirmation during the order picking process. During the laboratory tests a series of tests were accomplished with confirmation step (level 1), while some tests were executed without confirmation step (level 2). According to the results of literature review, most studies use a confirmation system, in order to increase the accuracy of the process. The confirmation of picks can be done with different ways. According to Bräuer and Mazarakis, (2018), an effective way for the picks confirmation is the scanning of items' QR codes with an external QR code reader, while Weaver *et al.,* (2010) suggest the use of a RF scanner. Also, Reif *et al.,* (2010), Schwerdtfeger *et al.,* (2011) and Hanson *et al.,* (2017) mention that a voice confirmation is a reliable solution, while other studies assess the use of a confirmation button for the picks confirmation (Baumann *et al.,* 2011; Krajcovic *et al.,* 2014). During the laboratory tests, RFID technology was used for the picks confirmation, based on Hanson *et al.,* (2017) recommendations. More specifically, RFID tags were placed on the picker's hands as well as on the plastic bins of the cart (each plastic bin was assigned to one order). Each time a picker was placing a picked item into a bin, the system checked (via RFID technology), if the picker placed them in the correct bin. If the putting of item in the plastic bin was correct the system confirmed the movement of picker. On the other hand, if the picker put the item in a wrong bin, then the system via the head-mounted display informed the picker with an error message.

5.3. Choice of experimental design

Based on Antony (1999), the most preferably used experimental designs in industrial processes and systems are the classical experimental design (full and fractional factorial designs), especially when the experimenters want to evaluate the performance of a system, by alternating the input variables (levels of factors). Nevertheless, the choice of a suitable experiment design is a critical procedure that should be taken into consideration before performing any experiment. Indeed, the choice of experimental design is one of the most critical dimensions for the success of any experiments, and depends on the objectives of the experiment and the number of factors to be investigated (Antony, 1999). According to the Handbook of Statistical Methods, there are three main types of experimental designs, based on the objective which are presented below (NIST/SEMATECH, 2012).

Type 1 - Comparative objective: This type of design can be used when the aim of the experiment is to make a conclusion about one a-priori important factor. The adoption of this type of design is more when the question of interest is whether or not one or more factors are statistically significant". To this end, the use of this design is preferable in order to choose between alternatives, a) with narrow scope, suitable for an initial comparison and b) with broad scope, suitable for a confirmatory comparison.

Type 2 - Screening objective: This type of design (are also termed main effects design) used by the experimenters when they want to select or screen out the few important main effects from the many less important ones. Therefore, this type of design suggested in order to be identified which factors/effects are important.

Type 3 - Response Surface objective: This type of design is proposed when the experimenters want to estimate interaction and even quadratic effects, and therefore give them an idea of the (local) shape of the response surface they are investigating. This type of design, can be used to reduce variation by locating a region where the process is easier to manage, maximize or minimize a response, make a product or process more robust against external and non-controllable influences.

Taking into consideration the 3 aforementioned types of experimental design as well as the number of investigated factors, Table 5.3 presents the available experimental design approaches.

Following the suggested guidelines, as well as by considering the objective of this research (*Objective: Identification of the most important factors / effects which affect the performance of the vision picking system in terms of order picking time and accuracy*), we may conclude that the most suitable experimental design type is the screening. As a result, the classical experimental design (factorial design) was selected for our experiments.

Table 5.3 Experimental design selection guideline, (NIST/SEMATECH, 2012)

Number of factors	Comparative objective	Screening objective	Response Surface objective
1	1-factor completely randomized design	-	-
2 - 4	Randomized block design	Full factorial or Fractional factorial	Central composite or Box-Behnken
5 or more	Randomized block design	Fractional factorial or Plackett-Burman	Screen first to reduce number of factors

A factorial design can be either full or fractional factorial. By taking into consideration the number of selected factors (4 factors in our case) as well as by considering Antony's (2014) statement which argues that "when the number of factors is less than or equal to 4, the full factorial design is the most suitable choice", the full factorial design was selected for the conduction of our experiments. A full factorial designed experiment consists of all possible combinations of levels for all factors and the total number of experiments for studying k factors at 2-levels is 2^k (Antony, 2014; Montgomery, 2012).

According to the analysis above, a full factorial design used for our experiments that incorporates 4 factors at two levels (2^4 full factorial design). All possible combinations of these factors across their levels have been used in the design and are presented in Table 5.4. By considering the 4 factors as well as their corresponding levels, there were fifteen degrees of freedom between sixteen (2^4) different configurations.

Four degrees of freedom were associated with the main effects of Display Holder, Field of View, Barcode Type and Existence of confirmation. Six degrees of freedom were associated with 2-way interactions, one each with Display Holder*Field of View, Display Holder*Barcode Type, Display Holder*Existence of confirmation, Field of View*Barcode Type, Field of View*Existence of confirmation and Barcode Type*Existence of confirmation. Four degrees of freedom were associated with 3-way interactions, one each with Display Holder*Field of View*Barcode Type, Display Holder*Field of View*Existence of confirmation, Display Holder*Barcode Type*Existence of confirmation and Field of View*Barcode Type*Existence of confirmation and one degree of freedom was associated with 4-way interactions, one each with Display Holder*Field of View*Barcode Type*Existence of confirmation.

Table 5.4 The design matrix

Run	Display Holder	Field of View (Mounting Options)	Barcode Type	Existence of confirmation
1	Glasses	Above of line of sight	1D	Yes
2	Glasses	Above of line of sight	1D	No
3	Glasses	Above of line of sight	2D	Yes
4	Glasses	Above of line of sight	2D	No
5	Glasses	Below of line of sight	1D	Yes
6	Glasses	Below of line of sight	1D	No
7	Glasses	Below of line of sight	2D	Yes
8	Glasses	Below of line of sight	2D	No
9	Headbands	Above of line of sight	1D	Yes
10	Headbands	Above of line of sight	1D	No
11	Headbands	Above of line of sight	2D	Yes
12	Headbands	Above of line of sight	2D	No
13	Headbands	Below of line of sight	1D	Yes
14	Headbands	Below of line of sight	1D	No
15	Headbands	Below of line of sight	2D	Yes
16	Headbands	Below of line of sight	2D	No

Furthermore, the design of experiment that was developed included 5 replicates per run, so the total number of sample was n = 80. It is also worth mentioning that the 80 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.

5.4. Performing the experiment and analyzing the results

The objective in this experiment was to evaluate if and how the selected factors (Field of view, Display Holder, Barcode type and Existence of Confirmation) affect the order picking time as well as the accuracy of order picking process. Taking into consideration the sixteen possible configurations, the aim was to test appropriate hypotheses about the configurations effects and estimate them.

5.4.1. Formulation of Research Hypothesis

For the evaluation of vision picking system two parameters that affect the productivity, performance as well as the customer service level, were measured as mentioned previously. The first parameter was the order picking time and the second was the accuracy of order picking process. The order picking time was measured with a common stopwatch, while the accuracy was calculated by taking into consideration the error rate. The error rate was counted manually after the completion of order picking process.

For these parameters as well for the four factors that have been taken into account for the evaluation of vision picking system, certain null hypotheses were introduced. As it can be seen below, there were four null hypotheses for the order picking time and four null hypotheses for the order accuracy.

The first null hypothesis ($H_{0,1}$) states that the order picking time was the same when either glasses or headbands were used:

$$H_{0,1}: t_{glasses} = t_{headbands} \tag{5.1}$$

The second null hypothesis ($H_{0,2}$) states that the order picking time was equal when either the display was above of line of sight or the display was below of line of sight:

$$H_{0,2}: t_{above\_of\_LS} = t_{below\_of\_LS} \tag{5.2}$$

The third null hypothesis ($H_{0,3}$) states that the order picking time was equal either when the barcode type was 1D or the barcode type was 2D:

$$H_{0,3}: t_{barcode\_1D} = t_{barcode\_2D} \tag{5.3}$$

The fourth null hypothesis ($H_{0,4}$) states that the order picking time was equal either when there was confirmation during the order picking process or not:

$$H_{0,4}: t_{confirmation\_yes} = t_{confirmation\_no} \quad (5.4)$$

The fifth null hypothesis ($H_{0,5}$) states that the accuracy when glasses were used was the same with the accuracy when headbands were used:

$$H_{0,5}: f_{glasses} = f_{headbands} \quad (5.5)$$

The sixth null hypothesis ($H_{0,6}$) states that the accuracy when the display was above of line of sight was equal with the accuracy when the display was below of line of sight:

$$H_{0,6}: f_{above\_of\_LS} = f_{below\_of\_LS} \quad (5.6)$$

The seventh null hypothesis ($H_{0,7}$) states that the accuracy when the barcode type was 1D was equal with the accuracy when the barcode type was 2D:

$$H_{0,7}: f_{barcode\_1D} = f_{barcode\_2D} \quad (5.7)$$

The eighth null hypothesis ($H_{0,8}$) states that the accuracy was equal either when there was confirmation during the order picking process or not:

$$H_{0,8}: f_{confiramtion\_yes} = f_{confiramtion\_no} \quad (5.8)$$

5.4.2. Performing the experiments: subject’s features

As it can be seen in Figure 5.2, a total of 16 subjects took part in laboratory tests: nine (9) male and seven (7) female, all in the ages between 23 and 58 years. The average age of participants was 35.83 (standard deviation 10.35). Fifteen (15) subjects were right-eye dominant and one (1) is left-eye dominant eye. Four (4) of them used prescription glasses.

Subjects without previous experience of order picking process were selected to avoid previous experience biasing the results of our experiments. To compensate the lack of experience and minimize learning effects, the subjects attended a training session, where each of the subjects executed a series of orders' picking in the laboratory, making themselves familiar with vision picking system.

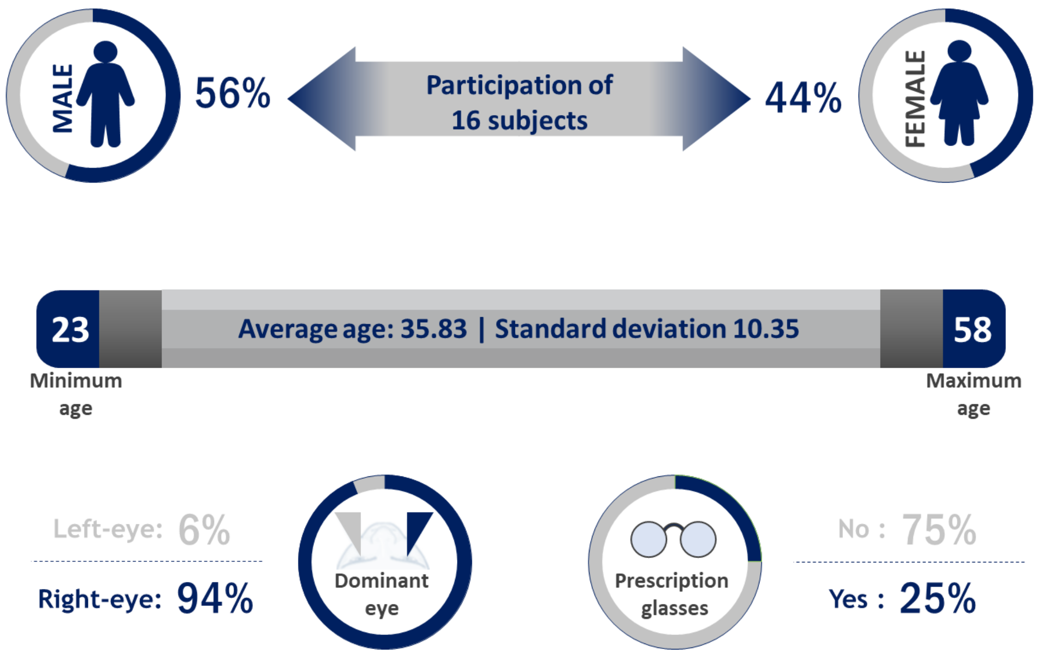


Figure 5.2 Subjects features

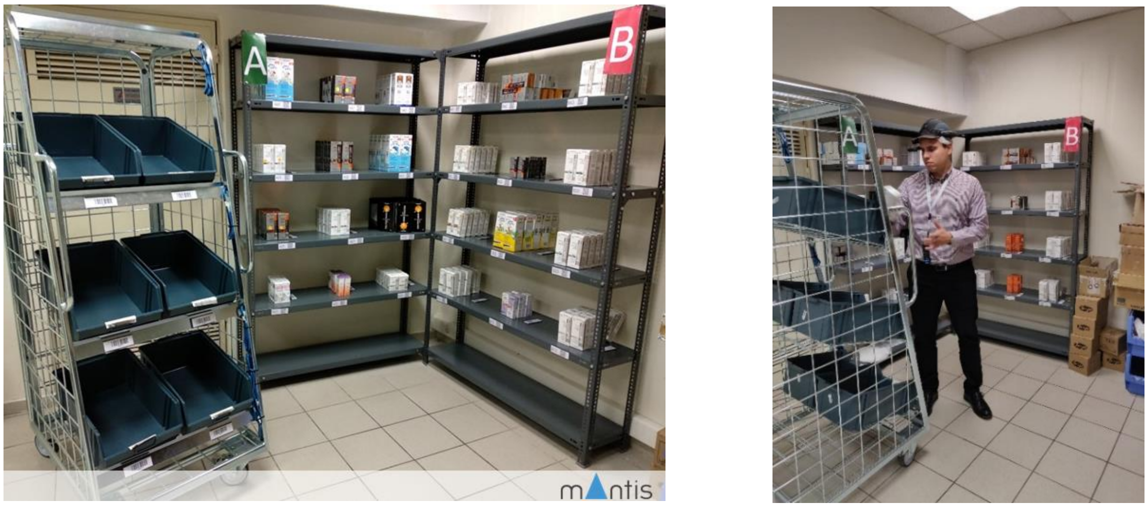
All subjects were native Greek speakers, so all instructions and survey instruments were provided to the subjects in Greek during this study. All the data for this study were collected via personal questionnaires.

5.4.3. Performing the experiments: experimental setup and equipment

The testing and evaluation of vision picking system took place in a dense-picking laboratory environment which was hosted in the headquarters of Mantis Informatics S.A. in Athens (Figure 5.3).

Our laboratory environment consisted of 24 pick bins divided between two shelving units (light duty shelving system), A and B. Each shelving unit had four rows and three columns, and each pick bin contained 10 – 15 items. The order cart, which was used during the multiple order picking, had three storage levels and each level hosted two plastic bins (totes). Each subject could pick up to 6 orders, simultaneously (each plastic bin was assigned to one order).

The subject had to finish 5 picking lists using vision picking system. Each picking list contained six orders (6) while each order included an average of seven (7) order lines. The average number of items per order line was two (2). The items were boxes in different sizes and with different weights, while all items could be handled with one hand.



(a) (b)

Figure 5.3 a) Dense-picking laboratory (Mantis Informatics S.A.) b) Photos from the execution of laboratory tests

All the experiments were accomplished by using specialized equipment. Two different types of head-mounted displays (HMDs) were used (Figure 5.4). The first HMD was the VUZIX M300 (Fieldsmir of view: 20 degrees & Weight: 380 grams) and the second HMD was the RealWear HMT-1 (Field of view: 16.7 degrees & Weight: 127 grams).

(a) (b)

Figure 5.4 a) Vuzix M300 (Smart Glasses) and b) RealWear HMT-1 (Headbands)

5.5. Statistical analysis of data

After performing the tests and collecting the necessary data (see laboratory test results in Appendix B), a quantitative analysis of the order picking time and accuracy was performed, by using ANOVA (Montgomery, 2012).

In order to evaluate the four main effects and their interactions, the P-value approach was adopted. 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 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 a-value (level of significance) which was used for this analysis was set at 5% (a=0.05).

Moreover, in order to ensure the adequacy of the underlying model it is necessary to analyze and assess a series of residual plots. More specifically, the normal probability plot is used to detect non-normality. Points that approximately follow a straight line indicate that the residuals are normally distributed. Also, the Histogram is used to detect multiple peaks, outliers, and non-normality. The normal histogram should be approximately symmetric and bell-shaped. Moreover, the residuals versus the fits is used to detect non-constant variance, missing higher-order terms and outliers. In this plot it is important to be observed residuals that are scattered randomly around zero. Furthermore, the residuals versus order is used to detect time-dependence of the residuals. In this plot, it is important to ensure that the residuals display no obvious pattern. Taking into consideration the above, the statistical analysis in terms of order picking time and order picking accuracy follows.

5.5.1. Order picking time: statistical analysis and results

In terms of order picking time, as it can be seen in Table 5.5 the results showed that only for the case of parameter “existence of confirmation” the results of ANOVA showed that there was statistically significant difference (p-values is less than 0.05). On the other hand, for all the other cases, the ANOVA results shown that there were no statistically significant differences (p-values is more than 0.05). Thus, it was proved that for the cases: $H_{0,1}$, $H_{0,2}$ and $H_{0,3}$, the null hypothesis was accepted, while for the case of $H_{0,4}$, the null hypothesis was rejected. This means that the use of vision picking system with confirmation step affects significantly the efficiency of order picking in terms of job completion, when compared with the use of vision picking system with no confirmation step.

Table 5.5 Results of statistical analysis (estimated effects) in terms of order picking time

Source of variation	Terms	P-Value
Main Effects	Display Holder	0.810
	Field of View	0.648
	Barcode Type	0.083
	Existence of confirmation	0.000
2-way interactions	Display Holder*Field of View	0.384
	Display Holder*Barcode Type	0.458
	Display Holder*Existence of confirmation	0.942
	Field of View*Barcode Type	0.116
	Field of View*Existence of confirmation	0.596
	Barcode Type*Existence of confirmation	0.662
3-way interactions	Display Holder*Field of View*Barcode Type	0.675
	Display Holder*Field of View*Existence of confirmation	0.343
	Display Holder*Barcode Type*Existence of confirmation	0.174
	Field of View*Barcode Type*Existence of confirmation	0.598
4-way interactions	Display Holder*Field of View*Barcode Type*Existence of confirmation	0.773

The results of ANOVA analysis can be confirmed in the Pareto chart (Figure 5.5). The Pareto chart uses the same significance level as the normal plot to determine the significance of effects, thus the “existence of confirmation” was the only statistically significant case in terms of order picking time.

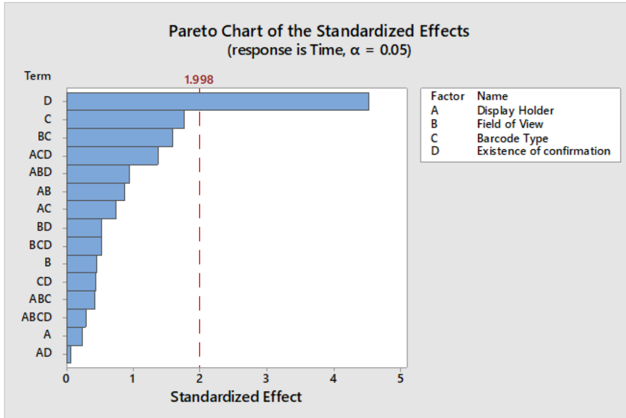


Figure 5.5 Pareto chart in terms of order picking time

In figure 5.6 the residual plots for order picking time are presented. As far as the normal probability and the histogram of the residuals' plots are concerned, it can be seen that the order picking time distribution is normally distributed, since the plot follows a straight line. Also, the residuals are scattered randomly around zero, while in the residual versus order plot no clear pattern is observed.

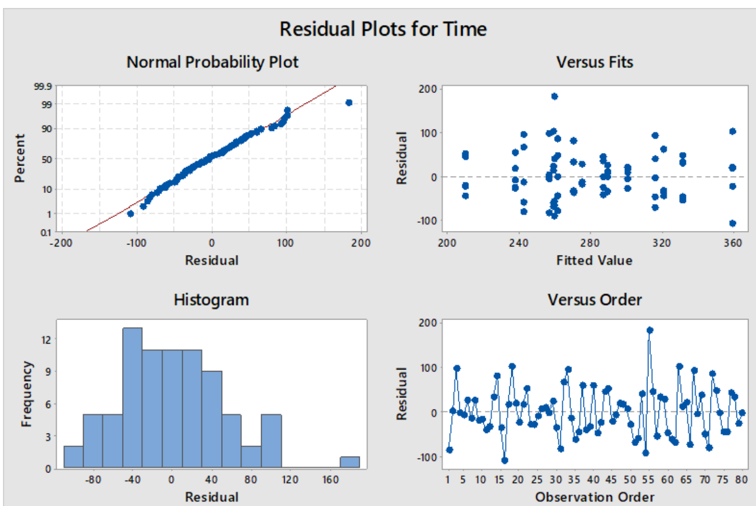


Figure 5.6 Residual Plots for order picking time

Based on the result of statistical analysis the levels of the fourth factor "existence of confirmation", affect significantly the job completion time of the vision picking. Indeed, according to the results of figure 5.7, vision picking process without confirmation can improve the order picking time on average by 19.3% (60.42 seconds reduction), when compared to the vision picking process with confirmation step.

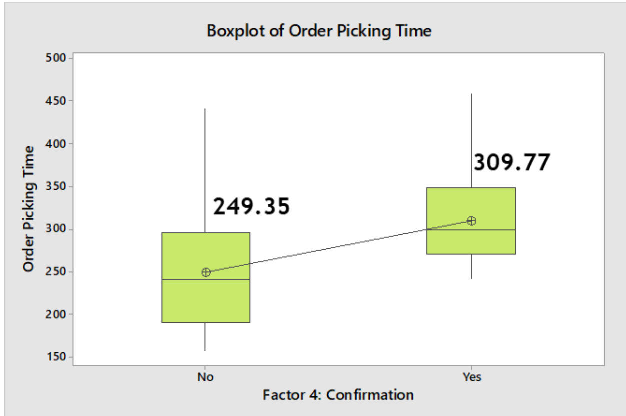


Figure 5.7 Boxplot of order picking time for the factor “existence of confirmation”

The interaction plot for all the configurations in terms of order picking time are shown in Figure 5.8.

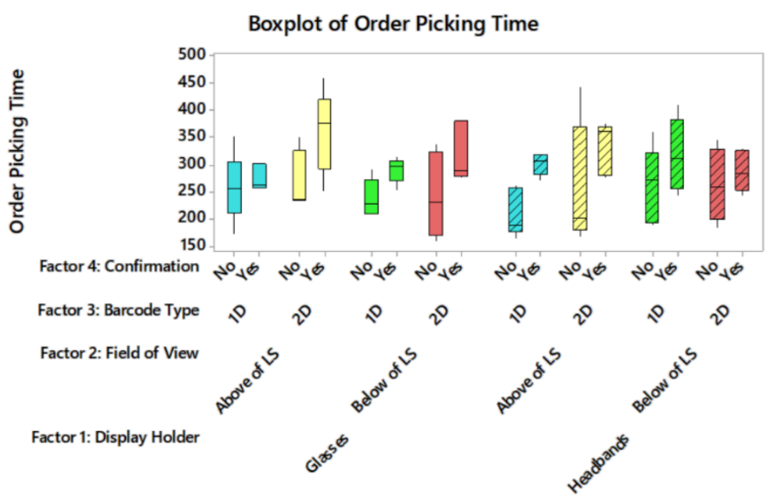


Figure 5.8 Interaction effects of Display Holder (glasses vs. headbands), Field of view / mounting options (Above of line of sight vs. below of line of sight), Barcode type (1D vs. 2D) and existence of confirmation (yes vs. no) on order picking time

Based on the results of Lab tests (see the detailed results in Appendix C), it can be seen that the differences (in terms of order picking time) in the above configurations are not statistical significant. Nevertheless, there are some configurations that provided low order picking time, when compared with the other configurations. Indeed, the “best” system configuration (set-up) in terms of order picking time (by taking into consideration all the possible configurations among the investigated factors and their levels) incorporates headbands, the display to be above of line of sight, 1D barcode and no confirmation step

(Q1 = 173.5 seconds, Median = 188 seconds, Q3 = 256.5 seconds). The second-best configuration includes headbands, the display to be above of line of sight, 2D barcode and no confirmation step (Q1 = 178.5 seconds, Median = 200 seconds, Q3 = 370 seconds). On the other hand, the configuration with the highest order picking time contains glasses, the display to be above of line of sight, 2D barcode and confirmation step (Q1 = 292 seconds, Median = 375 seconds, Q3 = 418.5 seconds).

5.5.2. Order picking accuracy: statistical analysis and results

In terms of order picking accuracy, as it can be seen in Table 5.6 the results showed that only the 2-way interaction "Field of View*Existence of confirmation" was statistically significant (p-values is less than 0.05). In terms of main effects, it was proved that for the cases: $H_{0,5}$, $H_{0,6}$, $H_{0,7}$ and $H_{0,8}$, the null hypothesis was accepted. Thus, it was concluded that the accuracy of vision picking system can be significantly affected, only by the configuration "Field of View*Existence of confirmation"; all the other configurations did not provide statistically significant differences (based on the ANOVA results) in terms of order picking accuracy.

Table 5.6 Results of statistical analysis (estimated effects) in terms of order picking accuracy

Source of variation	Terms	P-Value
Main Effects	Display Holder	0.200
	Field of View	0.635
	Barcode Type	0.498
	Existence of confirmation	0.157
2-way interactions	Display Holder*Field of View	0.177
	Display Holder*Barcode Type	0.122
	Display Holder*Existence of confirmation	1.000
	Field of View*Barcode Type	0.635
	Field of View*Existence of confirmation	0.045
	Barcode Type*Existence of confirmation	0.379
3-way interactions	Display Holder*Field of View*Barcode Type	0.224
	Display Holder*Field of View*Existence of confirmation	0.200
	Display Holder*Barcode Type*Existence of confirmation	0.343
	Field of View*Barcode Type*Existence of confirmation	0.177
4-way interactions	Display Holder*Field of View*Barcode Type*Existence of confirmation	0.310

The results of ANOVA analysis can be confirmed in the Pareto chart (Figure 5.9). The Pareto chart uses the same significance level as the normal plot to determine the significance of effects, thus the “Field of View*Existence of confirmation” configuration was the only statistically significant case in terms of order picking accuracy.

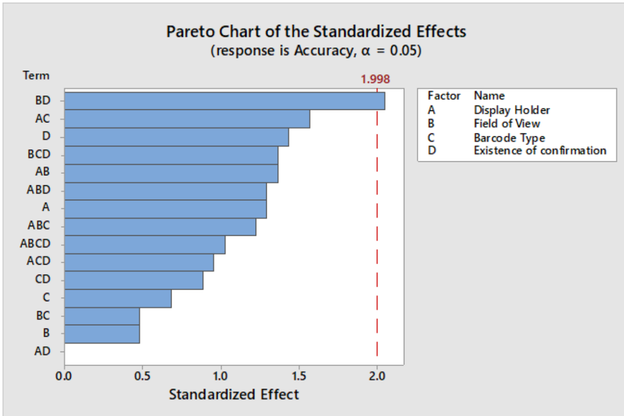


Figure 5.9 Pareto chart in terms of order picking accuracy

In figure 5.10 the residual plots for order picking accuracy are presented. As it can be seen the underlying order picking accuracy distribution is somewhat thinner (on the left side) than would be anticipated in a normal distribution. This tendency shows that the negative (on the left side) residuals are not as large as expected.

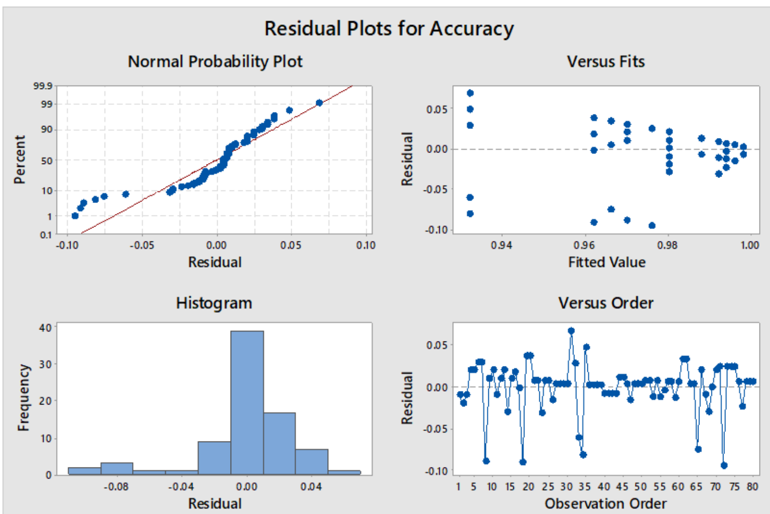


Figure 5.10 Residual Plots for order picking accuracy

The performance of order picking process in terms of accuracy can be affected significantly by the configuration “Field of View*Existence of confirmation” (Figure 5.11). Indeed, the interaction between the “Field of View” and the “Existence of confirmation” shows that when the existence of confirmation is "Yes" and the field of view (mounting options) is "Below of line of sight", the Vision picking process can be accomplished more accurate when compared with the other configuration shown in the figure 5.11.

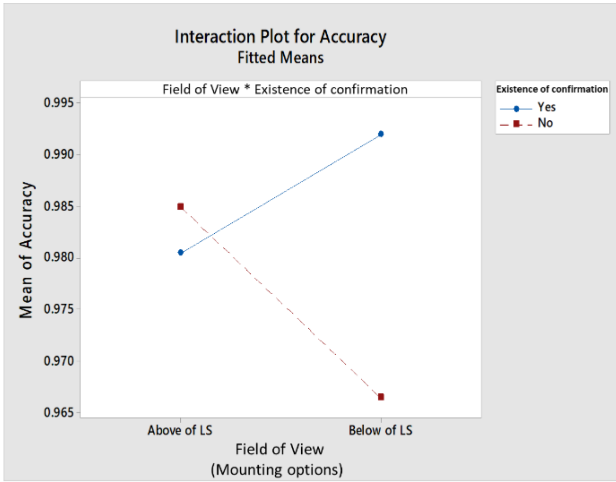


Figure 5.11 Interaction plot of Field of view / mounting options (Above of line of sight vs. below of line of sight) and existence of confirmation (yes vs. no) on order picking accuracy

The interaction plot for all the configurations in terms of order picking accuracy are shown in Figure 5.12.

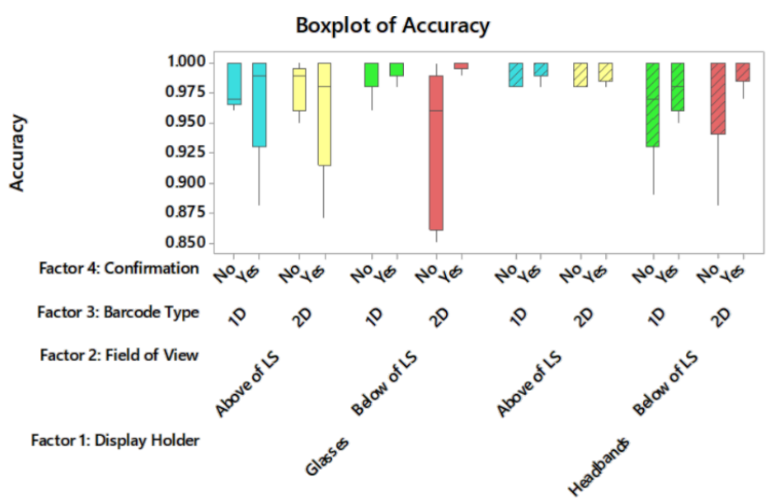


Figure 5.12 Interaction effects of Display Holder (glasses vs. headbands), Field of view / mounting options (Above of line of sight vs. below of line of sight), Barcode type (1D vs. 2D) and existence of confirmation (yes vs. no) on order picking accuracy

Based on the results of Lab tests (see the detailed results in Appendix D), it can be seen that the differences (in terms of order picking accuracy) of the configurations are insignificant. The order picking accuracy for all the configuration is high and very close to 100%. Nevertheless, there are some configurations that provide better order picking accuracy level, when compared with the other configurations. Indeed, the “best” configuration (taking into consideration all the possible configurations among the investigated factors and their levels) with the highest accuracy level embraces glasses, the display to be below of line of sight, 2D barcode and existence confirmation step (Q1 = 0.995, Median = 1, Q3 = 1), while the configuration with the lowest accuracy level includes glasses, the display to be above of line of sight, 2D barcode and no confirmation step (Q1 = 0.96, Median = 0.99, Q3 = 0.995).

5.6. Conclusions and recommendations

This chapter presented the results from 80 tests that have been conducted in lab environment in order to identify the optimal setup of a proposed vision picking system both in terms of picking efficiency as well as of picking accuracy. The best system set-up when picking efficiency is considered embraces no confirmation step. In terms of picking accuracy the best configuration for error reduction embraces the display to be below of line of sight and existence of confirmation step.

5.7. Summary

This chapter presented the evaluation of vision picking system during its testing in laboratory environment. The system was assessed in terms of order picking efficiency (time) and accuracy. In terms of order picking time, the results indicated that the only parameter that was statistically significant (based on the ANOVA results) was the “existence of confirmation”. Indeed, vision picking process without confirmation step can improve the order picking time, when compared to the vision picking process with confirmation step. In terms of order picking accuracy, the results showed that a 2-way interaction (i.e. “Field of View*Existence of confirmation”). In this case, the best configuration for high levels of accuracy, is achieved when the display is set to “below of line of sight” and no confirmation step exists.

Chapter 6. Evaluation of vision picking system perceived workload

In this chapter we adopt the NASA TLX survey for the assessment of the proposed system perceived workload. Initially, the theoretical background of NASA TLX technique, as well as its six subscales is described. Then, the implementation steps, the rating scale as well as the equation for the calculation of total NASA TLX score are presented. Finally, the last section of this chapter contains the presentation of the results obtained and a benchmarking that was made with the results of similar studies.

6.1. Theoretical background

A useful technique for workload evaluation is subjective assessment, which includes methods such as NASA-TLX, SWAT and CH (Yiyuan *et al.,* 2011). Among them, NASA-TLX is the most widely used, and it has achieved some solid goals in human factors research. NASA Task Load Index (NASA TLX) is a widely used subjective multidimensional assessment tool that rates perceived workload in order to assess a task, system or process (NASA, 1986) and is suggested to be used during system design and development phases.

As it can be seen in Table 6.1, the NASA TLX is based on a weighted average of ratings of six subscales (NASA, 1986; Farmer and Brownson, 2003). Three dimensions are related to the demands imposed on the subject (Mental demand, Physical demand and Temporal demand) and three to the interaction of a subject with the task (Effort, Frustration and Performance).

To this point, it is worth mentioning that a significant number of similar studies have taken into account the NASA TLX as a technique in order to evaluate the perceived workload of vision picking system (Schwerdtfeger *et al.,* 2009; Weaver *et al.,* 2010; Baumann *et al.,* 2011; Guo *et al.,* 2015; Wu *et al.,* 2015; Renner and Pfeiffer, 2017; Kim *et al.,* 2019). To this end, the NASA TLX methodology was used in this study in order to be assessed the perceived workload of vision picking system.

Table 6.1 The six subscales of NASA TLX (NASA, 1986)

Name of subscale	Description of subscale
Mental Demand	The first subscale is used to define how much mental and perceptual activity was required by the subjects during the execution of task. Also, this subscale assesses if the task was easy or demanding, simple or complex and exacting or forgiving.
Physical Demands	The second subscale is considered in order to describe how much physical activity was required. More specifically, this subscale evaluates if the task was easy or demanding, slow or brisk, slack or strenuous and restful or laborious.
Temporal Demands	The third subscale is taken into consideration in order to express how much time pressure, the tester (participant in experiment) felt due to the rate or pace at which the tasks or lack elements occurred. This subscale assesses if the pace was slow and leisure or rapid and frantic.
Performance	The fourth subscale is used to define how successful the tester was in accomplishing the goals of the task. More specifically, this subscale presents how satisfied the tester was with his/her performance in accomplishing these goals.
Effort	The fifth subscale is used to present how hard the tester has to work (mentally and physically) in order to accomplish his/her level of performance.
Frustration	The last subscale is used in order to express how insecure, discouraged, irritated, stresses and annoyed versus secure gratified, content, relaxed and complacent the tester felt during the task.

6.2. NASA TLX Implementation steps

According to NASA (1986), the implementation of NASA TLX includes two steps. The first step deals with the source of load (weights) and the second step with the magnitude of loads (rating).

Step 1: Source of load

During the first step, each subject has to evaluate the contribution of each factor (its weight) to the workload of a specific task. More specifically there are fifteen possible pair-wise comparisons (see Appendix C) of the six scales and each subject is necessary to circle the member of each pair that contributed more to the workload of that task. The total number of times that each factor is selected is tallied and the range of tallies can range from 0 (not relevant factor) to 5 (more important than any other factor) (NASA, 1986).

Step 2: Magnitude of load

In the second step each subject has to achieve numerical ratings for each scale that reflects the magnitude of that factor in a given task. This rating takes place by completing a form (see Appendix C) with rating scale from 0 (lowest workload) – 100 (highest workload) (NASA, 1986).

Upon completion of these two steps from all the subjects, the calculation of the overall workload for each subject takes place by using the equation 4.1:

$$Overal\ Weight == \frac{\left(\sum_{i=1}^{n} Ri \cdot Wi\right)}{15} \qquad (4.1)$$

Where,
Ri = Rating for factor (subscale) i, Wi = Weight for factor (subscale) i and n = the total number of factors (subscales).

6.3. Analysis, results and benchmarking

Taking into consideration the suggested experimental procedure (NASA, 1986), the NASA TLX survey was adopted, in order to assess the vision picking system in terms of perceived workload.

After performing the test, each subject had to complete the NASA TLX questionnaire after their participation in vision picking laboratory tests. A total of 16 participants completed the questionnaire, taking into account the implementation steps as well as some important instructions by the investigators. Figure 6.1, presents the results of NASA TLX survey.

According to the results in Figure 6.1, the NASA TLX score for vision picking system is: M = 35.1 *(SD = 12.4).* Focusing on the individual subscales of NASA TLX score, the physical demand *(M = 58.4)* and frustration level *(M = 55.3)* have the highest score, followed by mental demand *(M = 49.7)*, temporal demand *(M = 46.3)* and effort *(M = 42.5)*. On the contrary the performance is the subscale with the lowest score *(M = 21.9)*.

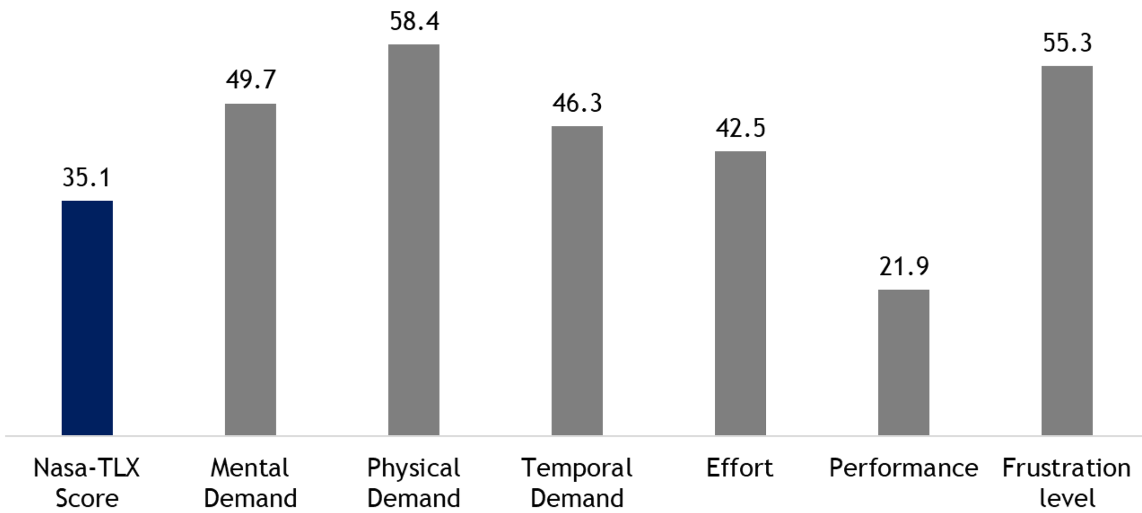


Figure 6.1 NASA-TLX results for vision picking system

According to the results of NASA-TLX score, it was revealed that the physical demand and the frustration level received a high score. Indeed, a significant number of subjects mentioned that it was tiring to crouch and pick items from the low levels of racks and as a result, they argued that the task was a bit strenuous and laborious for their legs. Furthermore, some others claimed that it was difficult to scan with their glasses or headbands the barcodes of the low levels of racks. Also, some subjects were stressed and annoyed during the first minutes, but they mentioned that as time went on, they felt better with the use of the equipment and the performing of their tasks. In terms of mental demand, the subjects said that the instructions and all the necessary information were available on display, and as a result medium mental and perceptual activity was required. As far as the temporal demand was concerned, the subjects felt that they performed their task quickly, but the most of them supported that they could execute the task even quicker if they were more familiar with the equipment. In terms of effort and performance, the results obtained showed that it was not necessary for the subjects to work hard in order to accomplish their level of performance and also that they felt quite satisfied with their performance. The general impression from all participants was that the proposed technology was not difficult to be used, but it required a significant amount of time in order someone to be familiar with it.

Table 6.2, depicts TLX scores from similar studies available in literature. Taking into consideration the NASA TLX score *(M = 35.1, SD = 12.4)* of our evaluation procedure, it can be seen that the perceived workload is adequate when compared with similar studies. To this end, the results of NASA TLX survey for this study, are encouraging and shown that the proposed system may have significant benefits during the execution of order picking process.

Table 6.2 NASA TLX score of similar studies (Vision Picking system testing)

Source	NASA TLX score
(Schwerdtfeger *et al.,* 2009)	Mean Value: 28
(Weaver *et al.,* 2010)	Mean Value: 12.3
(Baumann *et al.,* 2011)	[3]Mean Value: 46.1
(Wu *et al.,* 2015)	Mean Value: 45.7
(Renner and Pfeiffer, 2017)	Range Value: 20 – 56 *(these values are obtained for different types of display)*

Nevertheless, it is important to mention that the current score (M = 35.1, SD = 12.4) was obtained in a laboratory environment. If the same tests are conducted in real life scenario (industrial environment), this score may be altered (i.e. increased).

6.4. Summary

This chapter presented the results of NASA TLX survey. By taking into consideration the responses of 16 subjects (who filled the NASA TLX questionnaires), the results of the NASA TLX score showed that the perceived workload was adequate when compared with similar studies. While focusing on the individual subscales of NASA TLX score, the physical demand and frustration level have the highest score, followed by mental demand, temporal demand, effort and performance.

[3] Mean value of NASA TLX score is calculated by the author of this thesis, based on the primary data of the following article: (Baumann et al., 2011)

Chapter 7. Vision picking system managerial implications and gaps

The aim of this section is threefold. Initially the managerial implications that stem from the adoption of vision picking system are presented. Subsequently, gaps that currently exist, and which are crucial for both further investigation as well as for insights into the needs of practitioners, are presented.

7.2. Managerial implications

The digital transformation of an organization, via the adoption of vision picking system in order picking process, is a complex task and various issues should be taken into consideration in order for the business to have a smooth and successful transition to a new business model. The key implications mainly deal with: a) organizational culture, b) process re-engineering, c) staff resistance to change, and d) motivation for maintaining the new way of doing business. The latter are discussed below in more detail.

Organizational culture: Digital transformation may include automation tools such as vision picking system for logistics operations, but true digital transformation means more than updating technology or redesigning products. Because digital transformation can create discomfort within the workforce if not managed properly, it also requires a comprehensive and collaborative effort to shift an organization’s culture to understand, embrace, and advance it. The consequences for organizations that do not align their digital transformation goals with employee values usually can range from slow adoption of digital technologies to loss of market competitiveness to ultimate failure of the initiative and lost productivity and revenue (Deloitte, 2019).

Process re-engineering: Organizations is important to understand that using technology to transform their logistics operations is crucial, but the key to success lies in finding out what ails the business. This means that an initial step before introducing a new technology is to identify the logistics processes that are sub-par or inefficient and try to change them. The aim should be to transform these costly processes (e.g. order picking) to deliver more value to the customer by improvements in productivity. The introduction of a new technology could support such improvements.

Staff resistance to change: Technological innovation is a natural, healthy and wholly expected part of running a business. However, usually people resist technological change since the latter poses a major threat to workers' sense of security, stability and purpose. The same applies for the case of introducing a new method of executing order picking. Some strategies for encouraging employees to rapidly adopt such a technology include: continuous staff training and development, simple and user-friendly systems, and technologies that are connected to people's needs (i.e. the staff of a warehouse should be able to understand how vision picking will directly impact and transform their working lives, and how it will improve their workflow and productivity).

Motivation for maintaining the new way of doing business: Digital transformation does not stop up to the point that a system is installed and the users are trained. A continuous effort is needed for maintain the motivation of the users e.g. by giving them various incentives that are connected with the use of the new system. Furthermore, it is important to encourage people to share suggestions for improvements, create spaces for honest feedback, and respond to the concerns people raise.

7.3. Gaps for further investigation

The identification of the gaps for further investigation is based on an elaboration regarding the issues that have not been addressed in this thesis and focuses on human, technical and operational aspects that affect the adoption of vision picking system.

Human factor: Human factor is crucial when emerging s, such as vision picking, are put into practice especially in product picking, where the user (picker) should accomplish a complex task in a timely manner. Indeed, Schwerdtfeger *et al.* (2011) argue that large learning and fascination effects exist when using Augmented Reality (AR) for the first time in vision picking. This is an issue that may be tackled by providing extensive training sessions before use. Furthermore, in Schwerdtfeger *et al.* (2009), it is shown that although most people can work with the system over a longer period of time without being more strained than using a conventional paper-based picking system, yet there is still problem that some people had serious trouble to read continuously from a headband or a smart glass device. Other issues that should be further investigated include user mental and physical demand, performance and frustration level.

The role of User Interface on performance and workers' safety: Another important aspect in vision picking adoption is the User Interface (UI) of the headband/smart glasses. Schwerdtfeger *et al.,* (2006) present initial results on comparing visualization schemes for order picking across several types of displays. The results reveal that neither the 2D strip map nor the 3D visualization is on average faster for Wayfinding or Picking than the 1D textual list. However, separating the subjects into Augmented Reality (AR) / Virtual Reality (VR) experienced and unexperienced users showed that there is a group of users, which is faster and more productive with an AR system. Furthermore, walking while processing visual information presented via Head Worn Displays (HWD) may cause gait adaptations such as using more conservative and hesitant gait and more conservative obstacle crossing strategies (Licence *et al.,* 2015; Kim *et al.,* 2018). Thus, the use of such equipment for product picking may have important workplace safety implications given to the prevalence of slips, trips and falls-related injuries. Given this, and the limitations discussed above, future efforts are needed to investigate how different HWD types and UI designs may affect worker safety and work performance with routine or frequent use in a workplace, and also to understand better the impacts of HWD use on diverse working populations over time (Kim *et al.,* 2019).

Technical issues: One of the biggest obstacles, as mentioned also in Bräuer and Mazarakis, (2018), for porting such systems from the research stage into practical applications, is the hardware components, especially the HWD and the tracking system. Currently, there is a continuous development of these components since gaming industry starts adopting AR and HWDs and soon will be a part of the everyday life within mobile multimedia applications. Therefore, HWDs could be used in industrial applications within the next five years. Furthermore, integration issues of vision picking with other systems is another critical issue that should be further investigated. Indeed, according to Krajcovic *et al.,* (2014) the problem of AR applications in the processes of picking requires further research especially in terms of closer integration of AR and Warehouse Management Systems (WMS), increasing comfort of hardware components (wireless glasses, mobile terminal) and the possibility of linking the picking system with automatic identification systems such as barcodes, RFID tags and so forth. Last but not least, battery life and distance of scanning are also issues for further investigation.

Comparative assessment with other picking systems: Gaps currently exist also in the comparative assessment of vision picking system with other picking systems (such as pick-by-voice, pick-by-light, etc.). Indeed, experiments (either lab or field-based) should be conducted in order to explore the effects that vision picking may have in terms of picking accuracy and efficiency when compared with other picking systems. Furthermore, such experiments may be expanded by looking at the effects of adding context sensing to the environment. According to Weaver *et al.,* (2010), there are two ways that a warehouse inventory system can know that a part has been picked: (a) either the picker has performed some action, such as saying a command or pushed a button on the part bin, or (b) the system can use sensors to determine automatically when a part has been picked. Lastly, it is worth assessing error rates, speed, investment costs, and the flexibility of alternative picking systems in order to formulate a series of guidelines as to which system is best for a given environment.

Chapter 8. Conclusions and future research agenda

This chapter presents initially a summary of this research followed by its key findings from laboratory experiments in terms of vision picking efficiency, accuracy and perceived workload. Then the next steps as well as guidelines for future research are described.

8.1. Thesis summary and main conclusions

The main aim of this thesis was to design and test a vision picking system that can be used for product picking in a warehouse facility. In order to accomplish the aforementioned aim, three objectives were achieved. The first objective was to review a set of parameters that can be taken into consideration for vision picking system design, development and testing. The second objective focused on the selection of the most appropriate parameters for testing vision picking system, while the third dealt with the conduction of laboratory tests for the evaluation and assessment of vision picking system in terms of order picking time (efficiency), accuracy and workload.

The review of parameters for vision picking system was conducted by using the SLR method. The research identified 20 critical parameters that were classified into three categories, namely: a) system parameterization, b) operational performance and, c) comparative assessment with other picking systems. Based on the review, only 20 articles within the field of vision picking design parameters were identified. The latter supports the fact that vision picking system and design parameters for such systems are currently under investigation and further research should be conducted.

By taking into consideration the outcome of the Systematic Literature Review, a selection of three parameters (Display Holder, Field of View, Barcode Type) was made by using the Analytical Hierarchy Process (AHP), while one more parameter (i.e. existence of confirmation) which deals with the operational performance of vision picking process was considered based on the input received by logistics executives. The latter was included in the set of parameters that were tested in laboratory environment, since it affects both the acceptance of the system, by the end users as well as the performance of the system. The testing of vision picking system was accomplished via a series of laboratory tests that were conducted by adopting the Design of Experiments (DoE) methodology. A full factorial design has been used that incorporates 4 factors at two levels (2^4 full factorial design).

The laboratory setup which was developed in cooperation with a Greek IT company (Mantis Informatics S.A.), consisted of 24 pick bins divided between two shelving units. Each shelving unit had four rows and three columns and each pick bin contained 10 – 15 items. The order cart, which was used during the multiple order picking, had three storage levels and each level hosted two plastic bins (totes). Two different types of head-mounted displays (HMDs) were used. The first HMD was the VUZIX M300 and the second HMD is the Real Wear HMT-1.

Eighty (80) tests were conducted in order to identify the optimal setup of the proposed vision picking system both in terms of order picking efficiency and accuracy. Furthermore, the perceived workload of vision picking system was evaluated via NASA TLX survey.

In terms of order picking time, the results indicated that the only parameter that was statistically significant (based on the ANOVA results) was the “existence of confirmation”. Indeed, vision picking process without confirmation step can improve the order picking time, when compared to the vision picking process with confirmation step. In terms of order picking accuracy, the results showed that a 2-way interaction (i.e. “Field of View*Existence of confirmation”). In this case, the best configuration for high levels of accuracy, is achieved when the display is set to “below of line of sight” and no confirmation step exists. In terms of perceived workload, the NASA TLX score showed that the workload was adequate when compared with similar studies. While focusing on the individual subscales of NASA TLX score, the physical demand and frustration level have the highest score, followed by mental demand, temporal demand, effort and performance.

8.2. Future research agenda

Based on the findings of this thesis, a future research agenda on the design, development and testing of vision picking system is presented below.

Enhance User Interface (UI) design: Designing a user interface for vision picking systems requires a completely different approach when compared to other devices, such as RF-scanners and wearable barcode scanners that are also used for order picking. A critical issue is low information content, as the main goal should be not to block out user's view with lots of graphic objects. There is currently a lack of general guidelines for how to design efficient user interfaces making use of augmented reality.

Improve head worn displays and devices: Current head worn displays are not really wearable, and this fact affects negatively their everyday use on a warehouse. An initial drawback is that current vision picking devices weight too much and cannot be worn for extended periods. Furthermore, most head worn displays come with a cable running from the glasses to a handheld device or spare batteries attached to the operator, and this cable is often disturbing. Finally, for users that wear ordinary glasses, it is difficult to use such devices for order picking operation. All three issues mentioned above need further research.

Extend lab tests to field tests: Most of the research conducted in vision picking system as well as the results that are published are obtained mainly from lab tests. However, a warehouse differs greatly from lab environment since products are placed in multiple pick phases all over the area, pickers are stressed and are more to susceptible to mistakes and furthermore, such environments are also subject to considerable noise from machines and transportation. It is thus of great importance to test vision picking system in real-life environment and due to noise, voice recognition becomes a great challenge. To this end, special functionalities should be implemented in voice software to reduce noise and identify the right commands.

Enable benchmarking evaluation: Comparing vision picking system designs with each other to identify the best one, needs an effective and objective benchmarking method. To the best of the authors' knowledge there is currently no such benchmark method for evaluating the efficiency of augmented reality-based design (Wang et al., 2016). Developing a method for the benchmark evaluation of user interfaces for vision picking systems merits attention in the future.

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Appendix A – AHP questionnaire

In this appendix the questionnaire for the ranking of design and development parameters of vision picking system is presented.

Questionnaire - Type 1: Pair wise comparison matrix (PWCM) of criteria

Criteria	Fundamental scale of absolute numbers																	Criteria
Ergonomic aspects	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Visualization aspects
Ergonomic aspects	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Technical aspects
Visualization aspects	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Ergonomic aspects
Visualization aspects	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Technical aspects
Technical aspects	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Ergonomic aspects
Technical aspects	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Visualization aspects

Questionnaire - Type 2: Pair wise comparison matrix (PWCM) of ergonomic aspects dimension

Constructs under Ergonomic aspects dimension	Fundamental scale of absolute numbers																	Constructs inder Ergonomic aspects dimension
Display Type	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Interaction Device
Display Type	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Display Holder
Display Type	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Weigh of Equipment
Interaction Device	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Display Type
Interaction Device	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Display Holder
Interaction Device	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Weigh of Equipment
Display Holder	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Display Type
Display Holder	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Interaction Device
Display Holder	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Weigh of Equipment
Weigh of Equipment	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Display Type
Weigh of Equipment	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Interaction Device
Weigh of Equipment	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Display Holder

Questionnaire - Type 2: Pair wise comparison matrix (PWCM) of visualization aspects dimension

Constructs under Visualization aspects dimension	Fundamental scale of absolute numbers																	Constructs under Visualization aspects dimension
Field of view	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Information mode
Field of view	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Information availability
Field of view	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Display view
Field of view	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Existence of AR
Field of view	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Display Settings
Information mode	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Field of view
Information mode	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Information availability
Information mode	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Display view
Information mode	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Existence of AR
Information mode	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Display Settings
Information availability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Field of view
Information availability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Information mode
Information availability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Display view
Information availability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Existence of AR
Information availability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Display Settings
Display view	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Field of view
Display view	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Information mode
Display view	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Information availability
Display view	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Existence of AR
Display view	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Display Settings
Existence of AR	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Field of view
Existence of AR	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Information mode
Existence of AR	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Information availability
Existence of AR	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Display view
Existence of AR	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Display Settings
Display Settings	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Field of view
Display Settings	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Information mode
Display Settings	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Information availability
Display Settings	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Display view
Display Settings	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Existence of AR

Questionnaire - Type 2: Pair wise comparison matrix (PWCM) of technical aspects dimension

Constructs under Technical aspects dimension	Fundamental scale of absolute numbers																	Constructs under Technical aspects dimension
Barcode type	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Scanning distance
Barcode type	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Battery life
Barcode type	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Tracking system
Scanning distance	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Barcode type
Scanning distance	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Battery life
Scanning distance	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Tracking system
Battery life	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Barcode type
Battery life	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Scanning distance
Battery life	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Tracking system
Tracking system	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Barcode type
Tracking system	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Scanning distance
Tracking system	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Battery life

Appendix B – Detailed lab test results

In this appendix the results of vision picking laboratory tests are presented.

Factor 1: Display Holder	Factor 2: Field of View	Factor 3: Barcode Type	Factor 4: Confirmation	Order Picking Time	Order Picking Accuracy
Headbands	Above of LS	2D	No	190.0	1.0
Headbands	Above of LS	2D	No	200.0	1.0
Headbands	Above of LS	2D	No	298.0	1.0
Headbands	Below of LS	2D	No	180.0	1.0
Headbands	Below of LS	2D	Yes	242.0	1.0
Glasses	Below of LS	2D	Yes	275.0	1.0
Glasses	Above of LS	1D	Yes	300.0	1.0
Glasses	Above of LS	2D	Yes	250.0	1.0
Glasses	Below of LS	2D	No	158.0	1.0
Glasses	Above of LS	1D	Yes	260.0	1.0
Glasses	Below of LS	2D	Yes	380.0	1.0
Glasses	Above of LS	2D	Yes	375.0	1.0
Glasses	Above of LS	2D	No	230.0	1.0
Glasses	Above of LS	2D	No	235.0	1.0
Glasses	Above of LS	2D	Yes	460.0	0.9
Headbands	Above of LS	1D	No	162.0	1.0
Headbands	Below of LS	1D	No	196.0	1.0
Headbands	Above of LS	1D	No	185.0	1.0
Headbands	Above of LS	2D	Yes	376.0	1.0
Headbands	Above of LS	1D	No	253.0	1.0
Glasses	Above of LS	1D	No	170.0	1.0
Glasses	Above of LS	1D	Yes	301.0	0.9
Glasses	Below of LS	1D	No	253.0	1.0
Glasses	Above of LS	1D	No	257.0	1.0
Glasses	Above of LS	2D	No	302.0	1.0
Headbands	Below of LS	1D	No	188.0	1.0
Headbands	Above of LS	1D	Yes	292.0	1.0
Headbands	Above of LS	2D	No	167.0	1.0
Headbands	Above of LS	2D	Yes	275.0	1.0
Headbands	Below of LS	1D	Yes	242.0	1.0
Glasses	Below of LS	1D	Yes	295.0	1.0
Glasses	Below of LS	2D	No	307.0	1.0
Glasses	Above of LS	2D	No	350.0	1.0
Glasses	Above of LS	2D	Yes	377.0	1.0
Glasses	Below of LS	1D	Yes	299.0	1.0
Headbands	Above of LS	2D	No	442.0	1.0
Headbands	Below of LS	2D	No	345.0	0.9
Headbands	Below of LS	1D	Yes	408.0	1.0
Headbands	Below of LS	1D	No	360.0	1.0
Headbands	Below of LS	1D	No	270.0	1.0
Glasses	Below of LS	2D	No	337.0	0.9
Glasses	Above of LS	1D	Yes	255.0	1.0
Glasses	Below of LS	2D	No	228.0	0.9
Glasses	Below of LS	2D	No	180.0	1.0
Glasses	Below of LS	1D	No	290.0	1.0
Headbands	Above of LS	1D	No	260.0	1.0
Headbands	Below of LS	2D	No	308.0	1.0
Headbands	Above of LS	1D	Yes	318.0	1.0
Headbands	Below of LS	1D	No	280.0	0.9
Headbands	Below of LS	1D	Yes	310.0	1.0
Glasses	Below of LS	1D	No	208.0	1.0
Glasses	Above of LS	1D	No	353.0	1.0
Glasses	Below of LS	1D	No	209.0	1.0
Glasses	Below of LS	1D	Yes	287.0	1.0
Glasses	Below of LS	1D	Yes	313.0	1.0
Headbands	Below of LS	1D	Yes	354.0	1.0
Headbands	Above of LS	2D	Yes	363.0	1.0
Headbands	Below of LS	2D	Yes	330.0	1.0
Headbands	Below of LS	2D	Yes	320.0	1.0
Headbands	Above of LS	2D	Yes	360.0	1.0
Glasses	Above of LS	2D	No	234.0	1.0
Glasses	Above of LS	1D	Yes	258.0	1.0
Glasses	Below of LS	2D	Yes	280.0	1.0
Glasses	Below of LS	1D	Yes	252.0	1.0
Glasses	Below of LS	2D	Yes	287.0	1.0
Headbands	Below of LS	2D	No	258.0	1.0
Headbands	Below of LS	2D	No	215.0	1.0
Headbands	Above of LS	1D	No	188.0	1.0
Headbands	Above of LS	1D	Yes	315.0	1.0
Headbands	Above of LS	1D	Yes	306.0	1.0
Glasses	Above of LS	1D	No	253.0	1.0
Glasses	Below of LS	2D	Yes	380.0	1.0
Glasses	Above of LS	1D	No	248.0	1.0
Glasses	Below of LS	1D	No	227.0	1.0
Glasses	Above of LS	2D	Yes	334.0	1.0
Headbands	Above of LS	1D	Yes	270.0	1.0
Headbands	Above of LS	2D	Yes	283.0	1.0
Headbands	Below of LS	2D	Yes	260.0	1.0
Headbands	Below of LS	1D	Yes	266.0	1.0
Headbands	Below of LS	2D	Yes	283.0	1.0

Appendix C – Results of interaction effects on order picking time

In this appendix the results of interaction effects of Display Holder (glasses vs. headbands), Field of view / mounting options (Above of line of sight vs. below of line of sight), Barcode type (1D vs. 2D) and existence of confirmation (yes vs. no) in terms of order picking time are presented.

Factor 1	Glasses	Glasses	Glasses	Glasses	Glasses	Glasses	Glasses	Glasses	Headbands	Headbands	Headbands	Headbands	Headbands	Headbands	Headbands	Headbands
Factor 2	Above of LS	Above of LS	Above of LS	Above of LS	Below of LS	Below of LS	Below of LS	Below of LS	Above of LS	Above of LS	Above of LS	Above of LS	Below of LS	Below of LS	Below of LS	Below of LS
Factor 3	1D	1D	2D	2D	1D	1D	2D	2D	1D	1D	2D	2D	1D	1D	2D	2D
Factor 4	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Q1 (Second)	209	256.5	232	292	208.5	269.5	169	277.5	173.5	281	178.5	279	192	254	197.5	251
Median (Second)	253	260	235	375	227	295	228	287	**188**	306	200	360	270	310	258	283
Q3 (Second)	305	300.5	326	418.5	271.5	306	322	380	256.5	316.5	370	369.5	320	381	326.5	325

Appendix D – Results of interaction effects on order picking accuracy

In this appendix the results of interaction effects of Display Holder (glasses vs. headbands), Field of view / mounting options (Above of line of sight vs. below of line of sight), Barcode type (1D vs. 2D) and existence of confirmation (yes vs. no) in terms of order picking accuracy are presented.

Factor 1	Glasses	Glasses	Glasses	Glasses	Glasses	Glasses	Glasses	Glasses	Headbands	Headbands	Headbands	Headbands	Headbands	Headbands	Headbands	Headbands
Factor 2	Above of LS	Above of LS	Above of LS	Above of LS	Below of LS	Below of LS	Below of LS	Below of LS	Above of LS	Above of LS	Above of LS	Above of LS	Below of LS	Below of LS	Below of LS	Below of LS
Factor 3	1D	1D	2D	2D	1D	1D	2D	2D	1D	1D	2D	2D	1D	1D	2D	2D
Factor 4	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Q1	0.965	0.93	0.96	0.915	0.98	0.99	0.86	0.995	0.98	0.99	0.98	0.985	0.93	0.96	0.94	0.985
Median	0.97	0.99	0.99	0.98	1	1	0.96	1	0.98	1	1	1	0.97	0.98	1	1
Q3	1	1	0.995	1	1	1	0.99	1	1	1	1	1	1	1	1	1

Appendix E – NASA TLX questionnaire

In this appendix the form for the weighting of factors is presented.

Name of participant: ……………………… Date: ………………………..

Rating Scale Definitions		
Mental Demand	**Low/ High**	How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical Demand	**Low/ High**	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
Temporal Demand	**Low/ High**	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
Effort	**Low/ High**	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Performance	**Low/ High**	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
Frustration level	**Low/ High**	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Step 1: Evaluate the contribution of each factor to the workload

Select the most important factor for each of the following 15 combinations.

Effort Or Performance	**Temporal Demand Or Frustration**	**Temporal Demand Or Effort**
Physical Demand Or Frustration	**Performance Or Frustration**	**Physical Demand Or Temporal Demand**
Physical Demand Or Performance	**Temporal Demand Or Mental Demand**	**Frustration Or Effort**
Performance Or Mental Demand	**Performance Or Temporal Demand**	**Mental Demand Or Effort**
Mental Demand Or Physical Demand	**Effort Or Physical Demand**	**Frustration Or Mental Demand**

Step 2: Assess the magnitude of each factor

Rate the magnitude of each factor based on the rating scale

Mental Demand

How mentally demanding was the task?

0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100

Physical Demand

How physically demanding was the task?

0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100

Temporal Demand

How hurried or rushed was the pace of the task?

0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100

Performance

How successful were you in accomplishing what you were asked to do?

0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100

Effort

How hard did you have to work to accomplish your level of performance?

0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100

Frustration

How insecure, discouraged, irritated, stressed, and annoyed were you?

0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100