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Air Transportation Management Department

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MASTER THESIS
(EXPLANATORY NOTES)

Theme: “Drones usage in the airport warehouse system”

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МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ
НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ
Факультет транспорту, менеджменту і логістики
Кафедра організації авіаційних перевезень

ДОПУСТИТИ ДО ЗАХИСТУ
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ДИПЛОМНА РОБОТА
(ПОЯСНЮВАЛЬНА ЗАПИСКА)

ВИПУСКНИКА ОСВІТНЬОГО СТУПЕНЯ «МАГІСТР»

Тема: «Застосування дронів в складській системі аеропорту»

Виконавець: Копін О.

Керівник: к.т.н., доцент, Шевченко Юлія Вікторівна.

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Київ 2020

NATIONAL AVIATION UNIVERSITY
Faculty of Transport, Management and Logistics
Air Transportation Management Department
Major 8.07010102 «Air Transportation Management»

APPROVED BY
Head of the Department
____________________ Yun G.M.
“______”_________________2020

TASK
of completion the master thesis
Oleksii Kopin

1. Theme of the master thesis entitled “Drones usage in the airport warehouse system” was approved by a decree of the Rector order № 2401/st.of October 17th, 2019.

2. Term performance of thesis: from 14.10.2019 to 29.12.2019 and from 20.01.2020 to 9.02.2020.

3. Initial data required for writing the master thesis: innovative warehouse technologies, drones statistics, worldwide air cargo statistical data, warehouse automation statistical data.

4. Content of the explanatory notes: abstract, contents, notation list, introduction, theoretical part (general characteristics of industry 4.0: opportunities, challenges of airport and airline management practices, industry 4.0 and the current status as well as future prospects on logistics, models for warehouse management: classification and examples); analytical part (a human-centric perspective exploring the readiness towards smart warehousing: the case of a large retail distribution warehouse, analysis of classifications, applications, and design challenges of drones), design part (development, implementation and technical support of the drone system for airport warehouse), conclusions, references.

5. List of mandatory graphic matters: worldwide air cargo analytics: facts & figures; comparison of three cost scenarios of development, implementation and maintenance of the drone system for airport warehouse logistics and inventory.

6. Planning calendar

№	Assignment	Deadline for completion	Mark on completion
1.	Collection and processing of statistical data	14.11.19 - 16.11.19	done
2.	Writing of the analytical part	17.11.19 - 22.11.19	done
3.	Writing of the design part	23.11.19 - 30.11.19	done
4.	Writing of the introduction and summary	31.11.19 - 01.12.19	done
5.	Execution of the explanatory note, graphic matters and the presentation	02.12.19 - 04.12.19	done

7. Given date of the task: October 14, 2019.

Supervisor of the bachelor thesis: ___________ Yu. Shevchenko

Task was accepted for completion: ____________ O. Kopin

ABSTRACT

Explanatory note to the diploma project “Drones usage in the airport warehouse system”: 170 pages, 28 figures, 11 tables, 28 equations and 30 references.

Keywords: DRONES, INVENTORY SYSTEMS; WAREHOUSE MANAGEMENT; INOVATIVE TECHNOLOGIES, INVENTARIZATION, INDOOR LOGISTICS.

The research is devoted to development, implementation and technical support of drone system in airport warehouse for reducing labor costs.

The object of research. Airport warehouse automation technologies.

The subject of research. Drone system in airport warehouse.

The aims and objectives of the research. The aim is to create drone system for airport warehouse and assess self-repayment of the system period for three cost scenarios.

To achieve the aim during performing, it is necessary to perform a number of tasks:

- identify the innovative technologies in warehouse and supply chain research areas and choose one for research;
- collect and analyze trends in the warehouse management systems;
- calculation of total development, implementation and technical support of the drone system at the airport warehouse and application of it based on three defined scenarios;
- assessment of self-payment period of the system.

The techniques presented in this research can be easily adapted for larger airport warehouses.

CONTENTS

NOTATION LIST

IT – Information Technology
AI – Artificial Intelligence
IoT – radio frequency identification
JIT – just in time
IoT – Internet of Things
WMS – Warehouse Management System
LCSM – Logistics and Supply Chain Management
SaaS – software as a service
NASDAQ – National Association of Securities Dealers Automated Quotation
QR-code – quick response code
R&D – research and development
UAV – Unmanned aerial vehicle

INTRODUCTION

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The digital transformation of warehouses - driven by safety, cost and revenue benefits – is underway across the world. Technologies such as IoT, AI and drones are augmenting the business value created by adoption of RFID, robots and real-time analytics. UAVs have started playing a central role in the intelligent automation of warehouse operations – given their ability to fly & hover autonomously, carry payloads, avoid obstacles, navigate indoors & land precisely, operate in fleets and be remotely used. The business benefits from drones are significant and immediate given low CapEx & infrastructure investments, access to commoditized drone hardware, and SaaS-based solutions for warehouse operations. The cloud-connectivity of drones, combined with API-based integration, make it easy for existing warehouse management systems to onboard autonomous drone fleets into enterprise workflows. Capabilities such as custom dashboards, remote control via telepresence over 4G/5G, high-quality video recording are key to realizing the value in warehouse applications such as inventory reconciliation & audit, safety & surveillance, item search & recognition, etc. The pioneers in Warehouse 4.0 have already done PoC projects on multiple use-cases, by involving stakeholders from R&D, IT, operations and senior management. These are now running pilot programs that involve repeatable missions of drone fleets – this building a wider set of business cases that mature into large-scale drone deployments across the supply chain.

A modern warehouse is expected to leverage technologies such as RFID, QR code, bio-metrics and CCTV, warehouse management software solutions, autonomous ground vehicles, pick-and-place robots, computer vision and networked sensors.

Nevertheless, these technologies remain inadequate in view of the increasing supply chain volatility, demand uncertainty, and operational complexity.

Hence the emergence of Warehouse 4.0 - the next wave of technology adoption by warehouses, driven by AI, IoT, digital twins and commercial drones. The promise of Warehouse 4.0 is inventory counting that takes hours and days instead of weeks, zero safety and theft incidents, nearly 100% accuracy of inventory reconciliation, minimal downtime, predictive maintenance, and most importantly – intelligent automation at the heart of warehouse operations.

The use of drones in warehouses has been increasing over the past years. Large warehouses are aiming to increase efficiency by investing more in automation and robotics. This is not without precedence since the cost of warehousing operations account for 30% of the total costs in logistics. Furthermore, difficulty to attract skilled labors, increasing demand for customer services and the rise of e-commerce have intensified the need to further increase efficiency in warehouse operations.

The fourth industrial revolution is also affecting warehouses. They become more digital and more connected—as in “warehouse 4.0”. New scanning technologies, bar codes, QR codes, radio frequency identification (RFID) technologies and artificial intelligence (AI) enable drone-driven automations in warehouses. Moreover, onboard computing power and efficient algorithms allow for the implementation of scalable drone applications . However, the structure of warehouses are diverse with different complexities, which impose constraints for the rollout of a drone program. They differ in terms of geographic location, type of stored items, layout (e.g. shelf, pallets, and boxes), size and technology. The function of warehouses is also diverse. For example, a distribution warehouses is operating differently from cross-docking warehouse and factory warehouses for raw materials and finished goods.

Drones have started to play a central role in the automation of current warehouses. They are popular due to their ability of drones to fly and hover autonomously, avoid obstacles in different warehouse layouts, navigate indoor, land precisely and potentially operate in fleets.

The three most promising areas of indoor drone use cases in warehouses are inventory management, intra-logistics of items, as well as inspection and surveillance.

The high efficiency, flexibility and low cost of drones or Unmanned Aerial Vehicles (UAVs) present huge application opportunities in various industries.

Among those various applications, we focus herein on the use of UAVs in delivery logistics. The UAV logistics system has some fundamental characteristics that distinguish it from the usual ground logistics such as limited flight time, loadable capacity, effect of cargo weight on flight ability, and others.

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1. THEORETICAL PART

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1.1. Industry 4.0 and the current status as well as future prospects on logistics

Industry 4.0, referred to as the “Fourth Industrial Revolution”, also known as “smart manufacturing”, “industrial internet” or “integrated industry”, is currently a much-discussed topic that supposedly has the potential to affect entire industries by transforming the way goods are designed, manufactured, delivered and payed. This paper seeks to discuss the opportunities of Industry 4.0 in the context of logistics management, since implications are expected in this field. The authors pursue the goal of shedding light on the young and mostly undiscovered topic of Industry 4.0 in the context of logistics management, thus following a conceptual research approach. At first, a logistics-oriented Industry 4.0 application model as well as the core components of Industry 4.0 are presented. Different logistics scenarios illustrate potential implications in a practice-oriented manner and are discussed with industrial experts. The studies reveal opportunities in terms of decentralization, self-regulation and efficiency. Moreover, it becomes apparent that the concept of Industry 4.0 still lacks a clear understanding and is not fully established in practice yet. The investigations demonstrate potential Industry 4.0 implications in the context of Just-in-Time/Just-in-Sequence in a precise manner. Practitioners could use the described scenarios as a reference to foster their own Industry 4.0 initiatives, with respect to logistics management.

In recent years, complexity and requirements in the manufacturing industry have steadily increased. Factors such as growing international competition, increasing market volatility, demand for highly individualized products and shortened product life cycles present serious challenges to companies. It seems that existing “approaches” of value creation are not suited to handle the increasing requirements regarding cost efficiency, flexibility, adaptability, stability and sustainability anymore. On one hand, requirements in the manufacturing industry have increased. On the other hand, the rapid technological progress in the more recent past has opened up a range of new business potentials and opportunities.

Trends and new catchwords such as digitalization, the internet of things (IoT), internet of services (IoS) and cyber-physical systems (CPS) are becoming more and more relevant. Against this backdrop, Germany, which is well known for its strong manufacturing sector, launched the so-called "Industrie 4.0" initiative in 2011 as part of its high-tech strategy, introducing the idea of a (fully) integrated industry [3,4]. Since then, Industry 4.0 has gained attention importance – also beyond the German-speaking area – and has even been listed as a main topic on the 2016 World Economic Forum's agenda.

Prophetically, Kagermann et al. [5] expect that strong industrial nations such as Germany will only remain successful if they manage to actively participate in the Industry 4.0 initiative. In concrete terms, this means participating in the development, merchandising and operation of autonomous, knowledge- and sensor-based, self-regulating production systems. The opportunities and benefits that are anticipated to come along with Industry 4.0 seem to be manifold, e.g. resulting in highly flexible mass production, real-time coordination and optimization of value chains, reduction of complexity costs or the emergence of entirely new services and business models.

As far as the field of logistics is concerned, major implications are predicted, too. In fact, logistics represents an appropriate application area for Industry 4.0 [3]. The integration of CPS and IoT into logistics promises to enable a real-time tracking of material flows, improved transport handling as well as an accurate risk management, to mention but a few prospects. In fact, one could argue that Industry 4.0 in its pure vision can only become reality if logistics is capable of providing production systems with the needed input factors at the right time, in the right quality and in the right place.

As promising as the idea of a self-prophesying "Fourth Industrial Revolution" may sound at first sight, it is essential to remark that there is a multitude of challenges, risks and barriers with regard to its implementation. Traditional industry boundaries will vanish due to the reorganization of value creation processes and cause severe changes within and across organizations. Defining appropriate infrastructures and standards, ensuring data security and educating employees are among the issues that need to be addressed on the road to Industry 4.0.

Unsurprisingly, a huge number of practitioner-oriented articles and papers address the opportunities of Industry 4.0 and seek to motivate (or even urge) companies to participate in the initiative. Although the term Industry 4.0 roots back to Germany's high-tech strategy and thus has received a lot of attention recently, it still lacks a precise, generally accepted definition. This situation must be considered unsatisfying, especially from a scientific point of view.

The present chapter picks up on this deficit and aims to sharpen critically the picture of Industry 4.0 with regard to logistics management, since major consequences are expected in this field. Based on a theoretical and conceptual ground work, the authors select some prominent logistics concepts so as to describe potential implications and pitfalls of Industry 4.0 in detail. After that, the findings are reflected and discussed with experts in terms of practical feasibility.

Against this backdrop, our ambitions are reflected by the following research question:

What are the implications of Industry 4.0 for future logistics management? In particular: How may Industry 4.0 affect logistics concepts and Just-in-Time/Just-in-Sequence?

Current research still lacks consistent knowledge about how the "Fourth Industrial Revolution" is going to affect future industries. Against this background, we follow a conceptual research approach as described by Meredith [6], serving an exploratory purpose so as to provide a better understanding of this rather undiscovered topic. The research process can be divided into the following phases: The initial phase was devoted to narrowing down the topic and its scope. This was accomplished first through multiple unstructured discussions within the affiliated research team of the authors as well as through desk research. Following that, the authors conducted a literature review on the topic of Industry 4.0 in the second phase. The reason for examining past and current literature was twofold: On one hand, the review was conducted in order to investigate the background and origin of Industry 4.0. On the other hand – with respect to the fact that Industry 4.0 has become a buzzword recently but still lacks a generally accepted conceptual understanding – it served the purpose of identifying its key components and characteristics so as to sharpen the picture. In the third and main phase of this paper, we try to investigate potential implications and pitfalls of Industry 4.0 in the field of logistics management and thereupon construct and describe a number of scenarios with regard to specific logistics concepts. The findings are summarized in propositions. Moreover, eight experts in the field of logistics and supply chain management are interviewed in order to evaluate the propositions. The final phase comprises a (self-)critical review of the research process and findings by the authors.

With regard to the structure of this chapter, four main parts can be distinguished: The first section of the paper is devoted to introducing and emphasizing the topicality of Industry 4.0. Moreover, the aim, research question, structure and methodology are covered. Following that, a comprehensive literature review on the subject of Industry 4.0 is conducted in the second part so as to lay a solid theoretical foundation for the subsequent research. In Section 3, two well known logistics concepts are analyzed with respect to potential Industry 4.0 consequences. Experts from different industries are then questioned in order to evaluate the findings in terms of practical relevance. The last part of the paper comprises a critical review of the core findings and thereupon offers suggestions for future research.

Industry 4.0 definition and key components

The industrial sector plays a crucial role in Europe, serving as a key driver of economic growth (e.g. job creation) and accounting for 75% of all exports and 80% of all innovations [7]. However, the European manufacturing landscape is twofold. While Eastern Europe and Germany show a constantly growing industrial sector, many Western European countries such as Great Britain or France have experienced shrinking market shares in the last two decades. While Europe has lost about 10% of its industrial share over the past 20 years, emerging countries managed to double their share, accounting for 40% of global manufacturing. A few years ago, Germany started thinking about initiatives in order to maintain and even foster its role as a “forerunner” in the industrial sector. Eventually, the term Industry 4.0 was publicly introduced at the Hanover Trade Fair in 2011, presented as part of Germany’s high-tech strategy so as to prepare and strengthen the industrial sector with regard to future production requirements [8]. While the IoT is assumed to take on a leading role in the Industry 4.0 era, Hermann et al. [9] found that the IoS will find its way into factories, too. CPS, which are able to interact with their environment via sensors and actuators, constitute another element of Industry 4.0, since they are expected to enable factories to organize and control themselves autonomous in a decentralized fashion and in real time [4]. Due to their capabilities, these factories are often referred to as “smart factories”. Given all these concepts, the difficulty of finding a unique and concise definition for Industry 4.0 becomes apparent, and it is hardly surprising that opinions among researchers and practitioners diverge. Moreover, it is still uncertain how Industry 4.0 will manifest itself in practice and how much time that will take. With respect to a more precise understanding of the topic, we now try to clarify the core components of Industry 4.0.

Hermann et al. [9] identified four Industry 4.0 key components based on a review of academic and business publications, using different publication databases so as to ensure objectivity. These key components are now briefly described.

Cyber-physical systems (CPS): Industry 4.0 is characterized by an unprecedented connection via the internet or other distributed ledgers and so-called CPS, which can be considered systems that bring the physical and the virtual world together [10]. More precisely, “cyber-physical systems are integrations of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa” ([11]; p. 1). In the manufacturing context, this means that information related to the physical shop floor and the virtual computational space are highly synchronized [12]. This allows for a whole new degree of control, surveillance, transparency and efficiency in the production process. With regard to their structure, CPS have “two parallel networks to control, namely a physical network of interconnected components of the infrastructure and a cyber network comprised of intelligent controllers and the communication links among them” ([13], p. 928). CPS realize the integration of these networks through the use of multiple sensors, actuators, control processing units and communication devices.

Internet of things (IoT): The term “internet of things” became popular in the first decade of the 21st century and can be considered an initiator of Industry 4.0 [14]. “Smart, connected products offer exponentially expanding opportunities for new functionality, far greater reliability, much higher product utilization, and capabilities that cut across and transcend traditional product boundaries” [15]Porter and Heppelmann, 2014; p. 4). Also Nolin and Olson [16] note that the IoT “seems to envisage a society where all members have access to a full-fledged Internet environment populated by self-configuring, self-managing, smart technology anytime and anywhere” (p. 361). The IoT is expected to open up numerous economic opportunities and can be considered one of the most promising technologies with a huge disruptive potential. For the purpose of clarification, Fleisch [17] stresses the need to distinguish the IoT concept from the “ordinary” internet, arguing that “the nerve ends in the IoT are very small, in many cases even invisible, low-end and low energy consumption computers whereas the nerve ends of the Internet are full-blown computers” (p. 3). Moreover, the number of network nodes in the IoT is significantly higher than in the conventional internet (“trillions versus billions”). Eventually, literature provides a wide range of definitions for the IoT. Some of them are very specific, other ones feature a more general character. For pragmatic reasons, this paper sticks to a rather comprehensive definition by referring to the IoT as a world where basically all (physical) things can turn into so-called “smart things” by featuring small computers that are connected to the internet [17].

Internet of services (Io):SIt is often said that we are living in a so-called “service society” these days [18]. With respect to that, there are strong indications that, similar to the IoT, an internet of services (IoS) is emerging, based on the idea that services are made easily available through web technologies, allowing companies and private users to combine, create and offer new kind of value-added services [19]. It can be assumed that internet-based market places of services will play a key role in future industries. Whereas from a pure technological perspective, concepts such as service-oriented architecture (SOA), software as a service (SaaS) or business process outsourcing (BPO) are closely related to the IoS, Barros and Oberle [20] propose a broader definition of the term service, namely “a commercial transaction where one party grants temporary access to the resources of another party in order to perform a prescribed function and a related benefit. Resources may be human workforce and skills, technical systems, information, consumables, land and others” (p. 6).We will follow the latter definition.

Smart factory: Up to now, CPS, the IoT and IoS were introduced as core components of Industry 4.0. It must be noted that these “concepts” are closely linked to each other, since CPS communicate over the IoT and IoS, therefore enabling the so-called “smart factory”, which is built on the idea of a decentralized production system, in which “human beings, machines and resources communicate with each other as naturally as in a social network” ([14]; p. 19). The close linkage and communication between products, machinery, transport systems and humans is expected to change the existing production logic. Therefore, smart factories can be considered another key feature of Industry 4.0. In the smart factory, products find their way independently through production processes and are easily identifiable and locatable at any time, pursuing the idea of a cost-efficient, yet highly flexible and individualized mass production. [14] note that smart factories “will make the increasing complexity of manufacturing processes manageable for the people who work there and will ensure that production can be simultaneously attractive, sustainable in an urban environment and profitable” (p. 21). Hence, the potentials that might come along with smart factories are expected to be huge. It is important to understand that not only production processes but also the roles of employees are expected to change dramatically. Spath et al. [2] expect employees to enjoy greater responsibility, to act as decision makers and to take on supervising tasks instead of driving forklifts, for instance. In the same context, some critics have recently pointed out that the automated and self-regulating nature of the smart factory might cause severe job destruction. However, hardly any reliable study supports that fear.

Beyond these key components, there is an increasing set of further Industry4.0-technologies in a broader sense, such as wearables (e.g. smart watches, glasses or gloves), augmented reality applications, autonomous vehicles (incl. drones), distributed ledger systems (e.g. the blockchain1) or even big data analytics.

As a first preliminary summary, we define Industry 4.0 as follows:

Products and services are flexibly connected via the internet or other network applications like the blockchain (consistent connectivity and computerization).

The digital connectivity enables an automated and self-optimized production of goods and services including the delivering without human interventions (self-adapting production systems based on transparency and predictive power).

The value networks are controlled decentralized while system elements (like manufacturing facilities or transport vehicles) are making autonomous decisions (autonomous and decentralized decision making).

With respect to logistics management, Industry 4.0 is expected to achieve opportunities in terms of decentralization, self-regulation and efficiency.

Industry 4.0: implications for logistics management

We now aim to answer the question whether logistics management might be affected by Industry 4.0. Thereby, we follow the conceptual research approach suggested by Meredith [6]. Our argumentation is based on a simple logistics-oriented Industry 4.0 application model as described in Fig. 1.1. The model encompasses two dimensions:

(1) Physical supply chain dimension: Autonomous and self-con-trolled logistics sub systems like transport (e.g. via autonomous trucks), turnover handlings (e.g. via trailer unloading or piece picking robots) or order processing (e.g. via smart contracts on the blockchain technology) are interacting among each other.

(2) Digital data value chain dimension: Machine and sensor data are collected at level of the "physical thing" along the entire physical end-to-end supply chain. Via a connectivity layer the gathered data is provided for any kind of analytics (e.g. in the cloud), possibly resulting in potential value-added business services.

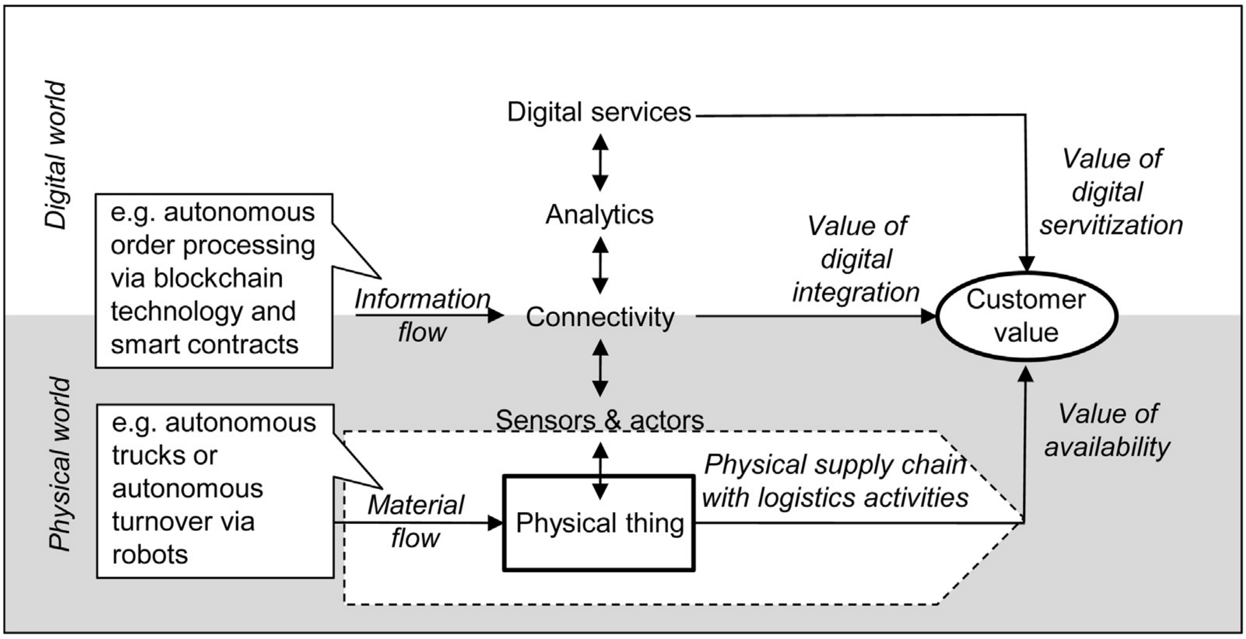

Fig. 1.1. A logistics-oriented Industry 4.0 application model

Out of this two-dimensioned application model, three customer value components are expected. First, the "value of availability", meaning making products and services available to the customer via autonomous delivering. Value creation through availability of goods or services is the main added value of logistics activities and services. Second, “value of digital integration” arises through a permeable transparency and traceability along the supply chain. Furthermore, order processing systems are interconnected, facilitating seamless business executions (e.g. object self-service, remote usages or condition monitoring). Third, consumption normally exceeds the classical point-of-sale (POS), but this does not mean that the supply chain ends at this point. There exist several IT-based service options going beyond the simple distribution of products or physical services (value of digital servitization”). Aside digitally charged things where physical products are “charged” with additional digital services, the data itself creates value outside the original use case (“sensor as a service”).

The units of analysis are common and well established logistics concepts. It is assumed that these concepts will pass through a digital transformation, too. Thus, the following needs to be kept in mind: First of all, it is not possible to consider all ideas, concepts and elements of Industry 4.0. Consequently, the scenarios only comprise a selection of those. Moreover, the described effects do no feature an exclusive character, meaning that if it is suggested that Industry 4.0 may affect concept x in a particular way, it might also affect concept y (e.g. JIT/JIT) in a similar way. Given these constraints, the authors do not seek to provide generally valid statements about how Industry 4.0 will affect logistics management, but rather aims to illustrate and discuss “some” potential use cases. Based on a comprehensive literature review, the main process steps and activities (phases) of the selected logistics concepts were elaborated. For each of these phases, potential implications of Industry 4.0 were identified. Here, in each case the central characteristics and components of Industry 4.0 are mentioned. Furthermore, real world examples and approaches were identified for illustrative reasons if possible. The central findings were further summarized in propositions. Finally, the results were subsequently reflected again with the experts. If it has been appropriate and necessary, adjustments were made in formulating. A critical discussion completes the explorative research.

Just-in-Time (JIT) and Just-in-Sequence (JIS)

Just-in-Time (JIT) is a prominent and widely accepted concept in production and logistics, especially in the automotive industry. Similar to the previously discussed Kanban concept, JIT follows a lean approach and is strictly pull oriented, meaning that material is only produced and supplied in case of an actual demand. JIT primarily focuses on the supplier-buyer relationship and can therefore be considered a cross-company approach. Its main objective is to realize a zero- or low-stock supply system. Moreover, JIT seeks for a demand-tailored realization of goods exchange processes within and across companies as well as short delivery respectively cycle times. Finally, JIT aims to increase overall supply chain flexibility and agility [29]. However, the implementation of JIT systems is far from trivial. First of all, production planning needs to be precisely aligned to actual demand. Furthermore, a high level of integration with regard to material and information flows needs to be established, since there is only little or no inventory kept as a buffer, e.g. in case material is directly shipped from the supplier’s production facility to the buyer’s production facility without temporary storage. Against this backdrop, a close coordination between suppliers and buyers is a prerequisite for success [30]. Finally, it has to be mentioned that a JIT strategy is primarily suited in case of high-value products that are consumed on a constant, well-predictable basis.

Whereas – in short – JIT calls for the right material to be supplied at the right time and in the right place, the so-called Just-in-Sequence (JIS) concept goes one step further by ensuring that the material also arrives in the right sequence with respect to its further processing. Hence, incoming material does not have to be sorted by the buyer anymore. JIS can therefore be considered an enhancement of JIT, which means that, apart from additional benefits (no sorting etc.), requirements are even higher, especially with regard to transport planning.

JIT/JIS systems generally pass the following process steps and activities: (i) production planning, (ii) production order, (iii) disposition and production, as well as (iv) delivery. Table 2 illustrates how JIT/JIS systems may be impacted by Industry 4.0. Since JIT/JIS particularly rely on planning accuracy, information transparency and well-coordinated transport processes, a special focus is put on these areas.

Fig. 1.2 again illustrates the typical process steps and activities of JIT/JIS systems, highlighting the main implications of Industry4.0.

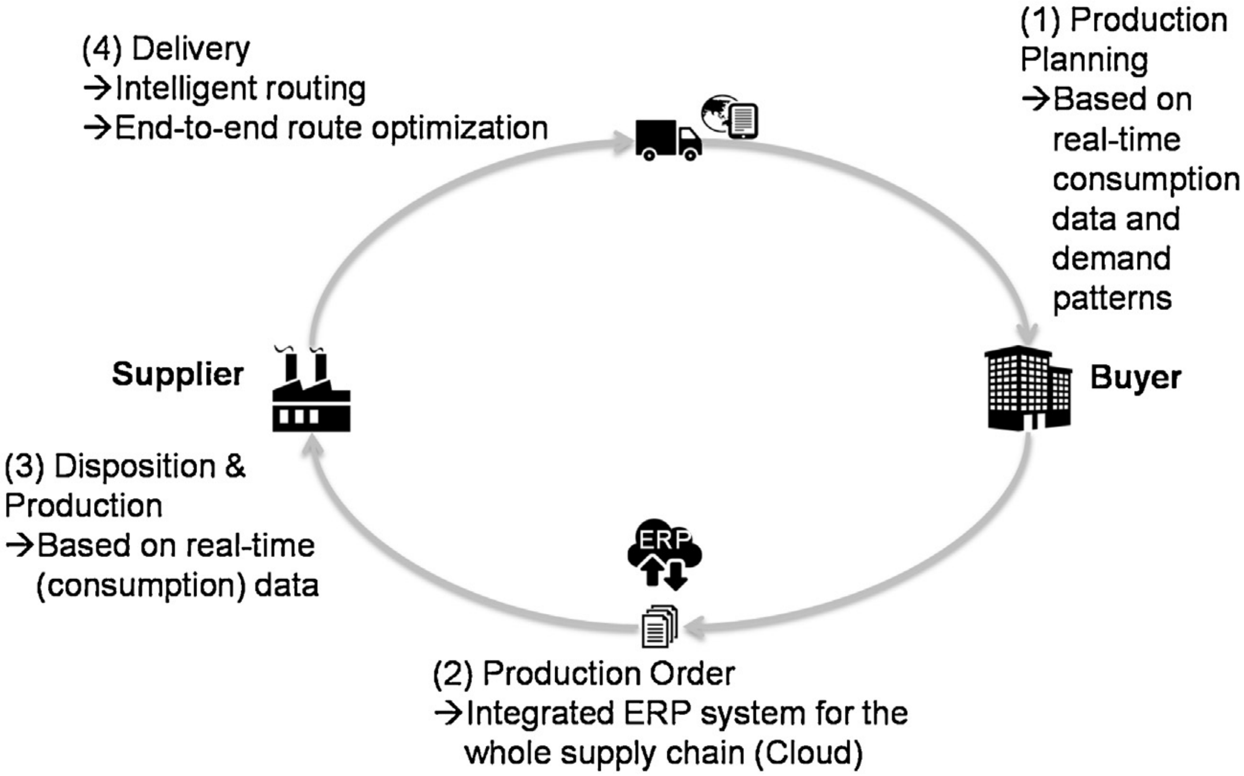

Fig. 1.2. Modified Just-in-Time/Just-in-Sequence cycle according the Industry 4.0 Scenario

As production planning is crucial in JIT/JIS systems, the increasing use of Auto-ID technologies has the potential to facilitate production planning or even make it futile (step 1). With respect to the coordination between supply chain actors, cloud or distributed ledger technology might enable the creation of a virtual ERP system for the whole supply chain, so that all actors can share and act upon the same information. Bullwhip effects may therefore be avoided or reduced (steps

2 & 3). Moreover, transport processes, which are also highly important in JIT/JIS so as to ensure delivery at the right time, might be coordinated in an end-to-end fashion across the whole supply chain (step 4). In conclusion, Industry 4.0 provides the opportunity to improve JIT/JIS systems, since it may enable actors to exchange and act upon real-time information in a coordinated end-to-end fashion.

Key findings

Within this chapter we showed that there is no commonly agreed-upon definition and understanding of Industry 4.0. In the authors' opinion, the Fourth Industrial Revolution can be best described as a shift in the manufacturing logic towards an increasingly decentralized, self-regulating approach of value creation, enabled by concepts and technologies such as CPS, IoT, IoS, cloud computing or additive manufacturing and smart factories, so as to help companies meet future production requirements. The comprehensive nature of this definition requires companies to individually define what Industry 4.0 means to them. As a consequence, there is not one single truth and reality behind this approach. Thus, this paper supports a somewhat dynamic perception, proposing an application model that comprises different dimensions and components of Industry 4.0.

The goal of this chapter was to identify and discuss the implications of Industry 4.0 in the field of logistics management. Considering this, it has to be noted that the investigations did not primarily address logistics management in a general, overarching manner. Instead, the focus was limited to two logistics concepts, since it was the authors' ambition to describe the effects in a precise and detailed fashion. Against this backdrop, the present study did not seek (and is not able) to make universally valid statements about how the Fourth Industrial Revolution will affect and impact logistics management. With respect to this, the investigations and described scenarios feature a hypothetical character and should therefore be understood in their respective context. In addition to that, the focus of this chapter was clearly on the potentials and opportunities of Industry 4.0, meaning that the risks, costs and implementation barriers that might accompany the digital transformation were mostly ignored. Hence, the validity of the different scenarios is limited, since only the beneficial aspects of Industry 4.0 were discussed.

In order to review and evaluate the findings, eight expert interviews were conducted. Yet, with regard to the interpretation of the results, there is a number of factors that need to be considered. On the one hand, the questioned persons all had a profound knowledge in the field of logistics and supply chain management. However, none of them considered himself/herself a specialist in the area of Industry 4.0. Thus, the level of knowledge and experience varied significantly among the interviewed experts. As a consequence, some of the dialogues were highly substantial and yielded interesting insights, whereas others merely scratched the surface of the topic. Therefore, it was difficult to directly compare the answers and opinions. Last but not least, the number of interviews was limited. In order to gain more representative and objective results, a larger base of interviews would have been required.

Existing academic literature lacks a clear and common definition of the Industry 4.0 concept. Therefore, the image of Industry 4.0 is still quite fuzzy, both among researchers and especially among practitioners. This impression was confirmed by the interviews that were conducted in the context of this paper. Against this backdrop, future research should aim to establish a more precise understanding of what the (constituent) characteristics of Industry 4.0 are, especially for different business sectors or areas of application.

In addition to that, we suggest that companies should be accompanied and supported on their road to Industry 4.0 in a practical manner. This could be achieved through concepts and frameworks, which features different building blocks and dimensions of Industry 4.0 and therefore may serve as an orientation guideline. An applied SWOT framework, for instance, could support companies by analysing the opportunities of Industry 4.0 in the context of a company’s strengths, weaknesses and environment. Moreover, an “Industry 4.0 Readiness Framework” could help identify potential implementation barriers by listing critical success factors such as availability of technology, degree of digitization, workforce capabilities and education.

Furthermore we see a strong need to concretize and substantiate the Industry 4.0 concept with regard to financials, i.e. revenue potentials and costs. In the context of the scenarios described in this paper, this could e.g. be achieved through a rough quantification of the benefits and cost advantages (e.g. reduction of inventory costs, complexity costs, wage costs) as well as the required investments (e.g. for infrastructure or employee training). We are aware of the difficulty of such a quantification. However, companies might not be willing to invest into Industry 4.0 unless they have a rough imagination of the financials.

Last but not least, the implications described in this paper need to be put into a wider context. The illustrated scenarios exclusively addressed potential consequences in the context of the respective logistics concepts. Yet, little was said about the implications beyond that. Therefore, future research should also investigate the effects of Industry 4.0 on e.g. the organizational, operational and legal structures of companies.

1.2. Industry 4.0: opportunities, challenges of airport and airline management practices

According to past years' statistics, it is expected there will be soft journeys that travelers will design for their habits and preferences in the coming years. Companies traveling in the aviation, travel and tourism sectors will optimize their customer experience by collecting data, exchanging data and constantly acquiring knowledge. Over time, travel will smoothly blend in with other daily activities and become frictionless. The greatest influence of these conveniences is that the world is moving toward digital transformation. And this digital transformation is called the industry 4.0. After this time, not only the aviation sector, but all sectors, must protect themselves by taking a precautions and drawing a strategic path. With the fourth industrial revolution, digitalizing enterprises need to create an innovation ecosystem that allows them to collaborate with all stakeholders. This study, conducted in the form of literature analysis, which is considered as the concept of innovation and business model of the industry 4.0 concept, and interconnected airlines and airports are conceptually discussed.

Digital transformations are increasingly impacting on companies. It is expected that businesses will develop appropriate strategies for this transformation, as automation-based production is increased, dark factories are created, and all devices are connected to one another and created by cyber environments. Although it is perceived as a threat by societies, it should be considered as an important competitive advantage especially in economic development. Because in the fourth industrial revolution, future business models are being created and integrated into all business operations. Of course, it is envisaged that large investments will be made especially in the digital production technologies in order to establish the necessary infrastructure within the adaptation process (Ovaci, 2017).

With the global competition and the intensification of globalization, it is necessary for aviation companies to act quickly in the adaptation process so that they can become a digital enterprise. The life expectancy of products is getting smaller, the service is getting more and it is a proof of how fast the change has to be. It is beneficial to be able to offer products to the market faster and with the best service and to utilize open innovation strategies to shorten the innovation cycle.

Depending on the increasingly digitized world, this paper addresses the business model and innovation in different segments by making it dependent on the Industrial Revolution. These concepts open up digital convergence at airlines and airports, making them subjected on Industry 4.0. It is one of the most important factors that affect the economy of the countries in the world. In this respect, from past experiences, more importance is giving to the future to this area.

The business model is an approach to generating revenue at an acceptable cost, which includes assumptions about how an enterprise will create and capture value. The business model includes assumptions about what the management wants and needs of the customers, and how the business can earn the best of these needs (Gambardella, McGahan, Alfonso, & Anita, 2010).

The similarity between the development of the "business model" concept and the business applications in the rapidly developing internet environment since the 1990s has been interpreted as the application of the internet is effective in the development of the business model concept. In an interesting research on this subject, several scientific publications from 1990 to 2003 investigated how many times the concept of "business model" was used and 7 publications were published as full articles on business model in 1990. This figure increased every year and reached 667 full articles in 2003 has been determined. Interestingly, the development trend of the NASDAQ index, which follows the performance of technology-intensive companies in the capital market between the same dates, is very close to the development trend of the business model concept. Interestingly, the development trend of the NASDAQ index, which follows the performance of technology-intensive companies in the capital market between the same dates, is very close to the development trend of the business model concept (Korçel, 2015).

The Canvas business model provides entrepreneurs with an environment where basic business and support activities in the supply chain process of new business ideas can be easily understood under the nine core components. These core components cover four main areas: customer, product, infrastructure and finance. Under these headings, the Canvas business model has nine titles to fill (Osterwalder & Pigneur, 2013).

An enterprise offers to its customers; price, quality, performance, choice, ease of use and so on are named as "customer value proposition" (Erk, 2009). Today, as customer demands and needs evolve and change, the value propositions presented to the customers are changing rapidly. In a changing competitive environment, as the value standards increase, we need to create different values for different customers. For example, Turkish Airlines competing with global competitors in the airline market and can create value for its customers through more destinations and service networks such as Emirates Airline.

Bill Aulet (Aulet, 2013), a professor at MIT Entrepreneurship, says, "A client is a client who pays a necessary and sufficient condition for a job." At this point, the customer is the patron of the classical phrase operator and it is important to know everything. This effort towards customer recognition reveals the need for different groups of customers to be classified by businesses. Customers are different and their needs are different. The value of each client is also different. (Peppers, 2004). For instance, Turkish Airlines is applying Miles&Smiles and Emirates Airlines is implementing Skywards ease according to their customer classes.

Channels that you will reach from the customer are valuable, and the customer is an important point related to the immobilization of your channels. According to a statement at Cloudnames site, "Today, customers want to be able to interact with loved brands on the internet. The personalized service period has returned to business. A good website, a quality blog and a powerful social media presence are tools for creating leads in the digital age " (Ensari & Eser, 2006).

After the industrial revolution, the effort to sell a surplus of the finished product of mass production became the first stage of customer valuation, and as a consequence of the increasing global competition after the 1980s, the customer became more important than ever. Nowadays, business model strategies are shaped by the needs of the customers.

Revenue streams show how we earn money from our customers. In the Business Model Canvas, different customer segments can pay us differently. Without a sale, a business will not work, which is why the concept is one of the most important aspects of an enterprise.

As a result, determining our income model, communication with the customer seems to have an effect on the way we communicate, but it is very important in terms of the continuity of the existing business.

Key Resources, describe the most important things that a business model should accomplish in order to live a good life. Basic activities such as basic resources also differ according to the business model (Osterwalder, A; Pigneur, Y, 2010).

They are the necessary and important sources for the emergence of a business model. Basic sources; can be defined as "all assets, capabilities, organizational processes, knowledge and learning that contribute to the effectiveness of the business and can be controlled by the business" (Barney, 1991).

It is important for companies to list their resources, firstly classifying their resources and then bringing them back to the forefront of their competitors. These resources are key in determining the business strategy and will affect the business performance.

Establishing a strong partnership in the market is a great way to make sure we promise to our customers that we can help our broaden that they can reach. If there is a doubt about the success of the project, which is considered due to lack of capital, need for resources or competitive position, it is necessary to turn to partnerships. It will also be useful to pre-design such issues as the designation of partners, the form of partnership and process.

The section that summarizes all the costs that will arise when constructing a business model is the section that has a lot of focal points in classical feasibility studies. Today's intensive competition environment enterprises are forced to spend cost structures in sight. The cost structure refers to the direct cost of first material, direct labor cost, and the ratio of overall production costs to total cost (Elitaş, Çonkar, & Erkan, 2006).

In order to organize the cost structures and make them more competitive, the enterprises have different applications. Concepts such as change engineering, Kaizen, and total quality management, which enable to reduce non-value-creating activities and continuously improve value-creating activities at this point, have become increasingly important and become mandatory for international businesses.

1.2.1. Innovation and Industry 4.0

The effects of the industrial revolutions that are living up to the day-to-day on the sophistication of society and countries are great. Each revolution; it is seen that the developed innovation has started as a result and triggered many economic, social, scientific, cultural and social changes. Production systems based on muscle power in the past centuries; has taken a different shape with the developed technologies. The increase of technological innovations has led to the emergence of new revolutions by changing the relation between production and consumption (Brettel, Friederichsen, Keller, & Rosenberg, 2014).

The technological opportunities that the new industrial revolution has provided are supporting the expansion of the open innovation paradigm as a competitive advantage. According to Chesbrough's definition in 2003, open innovation is a paradigm based on the idea of "businesses that want to keep pace with technological developments need to use internal and external innovation ideas and market channels" (Chesbrough, 2017). When evaluated in this respect, many technologies, policies and applications that have taken part in life together with Industry 4.0 are creating opportunities as important tools in the creation of open innovation.

The industrial revolution of 4.0 or the widespread use of Industry 4.0 is based on Kagermann's 2011 article. Industry refers to the evolution of the 4.0 revolution not only in automation, but also in intelligent observation and decision-making processes. Industry 4.0 is still a controversial issue. On the one hand it is a vision that it is really a revolution, on the other hand it is a sudden change in the industry and a revolutionary evolution of the revolution (Alçın, 2016).

One of the most controversial aspects of the industrial revolution is the effect on employment. It is argued that unemployment rates will increase with industry 4.0 solutions in many sectors that are not fully automated yet in need of human power. It is anticipated that this change in the labor market will affect not only non-qualified employees but also white collar and manager representatives (Bonekamp & Sure, 2015). Sectors have become heterogeneous due to changing customer expectations and needs. In order to meet these needs, efforts are being made to increase flexibility and capacity by using intelligent production systems. Simple and uniform processes are transformed into automation. However, in order to be able to complete operations related to other complex processes of production including the management stage, employees with creative and coordinating abilities started to need more strategic thinking. There are also anticipations that the revolution will create new lines of business and profession groups, which have caused changes in the workforce structure of enterprises (Hecklau, Galeitzke, Flachs, & Kohl, 2016).

Nowadays, digital is tightly connected to every business. However, even with technology as an integral part of the organization and its strategy, no people have been seen to support the success that continues to rediscover itself until now in the world. In 2016, Accenture Technology Vision draws attention to five new technology trends that shape this new landscape. Whether you start with any trending technology, you will see that each one of our "People First" theme is literate. Tomorrow's leaders are putting these trends and strategies into practice to secure their open digital advantage (Nanterme & Daugherty, 2016). These five steps will be briefly explained in the following paragraphs and in the third section of this article they will be explained as a strategy of use in the Airline and Airport markets.

Trend 1: Intelligent Automation

Intelligent automation is the launching ramp for new growth and innovation. With the help of Artificial Intelligence (AI), the next wave of solutions will gather data from unprecedented amounts of different systems and produce solutions that change the foundation of the organization by bringing systems, data and people together. It also improves what you do and how to do it at the same time.

Trend 2: Liquid Workforce

Companies are investing in the tools and technologies they need to keep pace with the digital age. But there is often a critical factor behind: the workforce. Companies need more than just the right technology; This technology needs to be used by the right people to make the right things in an adaptable, changeable and responsive liquid workforce.

Trend 3: Platform Economy

The next wave of devastating innovation will come from technology-based, platform-focused ecosystems that now form amongst the industry. Strategically leveraging technology to produce digital businesses, leaders are now creating an adaptable, scalable and interconnected platform economy that successfully supports an ecosystem-based digital economy.

Trend 4: Predictable Disruption

Every job now understands the power of digital transformation. However, the less dramatic and sustainable the changes from new platform-based ecosystems are, the less likely it is to be understood. It's not just business model that will turn heads. As these ecosystems create a strong, predictable deterioration, all industries and economic sectors will be completely redefined and rediscovered.

Trend 5: Digital Trust

Common new technologies are creating powerful new digital risk issues. Without trust, businesses cannot share or use data that supports their activities. For this reason, today's most advanced security systems go beyond providing environmental safeguards and are strongly committed to the highest ethical standards for data.

1.2.2. Innovative Relationship; Airlines and Airports

Over the past 30 years, the airline industry has seen a number of changes, such as the increasing market share of low-cost carriers (LCCs) and the challenges they face from volatile infestations from ill-fated disease outbreaks. As a new wave of technological change and innovation emerges, the next 30 years will be more turbulent. Some see it before the taxi driver arrives at Uber, sweeping the airline industry, citing the taxi industry, the music industry before downloading the internet, and the print industry before computer design software (Future Of The Airline Industry, 2017).

Air travel is in a period of great change. With a fast pace of innovation, airlines and aircraft manufacturers are constantly trying to keep up. Often, companies that make airline and aircraft are not everything well equipped to react quickly to change. A new plane has been in service for more than ten years and has been designed to continue flying for several decades. Like the automotive industry, aircraft manufacturers and people who fly their planes understand the need to prevent the development of aircraft hardware and software. An industry bound to the boundaries of flying metal is moving towards a future where software is important. At the moment, the industry is working on a number of potentially changing innovations that will find ways to use common airways for the next few decades (Zhang, 2017).

As smartphones become more common, there are many applications too. Today, even airline companies and aircraft manufacturers are adapting to accommodate in-flight use. Last year, for an application called Boeing vCabin, passengers started setting up lighting levels in the immediate vicinity, as well as launching an application that allows flight attendants to call, order food, and even control whether the toilet is free. In the meantime, the phones have also been adapted to internal components such as the Recaro CL6710 business class seat designed to allow mobile applications to move the seat back and forth (Stannard, 2017).

Over the next 12 months, airlines and airports around the world will be tasked with the challenge of identifying new and emerging technologies that have the potential to improve the customer experience, potentially improving both locally and instantly and have operational efficiencies. It would be right to discuss artificial intelligence without thinking about robots. This time last year, much talked about the robots face-to-face with the customer to provide on-site support to the passengers, but it could be the operational role that robots will have the most impact (Initiatives, 2017).

The Haneda Robotics Laboratory of Japan Airport Terminal has emerged as a frontrunner in this field and will soon judge seven robots in a live airport environment. These robots will be able to carry out various tasks ranging from proposing the potential security risks to the transport of suitcases. The ultimate goal is for a fleet of fleets to be deployed at Haneda Airport before the start of the

Tokyo Olympics in 2020. Incheon Airport is also investigating a new generation of robots in other parts of Asia and recently conducted a test of LG's Airport Guide Robot. and Airport Cleaning Robot.

1.2.3. Five Innovative Trends in Terms of Airlines and Airports

Trend 1: Intelligent Automation

Leaders will go into automation to create a new digital world that will not only benefit from the limitless speed of digital change, but also gain competitive advantage. Machines and artificial intelligence will be the newest members of the workforce, bringing in new skills that will help people to do new things and will rediscover what is possible. Machines and artificial intelligence will be the newest members of the workforce, bringing in new skills that will help people do new things and will rediscover what is possible.

In 2017, the artificial intelligence (AI) air transport industry was really ahead. After many years of labeling as "the next big thing," a large number of airways produced AI-focused products. Airlines from New Zealand Airlines to Aeromexico and from Air New Zealand to Lufthansa are now able to respond to more basic questions and now there are chat channels that can support customers on this channel.

Turkish Airlines, the intelligent luggage robot "Leo" transfer center, was introduced at the Atatürk Airport to passengers and the press. It was developed by Sita, one of the leading companies in the production of information technology for air transport, the luggage robot "Leo" was developed to serve passengers who complete check-in online at home, at the office, or at airport kiosks. "Leo" produces luggage labels by meeting passengers at the airport, boarding card or boarding square code on the mobile phone, and finally delivers the baggage to the baggage delivery staff safely (Milliyet, 2018).

Trend 2: Liquid Workforce

Companies are investing in the tools and technologies they need to keep up with the digital age. However, in order to achieve its ambitious goals, leaders often focus on a missing factor: the workforce. Technology is seen not only as an annoyance, but also as a facilitator that transforms people, projects and all their organizations into an extremely harmonious and volatile organization. In short, business world leaders think that the new liquid workforce can become a new competitive advantage (Accenture, 2016).

The greatest societal impact can be the impact of the digital transformation on the travel workforce, which can represent one person in every 11 jobs worldwide until 2025. Intelligent automation will change the nature of some travel affairs and completely eliminate others. However, digitally activated growth will create new employment opportunities that can overcome the automation of existing roles, especially as it predicts strong growth for the sector. Platforms also enable "liquid", flexible workforce models that will redefine the employer-employee relationship and create new challenges for organizing the workforce. Collaborative efforts on industry, government, educational institutions and civil society will be necessary to reduce adverse effects. Digital transformation requires a different skill set than employees in today's economy and will create new types of work. Aviation, travel and tourism players will need to adapt to this transition because they transform digital ecosystems and change is driven by the people in the organization. Challenges such as managing automation's impact on employment, reviving the industry workforce for digital economy, and creating a safety net for workers in a flexible workforce, should be addressed in collaboration with industry, regulators and policy makers.

Automation is likely to be an important influence in the workforce. Until now, the focus of the media fear that robots and artificial intelligence could take the place of human workers. However, the creation of a new generation of workforce that requires people and machines to work side by side will be an important trend.

Trend 3: Platform Economy

Leaders of the industry release the power of technology by developing digital platforms and developing platform-based business models and strategies. But technology changes are only the beginning. Transformation is covered by macroeconomics: traditional economy, new economy, production services. Digital is one of the developments that enable companies to offer services instead of products. As an industry, aviation, travel and tourism have a beginning because the spectrum is a dense ecosystem at the end of the "new economy".

The airports will be opened to cities with their own inner areas, called aerotropolis, which have their own business areas. Human resources costs may increase and technology improvements may decrease due to productivity and possibly automation in the name of security. The airports will no longer be just an outlet, but entertainment facilities that offer food, shopping and more (IATA/Global, 2017).

Trend 4: Predictable Disruption

Companies have become accustomed to demolishing in the past few years and will once again hear alarm bells. But this time there is a big difference: they can see their initiatives. Ecosystem degradation will usually be a predictable deterioration. Because of the fact that ecosystems naturally depend on sectors and business models, large organizations are particularly well positioned to estimate the course of the ecosystem and should benefit from them.

Technological developments also help create a revolution in the luggage space. The fall of the self-service pallet is, as we know it now, a widespread but new wave of development that completely redefines baggage operations. More passengers and bags work more than terminals at terminals around the world. Some stakeholders are already on the move. For example, the Lufthansa Group has partnered with Lufthansa, SWISS and Austrian Airlines to allow passengers traveling under the BAGTAG partnership to purchase reusable electronic bag tags, rather than using traditional paper bag tags attached to their bags each time.

Trend 5: Digital Trust

Trust is one of the most important factors in the digital economy. Without this, digital businesses cannot share data that supports their activities and cannot trust each other. In the digital sector, companies must gain the trust of individuals, ecosystems and regulators and have strong security and ethics rules at every stage of the customer journey. New products and services must be designed ethically. These entrepreneurs will have a high level of confidence that their customers will look at it as a guide to the digital future.

The distribution of new and emerging technologies which is the ongoing digitization of the air transport industry brings together a number of challenges and is one of the greatest tasks ensuring the safety of airline and airport comparisons. For instance, biomedical power is evident in the air transport industry, but now industry is gaining traction and technology can really start to have a transformative impact. The trend towards biometric processing can be seen around the world. In 2017, a number of US companies, including Delta and JetBlue (such as government agencies such as TSA and CBP), have invested in fingerprint and face recognition technology experiments.

Conclusion

To sum up, "Industry 4.0" and "Innovation" are vital for the aviation industry and its success is still very difficult. Tools like barriers and maps are useful, but not enough, to change the business model the digital process. Thus, the industry should follow the daily economy trends and other developments in the world. The trends mentioned in this article have an important factor in the innovation and business model of an industry. Organizational processes must also change with innovation. Companies should adopt an effective attitude towards business modeling. Some experiments will fail, but this should be expected - even encouraged - as long as the failure is aware of new approaches and the limits of economic losses. Companies that do not accept and follow innovation, expected to lose track of their development.

1.3. Models for warehouse management: Classification and examples

In this section we discuss warehousing systems and present a classification of warehouse management problems. We start with a typology and a brief description of several types of warehousing systems. Next, we present a hierarchy of decision problems encountered in setting up warehousing systems, including justification, design, planning and control issues. In addition, examples of models supporting decision making at each of these levels are discussed, such as distribution system design, warehouse design, inventory management under space restrictions, storage allocation, and assignment and scheduling of warehouse operations.

Introduction

According to the principles of supply chain management, modern companies attempt to achieve high-volume production and distribution using minimal inventories throughout the logistic chain that are to be delivered within short response times.

The changes outlined above have had a dramatic impact on warehouse management. Low volumes have to be delivered more frequently with shorter response times from a significantly wider variety of stock keeping units (SKUs). In a further attempt to decrease total inventory, many companies replaced several relatively small distribution centers (DCs) by a small number of large DCs with an extensive distribution network. Often, an entire continent, like North America or Europe, is serviced by a small number of DCs at strategic positions.

These developments have significantly influenced the existing paradigms in inventory research. Unfortunately, the attention paid by researchers in inventory theory to the management of storage systems such as warehouses has been relatively limited. Often, it was considered to be a mainly technical issue and therefore belonging to a different field, i.e., material handling research. The goal of this paper is to show that, apart from the close relationship between inventory and ware-house management problems, the latter often lend themselves to a profound and elegant quantitative analysis.

The new market forces, together with the fast technological developments in material handling, have affected the operation within warehouses tremendously. Shorter product life cycles impose a financial risk on high inventories and, consequently, on the purchase of capital intensive high-performance warehousing systems. Centralized inventory management, on the other hand, requires an increased productivity and short response times of the warehousing systems. The aim of this paper is to show that sophisticated models and decision support systems for the planning and control of warehousing systems may significantly contribute to the overall research in inventory management.

The developments have been made possible due to recent advances in information technology and the introduction of business information systems. Business information systems support the administrative processes of enterprises. For instance enterprise resources planning (ERP) systems are MRP-based business information systems that registrate all processes concerning finances, human resources, production planning and inventory management. Other functions that often are sup-ported by ERP-systems are, e.g., transportation planning, warehouse management, production scheduling and order-entry/order processing. Besides ERP-systems there are specialized systems that support these functions in complex operations. These various systems are linked together using electronic data interchange (EDI). Examples of such specialized systems are warehouse management systems that facilitate the registration, planning and control of warehouse processes, and inventory management systems. The models that are presented in this paper may be implemented in inventory management and warehouse management systems and thereby provide significant performance improvements in warehouse operations in comparison with the methods and models that are currently used.

1.3.1. Warehousing systems: A typology and a review

Material Handling is defined as the movement of materials (raw materials, scrap, emblaze, semi-finished and finished products) to, through, and from productive processes; in warehouses and storage; and in receiving and shipping areas [1]. Material handling concerns material flow and warehousing. Typical material flow devices are: conveyors, fork lifts, automated guided vehicles (AGVs), shuttles, overhead cranes and power-and-free conveyors. Warehousing concerns those material handling activities that take place within the ware-house, receiving and shipping areas, i.e., receiving of goods, storage, order-picking, accumulation and sorting and shipping.

Basically, we may distinguish three types of warehouses:

- Distribution warehouses,
- Production warehouses,
- Contract warehouses.

A distribution warehouse is a warehouse in which products from different suppliers are collected (and sometimes assembled) for delivery to a number of customers. A production warehouse is used for the storage of raw materials, semi-finished products and finished products in a production facility. A contract warehouse is a facility that performs the warehousing operation on behalf of one or more customers.

1.3.2. Warehousing activities

In this section we consider the flow of materials in a warehouse. Goods are delivered by trucks, which are unloaded at the receiving docks. Here quantities are verified and random quality checks are performed on the delivered loads. Sub-squinty, the loads are prepared for transportation to the storage area. This means that a label is attached to the load, e.g., a bar code or a magnetic label. If the storage modules (e.g., pallets, totes or cartons) for internal use differ from the incoming storage modules, then the loads must be reassembled. After this, the loads are transported to a location within the storage area.

Subsequently, whenever a product is requested, it must be retrieved from storage. This process is called order picking. An order lists the products and quantities requested by a customer or by a production/assembly workstation, in the case of a distribution center or a production warehouse, respectively. When an order contains multiple SKUs, these must be accumulated and sorted be-fore being transported to the shipping area or to the production floor. Accumulation and sorting may either be performed during or after the order-picking process.

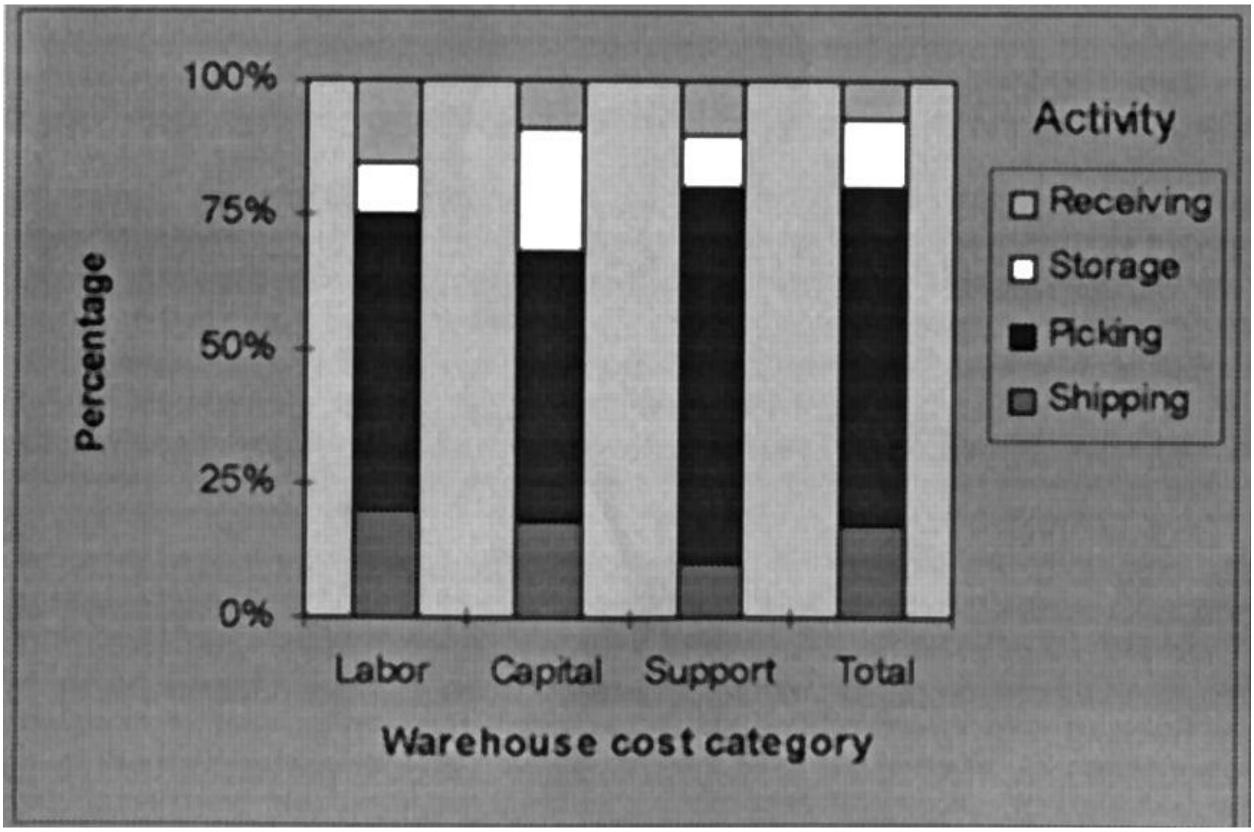

Fig. 1.3. Warehousing cost by activity

Hence, we may subdivide the activities in a ware-house into four categories: receiving, storage, order-picking and shipping. A study in the United Kingdom [2] revealed that order-picking is the most costly among these activities. More than 60% of all operating costs in a typical warehouse can be attributed to order-picking (Fig. 1).

1.3.3. A typology of warehousing systems

An item picking operation is an operation in which single items are picked from storage positions (less-than-case picking), as opposed to a pal-let-picking operation in which pallet loads are moved in and out. A warehousing system refers to the combination of equipment and operating policies used in an item picking or storage/retrieval environment. With respect to the level of automation, we may distinguish three types of warehousing systems:

1. Manual warehousing systems (picker-to-product systems),
2. Automated warehousing systems (product-to-picker systems),
3. Automatic warehousing systems.

We will discuss the three types of warehousing systems in the above sequence.

A short review of warehousing systems

A warehouse generally consists of a number of parallel aisles with products stored alongsides. A large variety of storage equipment and methods are in use. The most simple storage method is block stacking as is used, e.g., for the stacking of crates of beer or soft drinks. Bin shelving and modular storage drawers are often used for the storage of small items. For larger items, stored on pallets, pallet racks, gravity flow racks or mobile storage racks are often used. For a more elaborate discussion on storage methods we refer to [3].

In the preceding section we distinguished between manual, automated and automatic warehousing systems. Below, we describe each of these in some more detail.

Manual warehousing systems

In a manual warehousing system or picker-to-product system, the order picker rides a vehicle along pick locations. A wide variety of vehicles is available: we mention pick carts or container carts for manual horizontal item picking and man aboard storage/retrieval (S/R) machines for both horizontal and vertical item picking (often, but not necessarily, restricted to a specific aisle). For storage/retrieval operations, fork lift trucks and a variety of reachtrucks are often used.

Recall that an order may contain a list of quantities of different SKUÕs (each SKU in an order corresponds to a unique item of supply). Two fundamental approaches may be distinguished in manual order picking: single-order-picking and batch-picking. The former approach indicates that the order-picker is responsible for the picking of a complete order. The latter approach indicates that multiple orders are picked simultaneously by one order-picker, who is typically restricted to a certain zone in the warehouse (zoning). Batch picking reduces the mean travel time per pick. However, it requires that orders are to be sorted afterwards. The order-picker may either sort the orders while traversing the warehouse (sort-while-pick) or the items may be lumped together and sorted afterwards (pick-and-sort). To apply the sort-while-pick strategy, the order-picking vehicle must be equipped with separate containers for individual orders. Wave picking is a popular strategy if batching and zoning are both applied. This strategy implies that all order-pickers start picking in their respective zones at the same time. Only after all pickers have completed their tour, the next wave starts.

Instead of a vehicle we may also use a conveyor for the transportation of the picked products. The order-picker directly deposits the picked items on a conveyor that is positioned within the aisle. Such an operation is referred to as pick-to-belt.

Automated warehousing systems

The systems that we discussed so far, were picker-to-product systems. A carousel is an example of a product-to-picker system. A carousel is a computer-controlled warehousing system that is used for storage and order picking of small- to medium-sized products. A carousel may hold many different products stored in bins or drawers that rotate around a closed loop. The order picker occupies a fixed position at the front of the carousel. Upon request, the carousel automatically rotates the container with the requested product to the position of the order picker. The order picker may effectively use the rotation time of the carousel for activities such as sorting, packaging and labeling of the retrieved goods.

In some situations the order picker serves two to four carousels in parallel. The advantage of this configuration is that while the order picker is extracting items from one carousel, the other carousels are rotating. This reduces the waiting time of the order-picker. The rotary rack is a more expensive version of the horizontal carousel, with the extra feature that every storage level can rotate independently, thus reducing the waiting time of the order picker significantly.

The automated storage/retrieval system (AS/RS) is also a product-to-picker system. The AS/RS consists of one or multiple parallel aisles with two high bay pallet racks alongside each aisle. Within the aisle travels a storage/retrieval (S/R) machine or automated stacker crane. The S/R machine travels on rails that are mounted to the floor and the ceiling. In a typical configuration, the S/R machine may carry at most one pallet at the same time. Pallets for storage arrive at the input station and wait at an accumulator conveyor until the S/R machine transports them to a storage location in the racks. Consequently, storages are performed according to a first come first served (FCFS) routine. The S/R machine deposits retrieved loads at the output station, after which a transportation system routes them to their destination. The S/R machine has three independent drives for horizontal, vertical and shuttle movement. Due to the independent horizontal and vertical travel, the travel time of the S/R machine is measured by the maximum of the isolated horizontal and vertical travel times. In many applications the S/R machine is confined to one aisle. We may enable movement of the S/R machines between aisles by providing curves in the rails that connect the aisles. To maintain stability in the giant construction, the cranes have to assume creep speed in the curves. Another possibility that enables the S/R machine to enter multiple aisles, is to use a shuttle device that transfers the S/R machine between the aisles.

Due to its unit-load capacity, the operational characteristics of the S/R machine are limited to single-command cycles and dual-command cycles. In a single-command cycle either a storage or a retrieval is performed between two consecutive visits of the input and output station. In a dual-command cycle the S/R machine consecutively performs a storage, travels empty to a retrieval location and performs a retrieval. The empty travel between the storage and retrieval location is referred to as inter-leaving travel.

A miniload AS/RS is an AS/RS that is designed for the storage and order picking of small items. The items are stored in modular storage drawers or in bins. These containers may be subdivided into multiple compartments each containing a specific SKU. In a typical miniload AS/RS operation, the order-picker resides at the end of the aisle at a pick station. The pick station contains at least two container positions. While the order-picker extracts items from the container in one pick position, the S/R machine stores the container from the other pick position at its location in the rack and retrieves the next container. Also miniload AS/RSÕs with more than two pick positions per pick station do exist, as well as systems with a conveyor delivery system to transport containers to remote order pickers.

Automatic warehousing systems

Automatic order-picking systems perform high-speed picking of small- or medium-sized non-fragile items of uniform size and shape, e.g., compact disks or pharmaceuticals. If we replace the order picker of a carousel system or rotary rack by a robot, then we obtain an automatic order-picking system.

An A-frame automatic dispenser machine is another order-picking device without order-pickers. The A-frame consists of a conveyor belt with magazines arranged in A-frame style on either side of the belt. Each magazine contains a powered mechanism that automatically dispenses items onto the belt. Each order is assigned a certain section on the conveyor (a cell). When the cell passes a magazine that contains an item requested by the corresponding order, the item is automatically dispensed upon the passing cell. At the end of the belt the items belonging to the same order fall down into a bin or carton.

Order accumulation and sorting systems

Order accumulation and sorting systems (OASSs) are used to establish order integrity when orders are not picked in a single-order fashion. OASSs exist in various types, ranging from manual staging using a kitting matrix to high volume automatic systems. An automatic OASS usually consists of a closed-loop conveyor with automatic divert mechanisms and accumulation lanes. A sensor scans SKUs that enter the loop. SKUs corresponding to the same order are then automatically diverted into one lane. Also carousels and rotary racks are used for the accumulation and sorting of orders.

1.3.4. Warehouse management

Typical planning issues in warehouses are inventory management and storage location assignment. Intelligent inventory management may result in a reduction of the warehousing costs. For example, by applying sophisticated production planning and ordering policies we may reduce the total inventory, while guaranteeing a satisfactory service level. The service level specifies the percentage of the orders to be supplied directly from stock. Reduced inventory levels not only reduce inventory costs, but also improve the efficiency of the order-picking operation within the warehouse. Clearly, in a smaller warehouse, the travel times for order-picking are smaller.

Furthermore, an effective storage location assignment policy may reduce the mean travel times for storage/retrieval and order-picking. Also, by distributing the activities evenly over the ware-house subsystems, congestion may be reduced and activities may be balanced better among subsystems, thus increasing the throughput capacity.

The planning policies define a framework for the control of the warehouse processes. Inventory management and storage location assignment policies determine which products arrive and where these should be stored. Control problems typically deal with the sequencing of order picking and storage/retrieval operations, and hence with the routing of manual order pickers or S/R machines, the allocation of products to storage positions in a class-based or random location system, the internal movement of items to more attractive retrieval positions, the dwell point of S/R machines, etc.

1.3.5. Warehousing models

In this section, we discuss examples of models that have been presented in the literature or have been developed recently, to illustrate the application of operations research techniques for the planning of warehousing operations.

Inventory management/production planning decide which products are to be stored in the ware-house and in what quantities. Storage location assignment decides where the products are to be stored. Here we may distinguish between a forward and a reserve area while also the basic storage policy in S/R systems is determined (e.g., dedicated, class-based or random storage). First, we discuss inventory management.

Reduction of inventory levels

Intelligent inventory management/production planning may reduce the inventory levels and thereby the operational costs for storage/retrieval and order picking. Inventory reductions may be established by having smaller ordering quantities delivered more frequently. However, the total storage space needed may still be considerable if all deliveries occur at the same time. Hence, we may further reduce the need for storage space by care-fully scheduling the deliveries. Ultimately, products from incoming trucks are immediately transferred to outgoing trucks, a phenomenon known as cross docking.

Classical inventory management and production planning models determine ordering and production policies for a single product. Hadley and Whiten consider inventory models for multiple products with a constraint on the total storage space. They determine ordering policies for all products which minimize the long-run inventory holding and ordering costs per unit time by solving the following problem:

$$\min C_j D_j + A_j D_j / Q_j + rC_j Q_j / 2 \tag{1.1}$$

$$s.t. \sum f_j Q_j = F \tag{1.2}$$

where D_j is the demand rate in units per year for product j, A_j the fixed ordering costs for product j, C_j the unit variable purchase costs for product j, r the annual inventory carrying cost rate, Q_j the order quantity for product j, f_j the amount of space occupied by one unit-load of product j, and F the available storage space.

If the unconstrained solution exceeds the avail-able storage space, then a lagrangian multiplier technique is used to find the optimal ordering policies. Here, the storage space estimation is based on the possibility of receiving all deliveries at the same epoch. However, by properly staggering the deliveries in time, the peak demand for warehouse space may be moderated. The combined problem of order sizing and delivery staggering is known as the Economic warehouse Scheduling Problem (EWLSP). For a survey on the EWLSP we refer to [5].

All models discussed so far assume fixed cost parameters, a constant demand rate, no delivery leadtimes and no backlogging. Clearly, the problem of order sizing and staggering deliveries becomes much more complicated in a stochastic setting. Suppose for example that pallet loads for each SKU are ordered according to a (continuous review) (s, Q)-policy (cf. [6]). Under certain conditions, the number of pallets per SKU is uniformly distributed at an arbitrary point in time. Assuming stochastic independence of the demands for different SKUs, the total number of pallets can then be approximated by a normal distribution. Hence, under a random storage policy, the necessary stor-age space is determined by specifying a probability on stock overflow (cf. [7]). However, under rigid space restrictions, the orders for the different SKUs are no longer independent. Besides, many warehouse managers follow a can-order policy (cf. [6,8]) for groups of products to be delivered by the same supplier, thereby taking advantage of shared fixed costs or combined transport facilities. Hence, in such a situation, various orders of different SKUs arrive at the same time.

Storage allocation and assignment

A popular approach to reduce the amount of work associated with order picking is to divide the warehouse into a forward area and a reserve area. The forward area is used for efficient order picking. The reserve area holds the bulk storage and is used for replenishing the forward area and for picking the products that are not assigned to the forward area. The forward and reserve area may be distinct areas within the warehouse or the forward and reserve area may be located in the same (pallet) rack. In the latter case, the lower levels represent the forward area, the higher levels represent the reserve area. In some facilities the reserve area is once again subdivided into two separate areas: one for order-picking and one for replenishing.

The forward-reserve problem (FRP) is the problem of deciding which products should be stored in the forward area and in what quantities. If a product is not assigned to the forward area, then it is picked from the reserve area. Hackman and Rosenblatt [9] describe a heuristic for the FRP that attempts to minimize the total costs for picking and replenishing. Frazelle et al. [10] incorporate the heuristic into a framework for determining the size of the forward area together with the allocated products. The costs in the model for picking in the forward area and for replenishing depend on the size of the forward area.

Van den Berg and Sharp [11] focus on operations that observe busy and idle periods. In these operations, it is possible to reduce the number of replenishments in busy periods, by performing replenishments in the preceding idle periods. This not only increases the throughput during the busy periods, it also reduces possible congestion and accidents. A typical example is a distribution center in which trucks are loaded during the afternoon, so that the workforce is available in the morning hours for replenishing the forward area. The authors consider a picking period during which the order-picking operation takes place. Prior to the picking period, the forward area is replenished in advance. Their objective is to find an allocation of product quantities to the forward area, which minimizes the expected labor time during the picking period.

The authors consider a situation observed in many operations (e.g. pallet storage), where unit loads are replenished one at the time. They use the following notation:

S – set of products assigned to the forward area,

P_i – random variable representing the number of picks for product i during the picking period, $i = 1,2, N$,

R_{ij} random variable representing the number of concurrent replenishments for product i, if the forward area contains j unit-loads of product i at the beginning of the picking period, $i = 1,2, ... N$; j = 1,2, ... m_i,

U_i – random variable representing the number of unit-loads of product i that is needed to fulfill demand during the picking period.

The expected number of picks from the forward area and the reserve area are given by expressions (3) and (4), respectively.

$$\sum_{i \in S} E(P_i) \tag{1.3}$$

$$\sum_{i \notin S} E(P_i) \tag{1.4}$$

Let zi denote the number of unit-loads of product i that is stored in the forward area at the beginning of the picking period. Accordingly, the expected number of concurrent replenishments is given by expression (5).

$$\sum_{i \in S} E(P_{iz}) \tag{1.5}$$

We derive an expression for $E(R_{iz})$.

$$E(P_{iz}) = \sum_{k=z+1}^{\infty} (k-z) \cdot P(U_i = k) = \sum_{k=z+1}^{\infty} P(U_i \geq k) = E(U_i) - \sum_{k=1}^{z} P(U_i \geq k) \tag{1.6}$$

Subsequently, they formulate the FRP as the binary programming problem (B-FRP), using the following notation:

m_i – number of unit-loads available of product i, $i = 1,2,..., N$,

p_i $E(P_i)$,

u_i $E(U_i) - P(U_i \geq 1)$,

u_{ij} $P(U_i \geq j)$, i = 1,2,...,N, j = 2,..., m_i,

V available storage space in the forward area,

T^{pf} average time for performing one pick from the forward area,

T^{pr} average time for performing one pick from the reserve area ($T^{pr} > T^{pf}$),

T^{cr} average time for performing one concurrent replenishment.

They define decision variables x_i for $i = 1,2,...,N$, and y_{ij} for $i = 1,2,...,N$, j = 2,..., m_i.

$$x_i = \begin{cases} 1 \text{ if product } i \text{ is assigned to the forward area,} \\ 0 \text{ otherwise,} \end{cases}$$

$$y_{ij} = \begin{cases} 1 \text{ if } j\text{th unit-load of product } i \text{ is replenished in advance,} \\ 0 \text{ otherwise,} \end{cases}$$

(B-FRP)

$$\min \sum_{i=1}^{N} \left(T^{pf} p_i x_i + T^{pr} p_i (1 - x_i) + T^{cr} \left(u_i x_i - \sum_{j=2}^{m_i} u_{ij} y_{ij} \right) \right) \tag{1.7}$$

s.t.

$$\sum_{i=1}^{N} v_i \left(x_i + \sum_{j=2}^{m_i} y_{ij} \right) \leq V \tag{1.8}$$

$$y_{i2} \leq x_i, \quad i = 1,..N, \tag{1.9}$$

$$y_{ij} \leq y_{i(j-1)}, \quad i = 1,..N,\ j = 3,...,m_i \tag{1.10}$$

$$x_i \in \{0,1\}, \quad i = 1,..N, \tag{1.11}$$

$$y_{ij} \in \{0,1\}, \quad i = 1,..N,\ j = 2,...,m_i \tag{1.12}$$

The objective function follows from expressions (1.3)-(1.6) after substituting p_i, u_i and u_{ij} and multiplying each term with the corresponding labor-time average. Constraint (1.8) stresses that the space occupied by the unit-loads allocated to the forward area may not exceed the available space. The remaining set of constraints (1.9) and (1.10) allows the *j*th unit-load of product *i* to be stored in advance, only if unit-loads 1,..., (*j*-1) of product i are assigned to the forward area, for *i* = 1,...,*N*.

Conclusions, trends and further developments

In this chapter, we have presented a review of warehouse management systems and subsequently discussed examples of models in some specific areas that in particular highlight the relation between inventory control decisions and product allocation and assignment problems. Other fields of interest, not discussed here, include warehouse justification and design problems, as well as operational short-term routing problems. For instance, Gross et al. [14] outline the relation between multi-echelon inventory control policies and the choice of ware-house locations on a strategic level. Many authors concentrate on the development of smart order-picking strategies (both for manual order pickers and automatic storage and retrieval machines). Indeed, also the examples discussed here focus on a maximum reduction of retrieval time, e.g., the forward/reserve policy discussed in Section 4.2 has led to a reduction of the order pick time of more than 40% in a warehouse with 200 products and 800 storage locations. In one particular case study carried out at a distribution center of Yamaha Motor Co. at Amsterdam Airport, the class-allocation method discussed in Section 4.3 led to a 10% travel time reduction compared with the current four class-based strategy while the algorithm also compared favorably with other recent procedures (see e.g. [15]). In addition, a sophisticated class-allocation leads to a higher overall service level, since storage space is better used (i.e., for the right products). For a more detailed discussion of these results, as well as for an extensive literature review, the reader is referred to [16].

It will be clear that a higher warehouse service level and shorter response times may lead to additional savings downstream the logistic chain as well. For instance, in the case of a production warehouse supplying a two-bin operating assembly line, shorter response times may significantly reduce the total amount of stock placed along the line. In the food and retail sector, where many stores have moved towards just-in-time delivery, there is a constant pressure to improve response times of the warehouses. Wall Mart, a major retail chain in the U.S., has adopted cross docking (i.e., receive, sort and regroup, and ship) as the leading principle in their supply chain, as opposed to conventional storage in distribution warehouses. As a result, the interest in new, sophisticated sorting techniques is rapidly growing. ICA, the leading supermarket chain in Sweden, operates with order-picking robots that can handle a large variety of different cases and boxes, again in an attempt to move towards just-in-time delivery.

And that is still the beginning. The introduction of electronic shopping and ordering will radically change the logistics of the supply chain and lead to a drastic change in inventory management. An order to delivery cycle of 2.5 days, which is expected for the best consumer products, leaves less than 24 h for manufacturing, assembly, expedition and loading of the shelves of the retail store, after removing the average transportation time. Such a future places a tremendous pressure on the organization, planning and control of the production warehouse, as well as on materials handling, manufacturing and assembly. Indeed, some companies are completely re-engineering their manufacturing systems by introducing a so-called

Use Point Manager concept in which warehousing, material handling, assembly and packing are completely integrated in independent cells within the factory (for an interesting account, the reader is referred to [16]). Trends such as cross-docking and electronic shopping are expected to remove some intermediate stages in the supply chain and lead to an, already observable, renewed interest in production warehouses as opposed to distribution warehouses.

The above observations clearly indicate the need for research that focuses on the mutual relations between warehousing and inventory management. Unfortunately, as once was the case with set-up times in manufacturing, many inventory re-searchers assume the storage and material handling infrastructure as given. A better insight in warehousing systems and in the key factors for improving both their design and control, may lead to significant further reductions of inventory levels and improvement of response times. Facing future market trends, in particular the increased use of electronic media such as Internet in shopping and ordering, the integration of inventory and ware-house management issues may prove to be a prom: rising research area.

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2.1. A human-centric perspective exploring the readiness towards smart warehousing: The case of a large retail distribution warehouse

The explosive rise in technologies has revolutionized the way in which business operate, consumers buy, and the pace at which these activities take place. These advancements continue to have profound impact on business processes across the entire organization. As such, Logistics and Supply Chain Management (LSCM) are also leveraging benefits from digitization, allowing organizations to increase efficiency and productivity, whilst also providing greater transparency and accuracy in the movement of goods. While the warehouse is a key component within LSCM, warehousing research remains an understudied area within overall supply chain research, accounting for only a fraction of the overall research within this field. However, of the extant warehouse re-search, attention has largely been placed on warehouse design, performance and technology use, yet overlooking the determinants of Artificial Intelligence (AI) adoption within warehouses. Accordingly, through proposing an extension of the Technology–Organization–Environment (TOE) framework, this research explores the barriers and opportunities of AI within the warehouse of a major retailer. The findings for this qualitative study reveal AI challenges resulting from a shortage of both skill and mind-set of operational management, while also un-covering the opportunities presented through existing IT infrastructure and pre-existing AI exposure of management.

While AI is still in its infancy, its marketing has reached maturity. In general, AI concerns understanding and learning the phenomena of human intelligence and to design computer systems that can imitate human behavioral patterns and create knowledge relevant to problem-solving (Min, 2010). As a result, the field of AI, Robotics and Machine learning are becoming increasingly pertinent, topical and relevant discussions from within social, academic and industrial settings. As a direct consequence of AI, it is reported the UK GDP will increase by 10.3% in 2030, equivalent to £232bn (PricewaterhouseCooper, 2017), thus making AI not only one of the biggest commercial opportunities in today’s fast-changing economy, but also a pertinent and timely topic for academic research. This 10.3% anticipated growth in GDP is largely projected through improved product quality (4.5%), more personalized goods and greater variety of goods (3.7%) resulting from AI, as well as increased productivity through augmentation of the labor force and automation of some roles (1.9%). As a result, the proliferation of AI can be seen as positively influencing the economic outlook for the UK in the foreseeable future.

However, the disruptive impact of AI and automation on employ-ability and job security remains a concern. For instance, it is estimated that 39–79 million jobs in the US may potentially diminish because of AI and automation, with approximately 20% of current jobs in the UK also being automated within the same period (McKinsey & Company, 2017). Contrariwise, such indicators and narratives necessitate over-view and contextualization. While it is accepted that technology adoption does cause significant labor stagnation in the short-term, historic trends indicate that in the long term, technology generates a myriad of opportunities, new jobs and triggers demand for existing jobs (Autor, 2015). To illustrate, it is reported that approximately 6% of all UK jobs in 2013 were such, which were non-existent decades earlier in the 1990′s (PricewaterhouseCooper, 2017). Similarly, a study also found that 0.56% of new jobs in the United States each year are in new occupations (Lin, 2011), thus implying that 18% of today’s workforce is employed in an occupation that in effect did not exist in the 1980′s. Much of this is attributed to the advent of new digital technologies such as computing and communications. Similarly, by the 2030′s, 5% or more of UK jobs may be in areas related to new robotics and AI, that currently are non-existent.

Unequivocally, the explosive rise in technologies and increasing reliance on information not only influences the choices we make from within social and business contexts, but also impacts how they are made. More specifically, through recognizing the significance of information to LSCM success, professionals within this field have explored numerous ways to manage and leverage information for decision making purposes. One such way includes AI, which is yet to be fully utilized in the area of LSCM. As such, the focus of this study lies in exploring the potential of AI technology from a LSCM viewpoint, within a distribution warehouse of a major food retailer.

Consequently, by taking a human-centric approach, underpinned by a qualitative orientation, this research focuses more on soft factors, as opposed to traditionally ‘hard’ factors relating to LSCM. In doing so, the soft factors aim to extend the approach towards understanding how ready the warehouse of a major retailer is to adopt AI technology. This approach is relevant, particularly given that research suggests logistics operations remains a highly human-centered process, displaying high degrees of flexibility and complexity, thus usually resulting in a series of uncertainties (Myers, Griffith, Daugherty, & Lusch, 2004). As a result, the research contributes to the sparse literature that has examined the relationship between key success factors in the form of IT developments and the perceptions of organizational actors from within a logistics context. Particularly as the role and advancements in IT capability and human perceptions from within the warehouse context have not drawn much attention thus far.

The extant warehouse literature has provided significant insights into warehouse operations (Gu, Goetschalckx, & McGinnis, 2007), its design and performance (Gu, Goetschalckx, & McGinnis, 2010) and also the role of technologies within warehouses (Hassan, Ali, Aktas, & Alkayid, 2015). Yet, given that the warehouse is an essential component within LSCM (Hassan et al., 2015) and that warehouse performance has considerable impact on the overall performance of the supply chain, current warehousing research makes up only a fraction of the overall supply chain research, thus presenting opportunities to address many challenging research questions and problems. The motivation of this research is rooted in the fact that there remains a significant gap be-tween published warehouse studies and its practical application; this gap can be attributed to a lack of convergence between practitioners and researchers’ groups, with either the knowledge produced not being relevant to managerial needs, or being incorrectly transferred (Carter, 2008). Thus, by effectively minimizing this gap can help benefit and improve the state-of-the-art in warehouse operations and design methodology (Gu et al., 2010).

Additionally, the extant warehousing literature is largely centered on design and technical factors related to performance, at the expense of human factors (Boysen, Briskorn, & Emde, 2017; Chakravorty, 2009; Dul & Neumann, 2009; Grosse, Glock, Jaber, & Neumann, 2015; Grosse, Glock, & Neumann, 2017; Neumann & Dul, 2010), while the scant studies addressing human factors has mainly been from an ergonomics and safety point of view (Davarzani & Norrman, 2015), and thus neglecting socio-technical aspects. Ryan, Qu, Schock, and Parry (2011) also highlight this, emphasizing the lack of collaboration between researchers on human factors and operational research, whereby attention towards human aspects in operations management research re-mains limited (Dul & Neumann, 2009; Neumann & Dul, 2010). Furthermore, the existing body of warehouse studies also focus on quantitative research methods and mathematical modelling, providing little practical insight without any examples from real cases (Davarzani &Norrman, 2015). Accordingly, this research aims to bridge the gap between human factors and warehouse literature by providing real case, practical insights into human aspects from an operational setting through exploring warehouse management and technology adoption. Similarly, while the significant impact resulting from AI is acknowl-edged (Kshetri, 2018), the factors determining AI readiness is an un-tenanted point of discussion from within warehousing literature. It is also worth noting that AI solutions may not be easy to implement because they are so esoteric and difficult for ordinary decision-makers to comprehend (Min, 2010). Thus, this paper aims to reduce the complexity often associated with technical AI insights by exploring it from managerial, operational lenses. As a result, the overarching aim of this research is to gain an insight into the readiness level of AI through the lenses of warehouse organizational actors. As such, the research questions for this study are:

1) What are the potential opportunities and barriers for AI adoption in a major retail distribution center?

2) Does the warehouse have the facilities to operationalize AI technology?

3) What skillsets does the warehouse operatives have to support AI adoption?

These questions will guide the research towards gaining an under-standing of the organizations technical and human resources cap-abilities, thus providing a suitable platform to explore technology readiness and adoption from a twofold perspective.

Background

Logistics

Reverse logistics, Block chain, Green logistics, Internet of Things and Cloud systems are a handful from a plethora of hot topics currently dominating LSCM literature. Yet, in general, the field of technology has continually gained momentum as an academic area of research, from understanding the role of technology, it architectural elements, through to its perceived impact and associated challenges in the workplace. The performance consequences associated with the implementation of IT continues to attract much interest, particularly in light of the continued disruptive nature of technology (Chaysin, Jirapun, & Nopphon, 2016; Sabherwal & Jeyaraj, 2015). Similarly, recent trends also indicate that the examination of logistics as a field of science which impacts value creation, overall competitiveness of organizations and focuses on the activities of organizations that offer logistical solutions, is both topical and relevant (Oláh, Karmazin, Pető, & Popp, 2018). Therefore, gaining an insight into the overall management success factors that contribute towards logistical competitiveness within organizations is not only necessary, but also a timely topic of discussion (Jazairy, Johannes, & Haartman, 2017; Wu, 2012).

Logistics can be defined as an industry made up of process-oriented businesses centered on managing the flow of material and abstract re-sources, between a point of origin and point of destination (Chow, Choy, & Lee, 2007; Langley & Holcomb, 1992). While logistics activities extend across the entire supply chain, developing and supporting these activities can improve an organizations overall supply chain performance. The underlying goal of logistics processes are to combine and consolidate all activities related to the acquisition, conversion and distribution of goods, from being in the form of raw materials through to finished goods for customers, so service objectives are achieved in a professional, cost efficient manner (Byrne & Markham, 1991). Gaining a comprehensive insight into the structure of business processes in LSCM is paramount for the overall success of organizations. Accordingly, it is reported that logistics in its very nature is a human-centered process (Myers et al., 2004; Wang, Caron, Vanthienen, Huang, & Guo, 2014). However, much of what is reported in this regard has pre-dominantly focused on 'hard' success criterion with a quantitative orientation, overlooking the human elements associated with logistics. According to Kowalski, Zelewski, Bergenrodt, and Klupfel, (2012) much LSCM focus has been on isolated performance indicators, driven by data, primarily center on limited quantitative objectives and developed for hard business criteria.

Warehousing and technology

A key feature of logistics is its warehouses, which today is becoming more and more critical to the overall success and failure of organizations (Frazelle, 2002). The warehouse holds much significance given it plays an intermediary role between various supply chain stakeholders, thus influencing supply chain costs and service (Kiefer & Novack, 1999). Furthermore, in recent times many organizations have taken steps to centralized production and warehouse facilities, in a bid to rationalize supply chain processes and manage them more efficiently (Faber, de Koster, & Smidts, 2013). As a consequence, this has led to the proliferation of larger warehouses in control of distribution to a larger, more diverse customer base, in a greater region and, therefore, with more complex internal logistic processes (ELA/AT Kearney, 2005). Due to such significance, the focus for this research is the logistics ware-house.

The utilization of traditional information and communication technology (ICT) plays a pivotal role in aiding logistical processes (Vieira, Coelho, & Luna, 2013) and providing visibility across the entire supply chain (Hartono, Li, Na, & Simpson, 2010). The extent to which technology is already being operationalized can reflect an organizations readiness to further implement newer forms of technology. Ware-housing is at the heart of the logistical system (Aziz, Razak, Yacoob, Hussin, & Razmin, 2016), with many technologies being utilised within these settings to ensure products are identified, traced and tracked throughout the warehouse. As such, Logistics intelligence relates to techniques that strive to improve logistical operations, through their capabilities in reducing uncertainties and risks in logistics (Moore, 1990). Building organisations logistic intelligence has attracted much attention (Jedermann & Lang et al., 2008; Mejia, 2014).

Currently, a variety of intelligent technologies are commonly used within logistics settings to facilitate logisticians with real-time knowl-edge (Siror, Huanye, & Dong, 2011). For instance, multi-agent techni-ques (Chow et al., 2007; Davidsson et al., 2005; Lang, Moonen, Srour, & Zuidwijk, 2008) and radio frequency identification (RFID) (Angeles, 2009; Bose & Pal, 2005; Brown & Russell, 2007; Chow et al., 2007; Leimeister, Leimeister, Knebel, & Krcmar, 2009; Wen, 2010) are intelligent technologies which provide transparency and enable updates and chains to be controlled intelligently in real-time. Therefore, these technologies play a significant role in facilitating logistics and overall supply chain processes, particularly if supply chain partners also adopt similar technologies, such as RFID (Matta, Koonce, & Jeyaraj, 2012).

Of the key technologies, the role of warehouse management system (WMS) in supporting the warehouse and delivery processes is paramount (Choy et al., 2014; Vijayaraman & Osyk, 2006). The design of a WMS must consider physical facility characteristics and product movement in order to maximize benefits. Other key warehousing technologies that are widely operationalized include automated storage and retrieval system (AS/RS) (Roodbergen & Vis, 2009), automatic sorting system and computer-aided picking systems (Kim, Kim, & Chang, 2016). While the literature reports various technologies that facilitate operations within warehouse settings, in general only a portion LSCM focuses solely on warehouse management (Watson, Rana, Whitley, & Howe, 1999; Rubrico et al., 2008; Chan & Kumar, 2009).

It has previously been reported that approximately 750,000 or more warehouse facilities exist worldwide (Lambert et al., 1998), two dec-ades on; this number is only expected to have increased exponentially. Warehouses are principally made up of processes, resources and structure (Karagiannaki, Papakiriakopoulos, & Bardaki, 2011). Goods which arrive at a warehouse undergo various activities. Thus, it is argued that for almost every warehouse, the single most labor-intensive and costly activity is order picking (Tompkins et al., 2003). Order picking involves responsively retrieving products from allocated storage areas for specific customer requests. It is estimated that this warehouse operation contributes up to 55% of the entire warehouse operating cost. Therefore, inefficient order picking has a profound impact, not only on service, but also on overall operating costs and the entire supply chain. As a consequence of these underlying factors, order picking is regarded as the main priority focus for productivity improvements (De Koster, Le-Duc, & Roodbergen, 2007). Accordingly, this research aims to focus primarily on AI for the purposes of order picking within the warehouse context. The underlying requirement for ware-house automation arises from potential human errors caused as a result of manual handling, thus leading to warehouse and overall logistical inefficiencies (Seifermann, Böllhoff, Metternich, & Bellaghnach, 2014). Fig. 1 reflects the typical operational processes in a warehouse and the proposed AI automation for this study.

The amalgamation of innovative technologies, newer IT architectures, big data and analytics presents an array of opportunities, certainly in the world of LSCM, whereby their proliferation can achieve highly linked, flexible, well-organized end to end supply chains, responsive to the needs of relevant stakeholders (Porter & Heppelmann, 2015). The implementation of digital technologies and complex data-rich systems allows the supply chain to become considerably efficient is one thing (Khajavi & Holmström, 2015), however a more drastic proposal is one in which such advancement have such profound impact which results in completely new production, business and operating models. From a warehouse perspective, the use of AI technology certainly presents such radical changes to the operating design and model of the warehouse.

Technology is now playing a leading role in aiding logistical processes, however, while the extant literature relating to warehouse technologies is well founded, only a handful of studies have explored the potential for AI technology and its implications within warehouse contexts (Chincholkar, Krishnaiah Chetty, ö Kuppuswamy, 1994; Curry, Peters, ö Lee, 2003; Hsieh, 1998; Knapp ö Wang, 1992; Seidmann, 1988) yet there seems to be an emergent relationship between ware-housing and AI (See 3.0). Therefore, in spite of the extant literature highlighting the opportunities presented through leveraging technology within logistics, a vacant discussion remains in relation to the readiness of a major retailer’s warehouse towards AI adoption, from a human-centric perspective.

While it is widely accepted that innovation and performance are directly related within logistics contexts (Flint, Larson, Gammelgaard, ö Mentzer, 2005; Ho ö Chang, 2015; Yang, Marlow, ö Lu, 2009), there remains a wider and highly pertinent question concerning the adequacy of both digital skills and attitudes at middle and senior management levels, including those within operational settings, such as the ware-house operatives. Although organizations may be committed to the opportunities presented through acquiring technology on a strategic level, a potential shortage of both skills and mind-set creates a major obstacle in exploiting the opportunities presented through digitalization within LSCM (Hennelly, Graham, Srai, ö Meriton, 2017). Therefore, this research also aims to address this shortfall by investigating whether the warehouse management are amply equipped to implement AI within their logistics operations.

While technological innovation has great potential for LSCM and quick response systems (Zhu, Mukhopadhyay, ö Kurata, 2012), the exploitation of new technologies has always been and continues to be a procedure of social negotiation by nature, with its success largely de-pendent on stakeholder acceptance and participation. The proliferation of email use and internet capabilities can be regarded as somewhat breakthrough technological innovations, which were both effectively deployed and managed within the work place. While AI and machine learning is becoming more pervasive and evident on a daily basis through machine translation, speech recognition, image classification and information retrieval, its deployment in organizations is marred by many challenges (Holtel, 2016).

Logistics & Machine learning cases: an emergent relationship Advancements in technology continue to reach new heights. The new automation age is here, whereby industrial robots and computers are being used beyond their traditional scope of performing highly accurate repetitive tasks, routine physical work tasks, through to more complex tasks that require cognitive capabilities such as making tacit judgements, sensing emotion and driving processes which previously seemed impossible. While robots and computation have long been as-sociated from manufacturing and production contexts, these forms of technologies are increasingly finding their place within LSCM contexts.

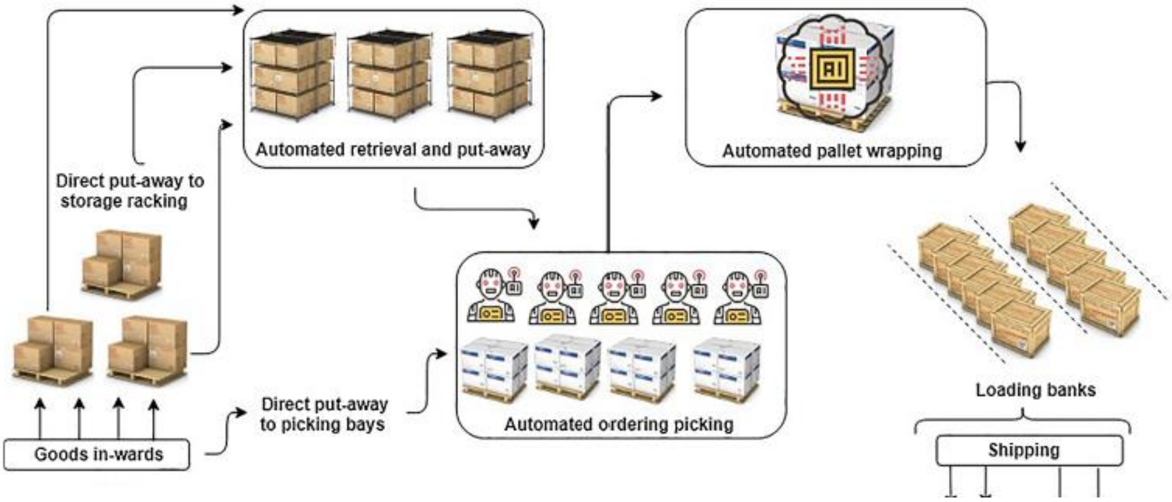

Fig. 2.1. Proposed warehouse AI automation.

In order to sustain profitability and meeting customer's requirements of quality and price, it is imperative to be aware of how to improve logistics processes (Džubáková ö Kopták, 2017). Internal logistics exploits labor and machine work through utilizing technology at different levels of mechanization and automatisation such as loading and unloading materials, transportation, and warehousing. Of the many organizations proactively pursuing innovative warehouse practices, e-commerce giants, Alibaba are leading the way, exploring the opportunities presented by technology through AI and machine learning to optimize its LSCM. Alibaba's increasing commitment to machine learning and automation is evident through what is regarded as China's largest smart warehouse. The smart warehouse is equipped with 60 robots, known as 'Zhu Que' or the 'Vermilion Bird', which are tasked with 70% of warehouse processes (Pickering, 2017a). These robots are reported to have achieved a threefold increase in output as a result of their Wifi-equipped, self-charging batteries and laser detection technology preventing collision across their 3000 square meter warehouse.

However, in the world of robotics and warehouse automation, the sky is (literally) the limit for French robotics company, Exotec Solutions. The AI specialist have developed warehouse robots that automate High level order picking (HLOP) by climbing up warehouse racks, picking orders and transporting them to warehouse operatives, in the process picking up to 400 orders an hour. The robots, known as 'Skypod' use AI and laser scanner navigation to process orders and are currently operational with one French online retailer (Pickering, 2017b).

From within the UK, E-commerce grocery chain and retailer partners Ocado continue to strive for innovative excellence, with a fully automated warehouse into full service and further plans to unveil a second automated warehouse. The warehouse is designed to have no aisles and is filled below the ceiling height with inventory, as a result Ocado have significantly reduced their human workforce by investing in hundreds of robots that works above the stacks of inventory, digging down to pick boxes and transport them to human warehouse operatives (Ocado solutions UK, 2018).

It is therefore evident that machine learning, automation and AI are now increasingly finding a place within warehousing and logistical distribution centers.

Yet, it is well known that logistics is an exceedingly human-centered process, consisting of high dynamics and complexities. Further emphasizing this human emphasis, studies report most decisions are made by human experts with varying kinds of hands-on experiences in the logistics processes (2007, Chow, Choy, Lee, ö Chan, 2005). Therefore, this study attempts to negotiate the dyadic relation-ship between advancements in technology and human capital.

Research methodology

This case study research utilizes a qualitative approach, particularly as an increasingly number of studies are opting for this type of research within LSCM (Cullen, Tsamenyi, Bernon, ö Gorst, 2013; Huemer, 2012; Varoutsa ö Scapens, 2015; Wagner ö Sutter, 2012). Accordingly, logistics as a field of research is undergoing a trend towards more naturalistic, interpretivist type research associated with qualitative methods (Halldórsson ö Aastrup, 2003). The motivations for a single case study approach were underpinned by the fact that this approach provides an in-depth description of the existence of phenomenon (Siggelkow, 2007), which is also favored when studying a group of people (Yin, 2003), such as key warehouse managerial actors. Case study is appropriate for the purposes of this research, particularly as case studies can be used to help develop an understanding of deep-rooted organizational issues associated to IT benefits realization (Dhillon, 2005). Additionally, the single case research is also recognized for its descriptive power and attention to context (Shakir, 2002), with these elements being vital in the context of this research. Single case studies provide reliable indications of future research, whilst providing new, deep and nuanced understanding of previously unexplored phenomena (Boddy, 2016). As a result, this case study research is supported by interpretive methods, particularly as the aim of interpretivism is to provide insights of a given phenomenon (Sachan ö Datta, 2005). The aim of this research is to gather information from subjective representations of interviewees which mirror the phenomenon being studied, which in this research context is technology and human interpretations relating to it.

Methods

The focus of this research is to explore the readiness of AI ware-housing technology from a human-centric perspective, through the lenses of warehouse operational staff and management. As such, the research makes use of semi-structured interviews as this is suitable for studying human behavior and behavioral changes, thus the intricacy related to technology attitudes, adoption and use can be meritoriously explored through qualitative lens. Additionally, qualitative orientations are appropriate for extracting people's interpretations of technologies and their actions around them (Orlikowski ö Gash, 1994). The key focus of this research is on attitudes regarding AI technology; therefore, this approach is highly suited. Interpretivism is the philosophical basis for this research, as it endorses in-depth insights, while also detecting fundamental values and attitudes which are essential, given the human-centric, soft focus of this research. The conceptual framework consisting of key theoretical constructs will be applied to help guide the enquiry during the interviewing and analyzing processes.

This research focuses on various organizational actors from within the warehouse at the case organization, in doing so 8 semi-structured interviews were conducted with operational staff in a variety of roles and seniority. In order to recruit the participants for this research, an exponential non-discriminative snowball sampling approach was used (Etikan, Alkassim, ö Abubakar, 2016). As a consequence, every research volunteer recruited another volunteer for the research. However, the initial research volunteer was recruited through the professional connections of the researcher.

The main motivations for the interview framing were provided from technology adoption literature (Baker, 2012; Oliveira ö Martins, 2011; Tornatzky ö Fleischer, 1990) as well as socio-technical literature (Klumpp, 2018; Kolbjørnsrud, Amico, ö Thomas, 2017; Lee et al., 2014) which explored various dimensions of technology readiness. The semi-structured interviews consisted of 8, open-ended, exploratory questions gleaned from relevant academic sources. Accordingly, as the research focuses on attitudes concerning AI technology, the interview schema addressed key aspects from firm level; technology, organizational factors, environmental factors and perceived benefits for the organization. Given the open-ended, semi-structured nature of the interview questions, additional themes were also discussed.

Qualitative thematic analysis was used to analysis the data, with the specific aim of exploring the research questions, whilst also allowing for unexpected insights to surface from the data (Klein ö Myers, 1999). This analytical approach consisted of data transcription, data coding and analyzing, and due to its flexibility is considered a highly beneficial analytical approach. Thematic analysis was deemed appropriate for this study as it offers rich and highly detailed, yet multifaceted accounts of the data (Braun ö Clarke, 2006), thus allowing for many themes of the research to be interpreted (Boyatzis, 1998). All the interviews were formal, semi-structured and were conducted within the warehouse offices, on a one to one basis. Ethical approval was granted by the University of Bradford, School of Management. In upholding anonymization, the participants' names were replaced with their initials in the study.

Conceptual framework

Technologies continue to advance, evolve and disseminate, thus perpetually driving technology adoption and user's acceptance discussions, while also continually presenting challenges from a management context (Schwarz ö Chin, 2007). Consequently, a plethora of models, theories and frameworks have been propagated over the years to help understand the dyadic relation between technology and organizational acceptance. Of the many, it is widely accepted that the technology acceptance model (TAM) (Davis, 1986), and its subsequent developments (Venkatesh ö Bala, 2008; Venkatesh ö Davis, 2000), theory of planned behaviour (TPB) (Ajzen, 1985), diffusion of innovation (DOI) (Rogers, 1995) and TOE (Tornatzky ö Fleischer, 1990) are key theories in this field. Given the overabundance of models, Venkatesh, Morris, Davis, and Davis, (2003) developed a unified model, The unified theory of acceptance and use of technology (UTAUT) that connects the divergent views on user and innovation acceptance.

Williams, Rana, and Dwivedi, (2015) performed a systematic review of articles that used the UTAUT model, highlighting it as a favored model for examining general purpose systems and specialized business systems. The UTAUT model has recently been enhanced and found to perform better through incorporating the attitude construct an integral part of the model, given the role of attitude in behavioral intention (Dwivedi, Rana, Janssen et al., 2017). Although UTAUT is not the theoretical focus of this re-search, it continues to contribute towards overall IS/IT adoption literature and thus a relevant point of discussion.

For instance, while it is widely recognized that the UTAUT model is encompassing, it was found to be less relevant in exploring more recent phenomenon, such as electronic government (e-government) due to the model lacking e-government-specific constructs such as trust, risk, se-curity and privacy. Nonetheless, the model has assisted in developing a unified model on e-government adoption, which is reported to have performed better than alternative IT adoption models, including the UTAUT model (Rana, Dwivedi, Williams, ö Weerakkody, 2016). Similarly, the conceptual and empirical similarities of other IS/IT adoption models, including the formulation process of the UTAUT were also used to develop the Unified Model of Electronic Government Adoption (UMEGA) (Dwivedi, Rana, Jeyaraj, Clement, ö Williams, 2017), to fa-cilitate in the understanding of e-government adoption. Rana, Dwivedi, Lal, Williams, and Clement (2017), also build on UTAUT to develop an e-government specific unified model through selecting the most appropriate measures of UTAUT (Venkatesh et al., 2003) and incorporating attitude as a mediating variable, thus raising the performance of the model allowing it to serve as a meaningful alternative for understanding e-Government adoption. Further highlighting the adaptability of the UTAUT model, Dwivedi, Shareef, Simintiras, Lal, and Weerakkody (2016) propose an enhanced UTAUT, that considers specific determinants relevant to cognitive, affective, and conative or behavioral aspects of citizens, which may be useful for policy-makers interested in developing mobile healthcare service systems for wider and better acceptance.

While these theories assist in our understanding of technology ac-quiescence, they offer differing focus from various perspectives. For instance, while the TOE and DOI have a firm level focus, the UTAUT, TPB and TAM models are centered on more of an individual level (Oliveira ö Martins, 2011). Conceptually, this research adapts a firm level focus, predominantly as the purpose is to establish a large distribution center's readiness to adopt AI. Nonetheless, the firm level focus will be explored through the lenses of various members of management from within the warehouse.

Consideration should also be given to the types of technology when deciding which model to utilize. For instance, the theoretical constructs from the aforementioned models may be more, or less applicable given the nature, orientation and complexity of the technology in question. Therefore, in line with the approach of Venkatesh et al. (2003), combining more than one theoretical model may help achieve a better understanding of the IT adoption phenomenon (Oliveira ö Martins, 2011). Combining theories to understand IT adoption is well evidenced within the extant literature, (Gibbs ö Kraemer, 2004; Hsu, Kraemer, ö Dunkle, 2006; Oliveira ö Martins, 2011; Zhou, Lu, ö Wang, 2010). Thus, given the complexity associated with AI adoption, this research in line with Kuan and Chau (2001) proposes to combine the key theoretical constructs of the TOE framework (Tornatzky ö Fleischer, 1990) and Iacovou, Benbasat, and Dexter (1995) models (Fig. 2) to explore AI readiness. Accordingly, based on the existing literature and drawing upon the research questions, this study presents the following proposition to address the readiness for AI adoption by the case company:

Proposition

The proposed TOE framework extension provides ideal lenses to explore AI readiness within a warehousing context.

Fig. 2.2 highlights many-to-one relationships between various elements from within technological, organizational, environmental contexts and the adoption of AI technology, whilst also considering its various perceived benefits.

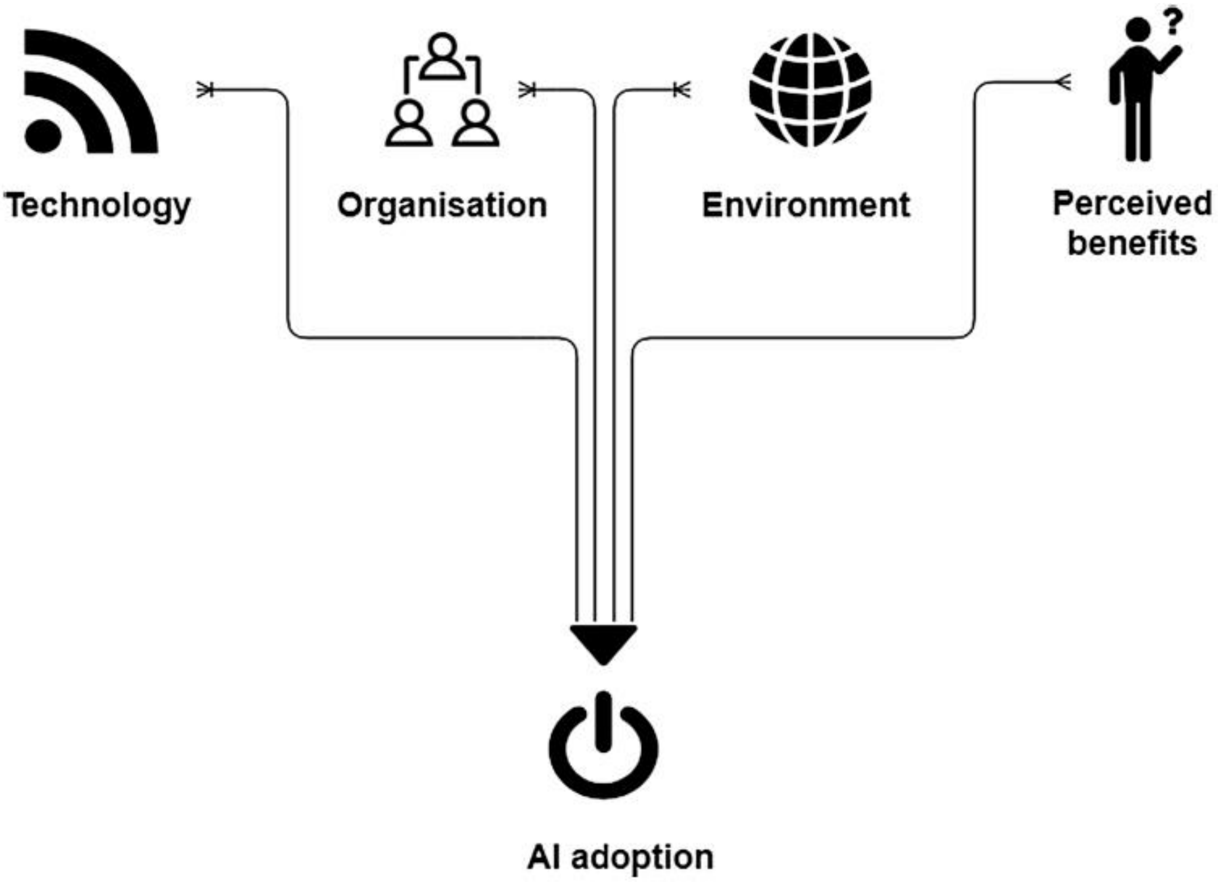

Fig. 2.2. Conceptual framework.

The Iacovo et al. (1995) model consists of ‘perceived benefits, organizational readiness and external pressures’. However, for the purposes of this research, only the ‘perceived benefits’ construct from the Iacovou et al. (1995) model will be integrated into the TOE model as the ‘organizational readiness and external pressures’ constructs are encompassed within the TOE model. Baker (2012) supports this compatibility by highlighting that the Iacovou et al. (1995) model is gradually becoming incorporated into the body of TOE research, thus the ‘perceived AI benefits’ will refer to the level of recognition of the relative advantage that AI technology can provide the organization. Previously, Chau and Tam (1997) also utilize the TOE model and incorporate perceived benefits in their exploration of open systems adoption. Thus, subsuming aspects of these theories has been found to be useful in under-standing the adoption of technological innovations.

According to Baker (2012), the TOE framework is regarded as being highly apt, given the frameworks freedom to vary the factors or measures for each new research context, accordingly, Baker (2012) presents an overview of the TOE framework and its adaption by a plethora of authors from varying research contexts. Aboelmaged (2014) utilizes the TOE framework to explore e-readiness at firm level, more recently, Jia, Guo, and Barnes (2017) explores information systems continuance using TOE, whereas Kim and Garrison (2010) has also utilized the framework to explore users' behaviors regarding supply chain technology. From an organizational context, TOE provides a suitable framework through which technological, organizational and environ-mental contexts are analyzed from a technology adoption context. Given that the case organization is already operationalizing AI technology within their supply chain (see 5.0), the TOE framework is useful in identifying technological, organizational and environmental factors and external and internal attributes which may impact AI adoption from within the distribution warehouse context in this research.

Case company: large food retailer

In order to survive and remain competitive in an ever-growing global market, managing the future is paramount (Patro ö Raghunath, 2015). Technology is a realistic pathway to achieving this. According to PricewaterhouseCooper (2017), by 2030′s, the transportation and storage industry will experience approximately 56% automation, with wholesale and retail also being forecasted high at 44%. Although, studies reveal that AI adoption outside of the tech sector is at an early, often experimental stage, with only a handful of firms deploying AI technology at scale (McKinsey & Company, 2017), the case examples provided previously (Alibaba, Exotec, Ocado) highlight how IT and specifically AI automation can drastically assist in restructuring the entire distribution set up to achieve higher service levels and lower inventory and logistics costs.

Similarly, the case company have also taken major strides towards utilizing technology advancements and AI as part of their logistic and supply chain processes. The company has recently enjoyed a growth in annual profits, with a reported increase in like-for-like sales. Much of this success is attributed to leading-edge machine-learning technology which has transformed the companies' forecasting abilities and auto-mated its replenishment processes, thus significantly impacting the overall logistical processes. The case company, through their partner-ship with a major AI and machine learning specialists have launched an innovative, ordering system capable of automatically analyzing historic sales data and other internal data sources, combined with external data such as weather forecasts and public holidays.

This AI technology, through its algorithms allows the company to predict the level of demand of every product for each store location, triggering a process that automates millions of decisions on a daily basis, balancing multiple and competing KPIs, to enhancing availability while reducing waste and significantly minimizing shelf gaps. While many companies are utilizing AI within the warehouse context as previously discussed, the case company's entire logistic operations are impacted by this AI technology, which conversely, is utilized at the start of their logistic operations. This operational transformation at the heart of its business plays a major role in determining the nature, pace and demand of operations in the case companies' distribution warehouses across the country (Fig. 2.3).

What makes the case company unique and an increasingly favorable case for this research is, firstly their adoption, commitment and current success resulting from AI and machine learning technology. AI and Machine learning serve a plethora of purposes, yet ultimately play a critical role in extracting meaningful information out of the zettabytes of sensor data collected daily. Yet for some AI applications, the purpose is solely to analyses and interpret vast datasets in order to identify trends (e.g., surveillance, portable/wearable electronics). Whereas, other forms of AI are tasked with taking immediate action based the data (e.g., robotics/ drones, self-driving cars, smart Internet of Things) (Sze, Chen, Emer, Suleiman, ö Zhang, 2017). Currently the case company are utilizing the former, whereby their AI ordering systems helps identify sales trends and thus triggers order picking figures for distribution on a daily basis.

Findings

The analysis revealed a plethora of insights regarding AI, as well as other forms of technology within the warehouse environment. It was evident from the analysis that AI operations has the potential within the case warehouse. However, many barriers to AI implementation also surfaced, as will be highlighted further. The senior implementation manager stated; ‘From the top, there is an absolute desire, as a direction for the business to go.’ The implementation manager refers to the ambition of high-level, senior management in committing to-wards this technology. These sentiments are a reflection of the organizations currently archaic, outdated operations, as supported by the following statement, ‘We know… that we have really pushed the boundaries of how far we can go with our current ways of working and technology.’ It is due to these factors, that this research explores the technology readiness level of this organization.

Technology

The technological characteristics and existing infrastructure of an organization play a vital role in adopting emerging technologies. The organization currently has AI solutions in place, such as their fore-casting and finance tools, thus potentially allowing for AI to make an easier transition into the warehouse. The project manager posits: ‘We’ve built the commas of the interfaces into (central) forecasting and finance tools, so it’s less of an upheaval and becomes a localized change in the warehouse as opposed to a business change’. Furthermore, M.B highlighted the role of the existing AI tool, when stating ‘before the forecasting system came in, there would have been a room of 100 people all trying to work out what each store wants.’ Thus, highlighting that the technology readiness level is significantly influenced by an organizations ongoing technological commitment.

It was revealed that while the warehouse has many challenges, the potential for AI adoption is a realistic option in the near future. The technology manager, S.H outlined: ‘We don’t have blockers, we have steps and phases of where we have to go to where the roadmap is taking us.’ He mentioned that while AI adoption in the warehouse may be in the distant future, the key for him was to ensure if the organization decided to go in that direction, that the technical architecture and infrastructure was in place to support it. This was further emphasized by another member of the implementation team: ‘First big step is the warehouse management system to bolt all this AI onto’. Therefore, ensuring that the technical infrastructure is in place is fundamental for potential AI.

The technology and implementation team expressed their optimism regarding AI which can be attributed to their skill-base and under-standing the scope of the current technology in the warehouse: ‘Its levels, everything we’re putting in place are a facilitator for AI.’ The implementation teams understand what is required to phase in AI in the future, however, attitudes from operational managers, differed. This can be seen here, when team manager, D.H outlined: ‘With the technology we’ve got in place, the warehouse is not ready. The systems are a long way behind what would be required.’ There seems to be very little understanding from the operational staff regarding the potential of the current systems and how they have the ability to ‘talk with AI’. This is further witnessed here when M.B, sarcastically posits: ‘We’ve only just moved from the big tin in the corner, to cloud hosting’, thus implying that embracing AI is out of the question.

On the contrary, the project manager outlined: ‘we can still manage AI through our new our existing infrastructure, except instead on directing tasks to people, it would direct tasks to automation’. The disparity between the technical experts and the operational management can be further seen when P.C, the senior implementation manager and M.B, a team manager discussed picking by paper. M.B, states: ‘When we picked on paper, we’d have more flexibility… We have to rely on the technology to work; sometimes it crashes and puts us behind!’ In contrast, P.C mentions: ‘Picking on paper very rarely see accident coming, the crash has already happened so how do you deal with that, the system gives you the visibility to see the accident happen before it does and being proactive.’ Therefore, the views pertaining to technology in general between various organizational actors are influenced by their role, with the warehouse managers driven by operations and metrics during their shifts, whilst the implementation team exercise more prudence and farsightedness.

Notwithstanding, the implementation team acknowledge that a warehouse move to AI would be challenging from an asset management perspective. P.C highlights: ‘There becomes a whole asset management discussion, where does stuff go? If that isn’t enough, you have to go and look at health and safety etc’. Similarly, S.A expresses ‘if a truck breaks down, we’ll strip it and fix it, but if a robot, or complex machine does, how quickly can we resume operations? Therefore, beyond the technology and infra-structure, assets management and maintenance are also key considerations.

Organization

The resources available to an organization play a vital role in the adoption of technology; these include managerial structure, linking structures and communication process. Accordingly, it was evident from the insights that executive management were drivers of the initiatives for the warehouse and the organisation as a whole. For in-stance, the senior implementation manager mentioned: ‘Roadmap comes from on high, so all the really seniors in every vertical, so from IT, from infrastructure, whatever they all work together, and they have an idea of where we need to be.’ Therefore, the readiness of the warehouse to embrace any form of technological change requires the support and acceptance firstly from the senior management.

However, there also seemed to be a lack of transparency between the strategy-makers and the warehouse management. This was also reflected by the implementation manager: ‘bomb door opens and out drops the bomb, it’s like okay, and we need to deal with this now.’ Here, the implementation manager refers to the bomb doors as the ‘go ahead’ and the ‘bombs’ as projects that requires implementing within the ware-house.

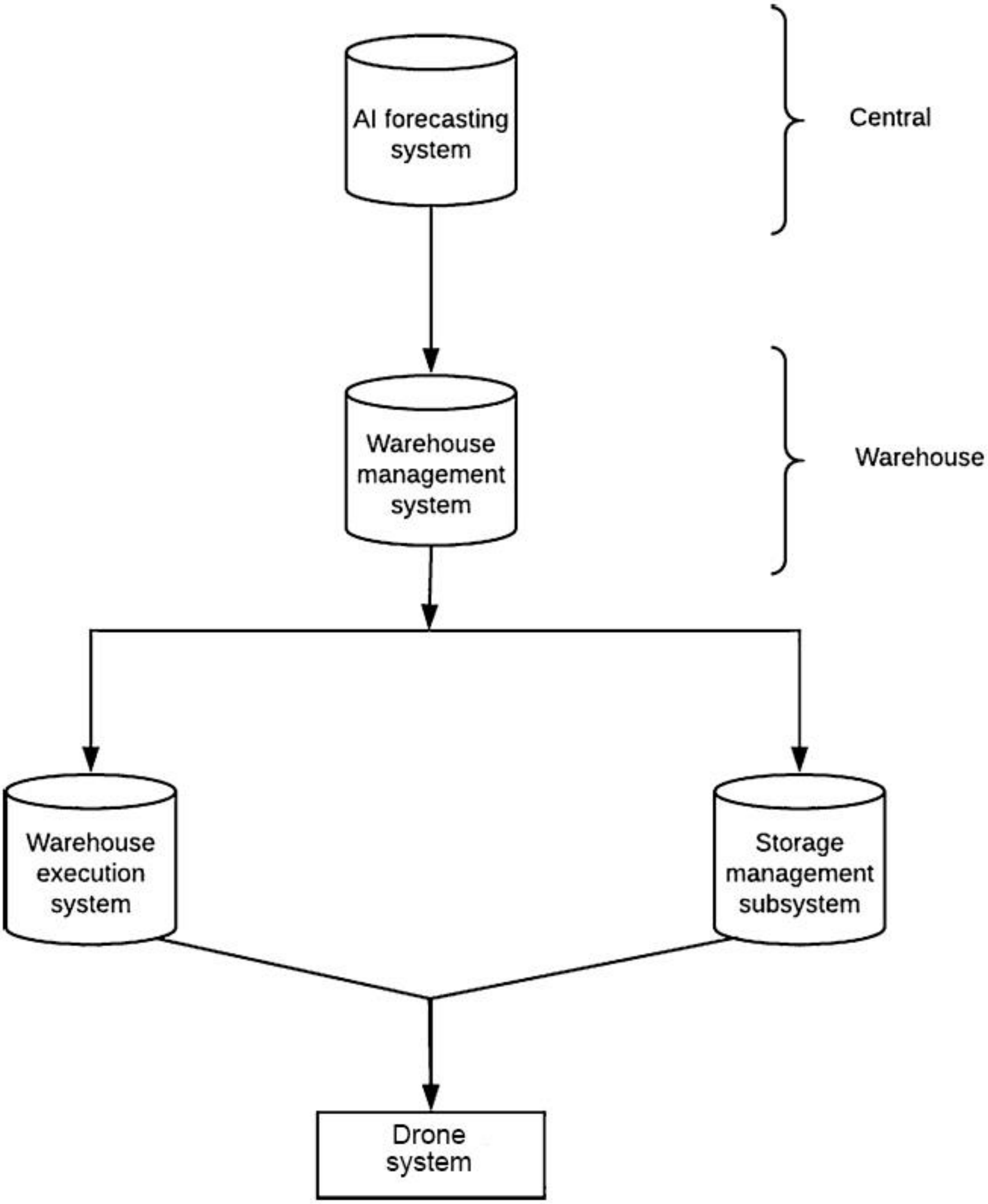

Fig. 2.3. Case companies existing AI system.

This indicates that projects may frequently require implementation on tight timescales, with limited prior notice, or that the projects may be beyond the scope of the warehouse, as further high-lighted: ‘There’ll be stuff on that roadmap we don’t know about yet, but we will be told what we need to work towards.’

Therefore, the role of the organization, particularly senior management can also be considered vital for AI adoption.

The skill-sets of warehouse operators and management were also highlighted as a key factor in AI adoption. One of the shift operational managers' highlights that skills within the warehouse were more operationally orientated rooted in old-fashioned ways of working as op-posed to being technical. Therefore, the adoption of AI would be disruptive. A.H posits: 'We are of a few places left that have a remarkable record on staff retention; we have people with up to 20–25 years' service. So, it's a massive step'. Although the manager was referring to the operational workforce, it was evident that upskilling was also required by the warehouse management. A project manager recollects the chaotic nature in which new technology and new ways of working has previously been put into practice within the warehouse: 'everybody is so focused on the new ways of working that they peddle really quickly but forget to steer'. Thus, highlighting that warehouse management place more effort than required, therefore lacking direction in the process. Furthermore, P.H, while recollecting his AI experiences from previous employment states: 'Permanent AI team onsite is a must, as in my previous work there'd be a Dematic team on site, all the time'. Hence, while there is a shortfall of AI skills-sets from within the warehouse, third party specialist may be an avenue, through which AI is supported and whereby operational management may also become upskilled.

Another key theme gleaned from the analysis was the psychological impact of technology adoption, particularly AI as it can be at the expense of people. A manager provides some further insight into the psychological elements management encounter: 'They amass experience which gives them the edge, ability of a TM to look at a warehouse full of pallets to say, I need 15 people and 3 h to shift that… that is purely experience. We put a system in and a report can tell you that. That's a massive hit for someone. That first barrier is biggest'. If AI and automation does not directly replace roles, it can certainly have a psychological impact, whereby operational operatives' skills and know-how may no longer be as relevant as previously. This is further witnessed here, as P.H posits: ‘we have a conveyor in the middle… But we don’t use it. Because people are scared of it, they don’t want to use it, they rather use man power’. P.H attributes the lack of engagement with the conveyor belt to reluctance and fear, while this is not AI, rather automation; it provides an understanding into warehouse mentality on a localized level.

It was also evident that managers who had previous experience of AI technology were more articulate and forthcoming of AI implementation. P.H, a shift manager has amassed AI experience during his various previous roles, which was evident throughout his narratives: ‘Unless you’ve seen it in action, and seen what it can do, you’ll always be dismissive of it’, and ‘I’ve had exposure to a lot more than the guys here’, thus, the lackluster and negative responses from other management may be due to the lack of AI exposure and insight. The psychological aspects touched upon earlier were also experienced by P.H: ‘I’ve seen it coming in and didn’t believe it’ll work, as I’m an old-fashioned manager, boots on the ground’ and ‘we thought it would be rubbish’. Therefore, there is a need for alignment, with concurrent technological practices and management mentality.

The change management associated with adopting new technology was a theme extensively discussed by the project and implementation teams. Given the nature of operations within a warehouse, the operational management plays a crucial role in ensuring the change is handled and delivered effectively. P.C mentions: ‘putting in a new desk, a new system, or AI, the process is the same… The biggest thing you have to face is change management’. While the adoption of AI would impact warehouse operatives, it would also have implications for warehouse management, this was succinctly described by A.A: ‘the management, who are tasked with managing the change for their teams, also require change management!’ Thus, this highlights the nature and scope of managing change related to technology.

A senior warehouse manager highlights warehouse structure and processes as being a challenge within the warehouse, which may impede the potential of AI, S.A states: ‘Some warehouses are off major motorways… so there’s issues of late or missing deliveries. Some older warehouses have a strange shape… So, it less about the system and more about the flow.’ Similarly, P.H, highlighted the warehouse design and space being incompatible with AI: ‘Space in here, the way the warehouse is laid out, it’s like putting a Ferrari engine into a reliant regal, it’ll topple over’. Similarly, R.B takes it further by suggesting AI should be operated in a purpose-built warehouse: ‘I believe warehouses need to be purpose built with AI or automation in mind. ‘As such, layout changes need to be considered, to facilitate AI operations. However, the resources and costs associated with reconfiguring warehouse layout are high, and thus presenting a challenge from an AI viewpoint.

Environment

‘Let’s not only catch up, but let’s also take some advantages’ – Competitive edge

It is apparent that while the warehouse practices may be outdated, with some operations still order-picking on paper, their AI motivation is driven by their competitors. This is supported when the implementation manger outlines ‘Everything I’m currently involved with is not a case of only trying to catch up… but also taking us to a place where we can take a big stride on top of that.’ Similarly, the extent to which external pressures impacts the adoption of technology is further epitomized by a project manager, who similarly posits: ‘it’s a mammoth task, 2 in 1, let’s not only catch up, but let’s also take some advantages.’ Therefore, the implementation and projects team understand that by investing in AI technology in the future, they can surpass competitors

Additionally, external pressures were also identified, as S.H out-lines: ‘our external relationship certainly impacts how we do things, we’re not as techy as them but I feel they’ll motivate us into managing our ware-houses differently.’ The case organization has recently entered in a wholesale partnership with several large online retailers and therefore S.H feels this may lead to sharing best practices between the organizations, particularly given that the trading partner organizations are technically advanced.

In terms of barriers, shift manager R.B touched upon the risk of redundancies resulting from AI and mentioned: ‘there’s always going to be resistance from union/colleagues with the threat of redundancies’. therefore, external pressure from union groups may result in not completely embracing AI completely, as this has the potential to make many operatives redundant. A further barrier identified was the extent to which the transport team were able to cope with the increased output generated by the AI. In this regard, S.H mentions: ‘We’ve got to see the impact at transport, if you squeeze a balloon, it’ll pop at the other end. Therefore, what good is it, if we can’t get products onto trailers!’ Accordingly, the impact of this on the transport team and other areas of the business really do require consideration, thus potentially restricting how much of the ‘AI dial can be turned up’.

‘Days and shifts are (like) different companies’ – Silo mentality The discrepancies in the ways of working and a lack of cohesion between day and night shifts was also identified as being a barrier, while also presenting opportunities from an AI perspective. S.A, mentions: ‘day and nights are (like) two different companies, we don’t operate using the same logic, approach of thinking, mainly because we have different challenges and priorities’. This was further emphasized by R.S: ‘I won’t say which [laughs], but one shift will break it [new tools, ways of working], and the other will spend time fixing it’. This therefore presents challenges for AI, as a disparity in skill-sets and support network between the shifts can hinder any warehouse wide AI progress. On the contrary, AI can bridge the differences between both shifts, as P.H, having experience of AI mentions: ‘it’s pointless having AI if it’s not operating 24 h a day, 7 days a week. So, shift would have no choice but to work more seamlessly, transparently, sharing best practice and ways of working’. Therefore, in order for organizations to maximize benefits from automation and AI, it should be operated 24 h. Thus, allowing for a smoother transition and hand-over between both shifts.

Perceived benefits

‘I’ve seen it work, I’ve seen how it can work’ - Perceived benefits From a warehouse operations viewpoint, travelling between locations involves cost, as

M.B outlines: ‘moving is dead time in warehouses, so when picking, moving between two places is dead, how can we control or shorten that?’ accordingly, AI can help provide more control and essentially reduce the travelling costs in warehouses. It was evident that various members of the warehouse management were aware of the benefits of AI: ‘We need to prove that we’re delivering benefits with this first step. Can’t be throwaway money’. The technology manager outlines that the ‘phases’ and current ways of working should present significant value to the organization, and that by only doing so, other more significant technological advancements will be delivered.

While shift manager R.B highlights potential issues which may hinder AI adoption, he was also aware of the long-term benefits for the organizations. For instance, he outlined: ‘AI can bring a cost benefit to the business once return of investment is achieved and of course service levels to customers would improve in the form of punctuality and accuracy.’ While much of the insights were based on perception, P.H referred to his personal experiences when highlighting: ‘I’ve seen it work; I’ve seen how it can work. I’ve seen shifts go from 100,000 to 150,000 units in the space of a year’.

It was also suggested that the containment of ‘scope creep’ is also imperative if AI benefits are to be experienced. A.A posits: ‘you may introduce something to drive accuracy, someone, somewhere thinks we can stretch the project to include more than what was originally planned, with the endless opportunities with AI, the project has to be contained.’ Consequently, AI potential can be maximized if the parameters of its project are not breached.

Discussion

This research set out to answer research questions relating to the potential opportunities and barriers of warehouse AI adoption, by focusing on warehousing resources and human skillset. As a result, the findings provide varying perspectives on the readiness of AI adoption from a warehousing perspective. Through the utilization of the ex-tended TOE framework, the warehouse management of the case company were able to present their views on AI technology adoption from technology, organization, environment and perceived benefits contexts. From a technological context, the excerpts of the organizational actors highlighted the significance of an organizations strategy and roadmap in the likelihood of AI adoption. The senior warehouse implementation manager outlined the importance of managing flexible planning techniques to support strategic and long-range planning, through matching short-term and long-term goals with specific technology solutions. As such, it is evident that success deployment of AI does not only depend on future technological strategizing but also on existing infrastructure and capabilities which would allow for the technology to be switched on seamlessly. Kolbjørnsrud et al. (2017) also support this, highlighting that AI strategies should be specifically tailored to local and organizational conditions, as this is a facilitator of its eventual adoption. Therefore, in addressing the research questions, it is argued that flexible and open technical infrastructure, can be seen as an opportunity for AI readiness, whilst rigid, incompatible technical infrastructures are a barrier to warehouse AI adoption.

The analysis also revealed disparity in the mind-sets of management. While the implementation managers were fully supportive of potential AI technology acceptance, the operational managers displayed more pessimistic attitudes, thus in agreement with Kolbjørnsrud et al. (2017) and the findings from their studies which emphasized the least level of AI acceptance was from front-line managers. Interestingly, it was only the operational managers with previous experience and exposure to AI, who recognized the benefits of its adoption and were hopeful of its implementation. This is further emphasized when an operational manager posited that the warehouse, was behind, both mentally and physically, highlighting the incompatibility of the ware-house layout as well as the incongruence of colleague mind-sets hindering AI acceptance. This also resonates with Klumpp (2018), who argues logisticians tend to actively and trustfully collaborate with AI following three forms of resistance, AI competence, AI decisions and AI autonomy. It is argued that the operational managers with previous AI experience overcame such areas of resistance, hence their optimism towards AI adoption.

Interestingly, the warehouse management also emphasized the nature and culture of warehouse operations, particularly the tensions between day and night shifts as presenting a challenge for AI adoption. It was revealed that while the same operation was in place on both shifts, the processes and way in which shifts were operated differed, as a direct result of different challenges, dynamics, disparate support network and skill-sets across both shifts. Wu and Chiu (2018) emphasizes the role of human relationships and shared sense of identity within LSCM, referred to as social capital and its increasingly important role in reducing the likelihood of conflicts and its ability in advocating co-operative behavior relating to shared vision, trust belief, and social ties between organizational actors. The warehouse manager with AI experience highlighted how AI adoption not only improves output and productivity, but also standardizes processes and operations across disparate shifts, thus presenting an opportunity of bridging differences between the organizational actors’ and their practices across both shifts.

Theoretical contributions

A number of key theoretical implications are garnered as a result of this research. Firstly, through exploring the extant literature, this re-search identifies a shortfall in studies from within the body of Logistics and Supply Chain Management literature which places emphasis on the warehouse and warehousing operations. This is startling, particularly given the key role of warehousing and its implications within logistics and across the entire supply chain. Moreover, through synthesizing the literature it was apparent from the scarce warehouse studies that focus has been towards design, technical factors and predominantly from an ergonomics perspective, thus presenting a gap in the warehousing literature which overlooks the dyadic relationship between humans and warehousing.

This research also contributes to an existing body of academic literature which traditionally has been critiqued as lacking relevance for mangers, due to knowledge being produced which is neither relevant to managerial needs nor transferred correctly (Carter, 2008). This, it is argued is a direct consequence of an over emphasis on quantitative methods and modelling within LSCM literature which fails to use real-case data, while also overlooking human factors (Davarzani ö Norrman, 2015). Accordingly, this research aimed at bridging this gap between theory and practice by providing practical insights and creating real knowledge that managers can use to better understand phenomena relating to that which impacts them.

Furthermore, majority of case study research conducted within warehousing contexts relate to warehousing operation strategy, which focus on high level decision- and policy-making activities (Davarzani ö Norrman, 2015) as opposed to aiming to understand managerial issues and factors involving technology adoption. Through consolidating the literature, this research fills this human-centric gap of warehousing studies by providing empirical insights underpinned by operational warehouse management. This research therefore consolidates the literature by providing insights into socio-technical aspects relating to warehousing. Furthermore, the research also presents a continuation of the TOE framework (Tornatzky ö Fleischer, 1990) for empirical re-search by extending the framework through the integration of an external construct in the form of ‘perceived benefits’. As such, in line with the literature (Baker, 2012), it is argued that this framework provides appropriate lens for exploring technology adoption, particularly as the findings and insights from this research highlights the relevance and applicability of the TOE framework from within the context of state-of-art technology such as AI. In terms of representativeness of findings, the research provides common lessons for logistics and warehousing in general. Particularly given that all the participants for this research accounted for several decades of logistics and warehousing experience, stemming from a variety of companies, across various sectors including manufacturing, retail, healthcare and food production. Thus, the in-sights gleaned from the participants were also reflective of more collective, wider understanding and interpretation of the research dyad.

Implications on practice

This research set out to provide some present-day, practical insights by minimizing the gap between human factors and operational research within a warehousing context. It is therefore argued that this has been achieved through exploring AI technology adoption challenges and opportunities by focusing on warehouse management staff within a real case context. As discussed in detail in Section 7, the findings and pertinent insights from this research may prove highly important to organizations that are potentially exploring advanced, state-of-the-art technology such as AI in their distribution warehouses. The findings derived from this research contribute to improving the understanding of the current challenges associated with smart warehousing through the multi-faceted contexts of technology, organization and environment, which are underpinned by human-centric, operational lenses. First and foremost, the findings will be of particular interest to Human Resources, as insights from this research can provide essential criterion for the recruitment activities of organizations that aspire to adopt AI technology within their logistic warehouses. Particularly as this re-search highlights that warehouse management possessing prior AI exposure and experience are more likely to engage and support any AI initiatives. Therefore, management acceptance is pivotal for organizations to maximize their chances of successful implementation of AI, with pre-existing knowledge and practical AI experience of managers being highly important in this process. This, therefore may prompt organizations that have AI on their future technology roadmap to recruit individuals possessing such attributes and mind-sets.

It is also advised that organizations involve managers with previous AI experience at earlier stages of AI projects, thus allowing them to communicate the benefits and operational advantage of the AI technology to key operational stakeholders, particularly warehouse actors such as warehouse operatives, front-line managers and senior management. The findings indicate a disparity between the operational and technological skills of warehouse staff and managers, whereby they possess significant operational knowledge and skills, whilst lacking more technological skills. Therefore, it is recommended that operational benefits such as how AI may significantly impact pick-rate, enhanced accuracy and visibility and improve the overall operations are highlighted to managers as opposed to emphasizing more technical aspects. As such approach would facilitate AI acceptance according to the skillset and mindsets of the operationally-orientated managers.

Another practical implication that can be considered from this re-search relates to the role of the warehouse layout in facilitating AI adoption. It is evident through the insights provided by various ware-house actors that the warehouse layout directly impacts the day-to-day productivity of warehousing operations, therefore should also be considered when exploring AI solutions for the warehouse. Management highlighted that although organizations have a real desire to adopt AI technology and automation within their warehouse, this may be hindered by the way in which the warehouse is laid out, with either in-effective flow or insufficient space allocation. More specifically, the managers expressed the need for either purpose-built warehouses, or warehouses that can be reconfigured with ease to compliment AI operations. Therefore, in addition to the managers skills-sets and attributes, organizations should explore their internal capabilities and facilities prior to committing to AI adoption within the warehouse. In addition to the implications, there any other significant learnings from this research, including technical infrastructure, transparency between strategy-makers and the warehouse management, senior management acceptance and the importance of standardizing shift mentality for successful AI adoption.

Conclusion

The extant warehousing literature has been critiqued for lacking collaboration between researchers and practitioners, resulting from studies which lack relevance and application in real organizational settings. In summation, this research aimed at reducing the research and practice gap through acknowledging human factors and addressing pertinent, contemporary issues relating to warehouse management and operations. As such, the research provides practical insights which are of relevance to managers, their environment and skills. The findings reveal various opportunities and potential barriers of AI adoption within warehouse context. It was evident that the implementation and technology teams were optimistic about

AI in the near future. Operational management who had previous experience of AI were also similarly expressive. However, the findings reveal that management that have little or no experience of AI failed to perceive significant benefits from AI implementation. Furthermore, it was also apparent that limited insights into the organizations technology roadmap further contributed to their negative disposition of operational managers. The teams closest to the roadmap, i.e. the implementation and technology teams would also prefer more insights into the technological direction of the organization, as this is something often cascaded down by senior, executive management. The findings also suggest that operational management lack skills in an increasingly digital world, to the extent.

2.2. Analysis of classifications, applications, and design challenges of drones

Nowadays, there is a growing need for flying drones with diverse capabilities for both civilian and military applications. There is also a significant interest in the development of novel drones which can autonomously fly in different environments and locations and can perform various missions. In the past decade, the broad spectrum of applications of these drones has received most attention which led to the invention of various types of drones with different sizes and weights. In this review paper, we identify a novel classification of flying drones that ranges from unmanned air vehicles to smart dusts at both ends of this spectrum, with their new defined applications. Design and fabrication challenges of micro drones, existing methods for increasing their endurance, and various navigation and control approaches are discussed in details. Limitations of the existing drones, proposed solutions for the next generation of drones, and recommendations are also presented and discussed.

Introduction

Drones are flying robots which include unmanned air vehicles (UAVs) that fly thousands of kilometers and small drones that fly in confined spaces [1,2]. Aerial vehicles that do not carry a human operator, fly remotely or autonomously, and carry lethal or nonlethal payloads are considered as drones [3]. A ballistic or semi-ballistic vehicle, cruise missiles, artillery projectiles, torpedoes, mines, and satellites cannot be considered as drones [4]. Advances in fabrication, navigation, remote control capabilities, and power storage systems have made possible the development of a wide range of drones which can be utilized in various situations where the presence of humans is difficult, impossible, or dangerous [5,6]. Flying robots for military surveillance, planetary exploration, and search-and-rescue have re-ceived most attention in the past few years [7]. Depending on the flight missions of the drones, the size and type of installed equipment are different [6]. Considerable advantages of the drones have led to a myriad of studies to focus on the optimization and enhancement of the performances of these drones. According to the mentioned characteristics, drones benefit from the potential to carry out a variety of operations including reconnaissance, patrolling, protection, transportation of loads, and aerology [8–12].

Drones often vary widely in their configurations depending on the platform and mission. There are different classifications for the drones based on different parameters. Watts et al. [13] described a variety of platforms. They identified advantages of each as relevant to the demands of users in the scientific research sector. They classified the drones' platforms for civil scientific and military uses based upon characteristics, such as size, flight endurance, and capabilities. In their drones' classifications, they classified them as MAVs (Micro or Miniature Air Vehicles), NAVs (Nano Air Vehicles), VTOL (Vertical Take-Off & Landing), LASE (Low Altitude, Short-Endurance), LASE Close, LALE (Low Altitude, Long Endurance), MALE (Medium Altitude, Long Endurance), and HALE (High Altitude, Long Endurance). In an overview of military drones used by the UK armed forces, Brooke-Holland [14] classified drones into three classes. Class I is subdivided into four categories (a, b, c, and d). The categorization process is initially based on the minimum take-off weight combined with how the drones are intended to be used and where they are expected to be operated. This classification is shown in Table 2.1.

Arjomandi et al. [15] classified drones on the basis of weight, range and endurance, wing loading, maximum altitude, and engine type. They classified drones as super-heavy with weights more than 2000 kg, heavy with weights between 200 kg and 2000 kg, medium with weights between 50 kg and 200 kg, light/mini with weights between 5 kg and 50 kg, and finally micro drones with weights less than 5 kg [15]. This classification which is defined based on drones' weight is shown in Table 2.2.

Gupta et al. [3] classified drones as HALE, MALE, TUAV (medium range or tactical UAV), MUAV or Mini UAV, MAV, and NAV. Cavoukian [16] categorized drones as three main types, namely, micro and mini UAVs, tactical UAVs, and strategic UAVs. He divided the tactical UAVs into six subcategories: close range, short range, medium range, long range, endurance, and medium altitude long endurance (MALE) UAVs [16]. Weibel and Hansman [17] classified drones as micro, mini, tactical, medium and high altitude, and heavy types. In Table 3, the proposed classification is indicated.

Table 2.1

The proposed drones' categorization by Brooke-Holland based on their weight

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

Table 2.2

The proposed drones' categorization by Arjomandi et al. based on their weight

Designation	Weight range
Super heavy	W > 2000 kg
Heavy	200 kg < W≤2000 kg
Medium	50 kg < W≤200 kg
Light	5 kg < W≤50 kg
Micro	W≤5 kg

Table 2.3

The proposed drones' categorization by Weibel and Hansman based on their weight.

Designation	Weight range
Micro	W < 2 lbs
Mini	2 lbs≤W≤30 lbs
Tactical	30 lbs≤W≤1000 lbs
Medium and high altitude	1000 lbs≤W≤30,000 lbs
Heavy	W > 30,000 lbs

Australian Civil Aviation Safety Authority (CASA) [18] categorized drones into three classes, namely, micro UAVs with weights less than 0.1 kg, small UAVs with weights between 0.1 kg and 150 kg, and large UAVs with weights more than 150 kg for fixed wing models and more than 100 kg for rotorcrafts [18]. United Kingdom – Civil Aviation Authority (CAA) [19,20] classified drones into three types consisting of small unmanned aircraft (weight ≤ 20 kg), light UAV (20 kg < weight≤150 kg), and UAV (weight > 150 kg). Zakora and Molodchik [21] classified drones based on their weight and range as follows: micro and mini UAV close range, lightweight UAVs small range, lightweight UAVs medium range, average UAVs, medium heavy drones, heavy medium range UAVs, heavy drone large endurance, and unmanned combat aircraft. They also categorized drones based on their missions, namely, (1) attack UAV multiple applications, (2) attack UAV expend-able, (3) strategic UAV, (4) tactical UAV, and (5) miniature UAV [22]. In Table 4, the presented drones' classification by Zakora and Molodchik is shown.

Table 2.4

The proposed drones' categorization by Zakora and Molodchik based on their weight and flight range.

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

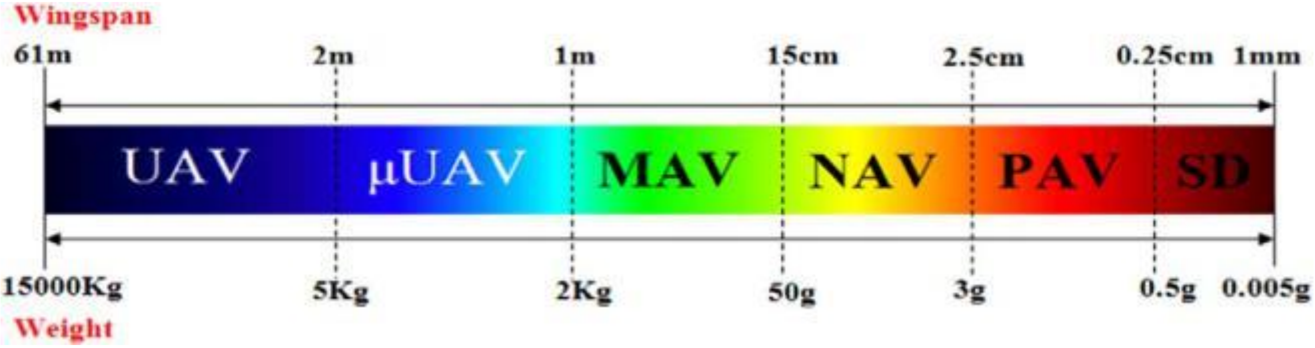

Fig. 2.4. Spectrum of drones from UAV to SD.

Nowadays different types of drones evolved from the advancement in miniaturization of electronic components, such as sensors, micro-processors, batteries, and navigation systems [23]. A wide variety of drones were used for military and civilian purposes. Drones range in size from vast fixed-wing unmanned air vehicle (UAV) to smart dust (SD) which consists of many tiny micro-electro-mechanical systems including sensors or robots. In Fig. 2.4, the spectrum of different types of drones is presented.

As shown in Fig. 2.4, there is a spread spectrum of drones from UAV class with maximum wing span of 61 m and weight of 15,000 kg [24] to smart dust (SD) with minimum size of 1 mm and weight of 0.005 g [25]. Between UAV and SD at both ends of the defined spectrum, there are various types of drones, which are called micro drones, such as micro unmanned air vehicle (μUAV), micro air vehicle (MAV), nano air vehicle (NAV), and pico air vehicle (PAV) [7]. In this study, we offer a new classification for drones which covers other types of classifications with better and more comprehensive categorization. The rest of this study is organized as follows: the unconventional classification of drones is presented in Section 2. In Section 3, the various applications of these drones are investigated and discussed. Design and manufacturing methods and their challenges are, respectively, studied in Sections 4 and 5. Different propulsion systems and actuators for drones, and their power supply and endurance are shown in Sections 6 and 7, respectively. Control and navigation, and swarm flight of drones and conclusions are, respectively, presented in Sections 8–10.

Classification of drones

In the recent decades, due to the development of a smaller air drone called micro air vehicle, the demands for intelligence missions have been increased [26]. Therefore, nowadays, there is a serious effort to design and fabricate air drones that are very small for special missions. These efforts have resulted in the development of different types of small drones with various shapes and flight modes. In Fig. 2.5, a comprehensive classification of all of the existing drones is shown, where HTOL is the abbreviation of Horizontal Take-Off and Landing.

Generally, drones can be categorized by their performance characteristics. Features including weight, wing span, wing loading, range, maximum altitude, speed, endurance, and production costs, are important design parameters that distinguish different types of drones and provide beneficial classification systems. Furthermore, drones can be classified based on their engine types [15]. For example, UAVs often apply fuel engines and MAVs use electrical motors. The types of propulsion systems which are used in drones are different based on their models. The offered classification of drones in Fig. 2 shows different models of drones as a function of their configuration. The indicated flowchart in Fig. 2 also considers the bio models of micro and nano air vehicles, which are defined as live controllable birds or insects and flying taxidermy birds.

Classification of UAVs

The main aspects that distinguish UAVs from other types of small drones (such as MAVs and NAVs) include the operational purpose of the vehicle, the materials used in its fabrication, and the complexity and cost of the control system [27]. UAVs vary widely in size and configuration. For example, they may have a wing span as broad as a Boeing 737 or smaller than a radio-controlled drone [2].

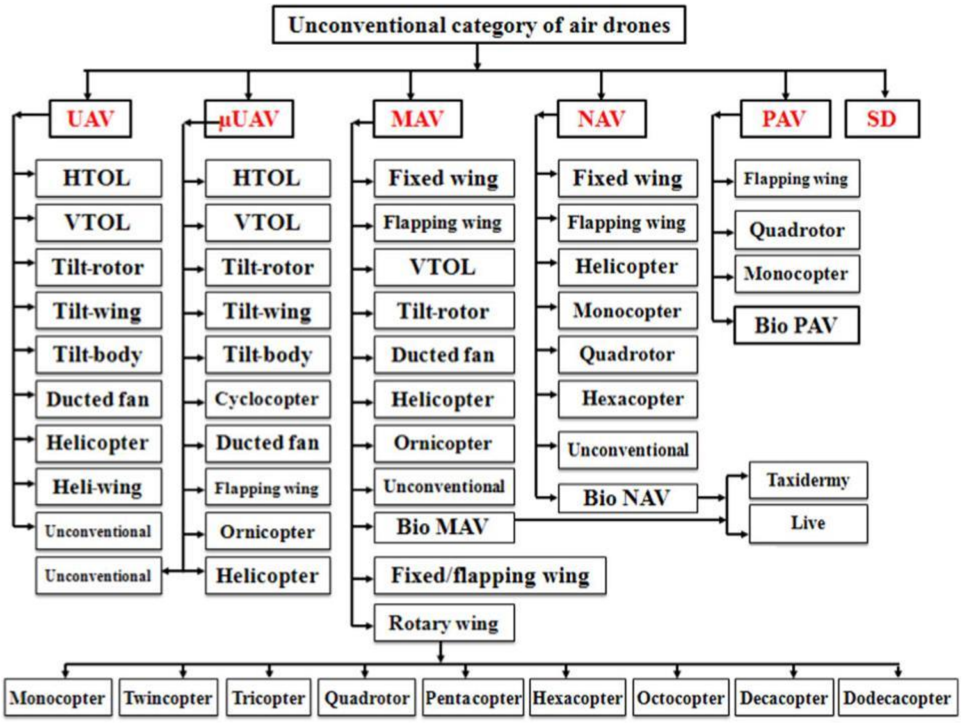

Fig. 2.5. Different types of air drones.

Different mission requirements created various types of UAVs. For this reason, it is often useful to categorize UAVs in terms of their mission capabilities [15]. As indicated in Fig. 2.5, UAVs can be considered as HTOL (horizontal take off landing), VTOL (vertical take-off landing), hybrid model (tilt-wing, tilt-rotor, tilt-body, and ducted fan), helicopter, heli-wing, and unconventional types. In Fig. 3, different types of unmanned air vehicles are presented. In Table 2.5, the characteristics of different types of UAVs shown in Fig. 2.6 are provided.

HTOL and VTOL UAVs

After many years of development in HTOL drones, there are four configurations for these UAVs, which are specified by lift/mass balance and by stability and control. They are tailplane-aft, tailplane forward, tail-aft on booms, and tailless or flying wing UAVs [37]. The mentioned configurations may have the propulsion systems at the rear of the fuselage (see Fig. 2.6(a)) or at the front side of the UAV. Fixed wing VTOL UAVs, often use a vertical propulsion system at the front of their fuselage, as shown in Fig. 2.6(b), and have cross wings. This type of drones can take off and land vertically and do not need runway for takeoff.

Tilt-rotor, tilt-wing, tilt-body, and ducted fan UAVs

For hovering flight mode, the VTOL drones are more efficient than HTOL ones. They have limitations in cruise speed because of the stalling of the retreating blades, but usually for longer range missions, UAVs with higher cruise speed are required [38]. However, the ability of vertical take-off and landing is valuable. Due to these limitations, the idea to have a type of drone which combines the capability of both VTOL and HTOL types was introduced [39]. Therefore, nowadays, there are different types of hybrid drones including tilt-rotor, tilt-wing, tilt-body, and ducted fan UAV, as shown in Fig. 2.6(c), (d), (e), and (f), respectively [40]. In tilt-rotor UAVs, at first, rotors are vertical in vertical flight, but for cruise flight they tilt forward through 90◦. In tilt-wing UAVs, the engines are usually fixed to wings, and tilt with wing. In this type of drone, the angle of the whole wing is changed from zero to 90◦in order to convert its flight modes from horizontal to vertical.

Both of these configurations flew successfully as drones, but the tilt-rotor UAV was the most efficient in hover flight and the tilt-wing UAV was the most efficient in cruise flight.

The free wing tilt-body UAV, as shown in Fig. 2.6(e), is a new kind of drones, distinct from fixed wings and rotary wings. It is neither fixed wing nor rotary wing nor any combination of the two. In this type of drones, the wing is completely free to rotate in pitch axis and the fuselage is a lifting body. Both the left/right wing pair and the central lifting body are free to rotate about the span wise shaft, free with regard to the relative wind, and free with regard to each other [41–46]. The tilt-body is also an unconventional attachment of a boom type to a fuselage such that it changes its incidence angle relatively to the fuselage in response to external commands. The merits of this type of drones are short take-off and landing (STOL), low speed loitering, and reduced sensitivity to center of gravity (CG) variation [41].

The ducted fan UAVs, are drones where their ‘thrusters’ are enclosed within a duct. The thruster of these drones is called ‘fan’. This fan is composed of two contra-rotating elements for minimizing the rotation of the body by a resultant torque. Ducted fan UAVs cannot only take off and land vertically, but can also hover and be controlled by two counter rotors and four control surfaces (vanes) [38,47]. Even though the transition into, and back from cruise flight is easy, flow separation from the duct is a concern [38].

Helicopter and heli-wing UAVs

Nowadays, researchers design and fabricate different types of unmanned helicopters for vertical takeoff, landing, and hovering flight. There are four types of helicopter UAVs, namely, single rotor, coaxial rotor, tandem rotor, and quad-rotor [38,48]. Heli-wing UAVs are other types of drones which use a rotating wing as their blade. They can fly as a helicopter vertically and also fly as a fixed wing UAV, as shown in Fig. 2.6(h) [49,50].

Unconventional UAVs

UAVs that cannot be placed in previous defined categories are considered as unconventional UAVs. Bio-inspired flying robots are usually placed in this group. For example, the FESTO AirJelly [51] which was inspired from jellyfish, as shown in Fig. 2.6(i), is considered as unconventional UAV. This drone glides in air thanks to its central electric drive unit and an intelligent adaptive mechanism. This drone is able to perform this task because it consists of a helium-filled ballonet. AirJelly is the first drone with peristaltic drive. This new drive concept, with propulsion based on the principle of recoil, moves the jellyfish gently through the air [51,52]. There are other unconventional UAVs that fly differently than conventional UAVs including the FESTO flying penguin [51].

Fig. 2.6. Different types of UAVs, (a) HTOL [28], (b) VTOL [29], (c) tilt-rotor UAV [30], (d) tilt-wing UAV [31], (e) tilt-body UAV [32], (f) ducted fan UAV [33], (g) helicopter [34], (h) heli-wing [35], and (i) unconventional UAV [36].

Table 2.5

The characteristics of different types of UAVs [28–36].

Name	Manufacturer	Weight	Wing span
[a] RQ-4 Global Hawk	Northrop Grumman	14,628 kg	39.9 m
[b] SkyTote	AeroVironment	110 kg	2.4 m
[c] Bell Eagle Eye	Bell Helicopter	1020 kg	7.37 m
[d] UAV Quad Tilt Wing	của GH Craft Ltd	23 kg	2 m
[e] Specs (Model 100–60)	Freewing Tilt-Body technology (USA	215 kg	4.9 m
[f] V-bat	MARTINUAV	31 kg	2.74 m
[g] MQ-8 Fire Scout	Northrop Grumman	225 kg to 1430 kg	8.4 m
[h] Boeing X-50 Dragonfly	Boeing and DARPA	645 kg	2.71 m
[i] Air Jelly	Festo	–	–

Classification of μUAVs

A μUAV or small UAV (SUAV) is an unmanned aerial vehicle small enough to be man-portable. It is usually launched by hand and does not need a runway for take-off. μUAVs are larger than micro air vehicles (MAVs), but can be carried by a soldier, and smaller than UAVs that cannot be carried and launched by hand. μUAVs vary widely in their configurations. As shown in Fig. 2.7, μUAVs can be categorized as HTOL, VTOL, hybrid model (tilt-wing, tilt-rotor, tilt-body, and ducted fan), helicopter, ornithopter (flapping wing), ornicopter, cyclocopter, and unconventional types.

HTOL, VTOL, tilt-rotor, tilt-wing, tilt-body, ducted fan, helicopter, and unconventional μUAVs are similar to UAV models but often have smaller size and weight compared to them, as shown in Fig. 2.7(a), (b), (c), (d), (e), (f), (g), and (k), respectively. In Table 2.6, the characteristics of some μUAVs shown in Fig. 4 are provided.

Fig. 2.7. Different types of μUAVs, (a) HTOL, (b) VTOL, (c) tilt-rotor, (d) tilt-wing, (e) tilt-body, (f) ducted fan μUAV [58], (g) helicopter, (h) ornithopter, (i) ornicopter, (j) cyclocopter, and (k) unconventional μUAV.

Ornithopter μUAVs

An ornithopter, is derived from the Greek words of ornithos meaning bird and pteron which means a wing, that is flying by opening and closing its wings. The idea of inventing bird wings to fly refers back to ancient Greek legends about Daedalus and Icarus. Roger Bacon, in his writings in 1260 CE, was among the first to propose the idea of advanced flying. Leonardo da Vinci, around the year 1490, began to study the flight of birds. He concluded that humans are too heavy to fly with wings attached to their arms. As a result, he thought about a machine which allowed he pilot to move big wings by means of hand axels, foot pedals, and a system of pulleys [64,65]. The first ornithopter was built around 1870 in France by Gustav Trouvé who flew for about 70 m in an exhibition in France [64,66]. Recently, researchers designed and fabricated some flapping wing drones. For example, FESTO designed a flapping wing, called Smart-Bird with a wing span equal to 1.96 m can fly like a seabird

Table 2.6

Name	Manufacturer	Weight	Wing span
[a] Q-11 Raven	AeroVironment	1.91 kg	1.3 m
[b] HeliSpy II	Micro Autonomous Systems LLC, USA	2 kg	–
[c] ITU Tilt-Rotor	Turkish UAV research	–	–
[d] QUX-02	Japan Aerospace Exploration Agency	3.4 kg	1.38 m
[f] T-Hawk	DARPA	–	–
[g] Sniper 032	Alpha Unmanned Systems	–	1.8 m
[h] SmartBird	FESTO	450 g	1.96 m
[j] Cyclocopter ADEX	Korean Aerospace Research Institute	–	–

Ornicopter µUAVs

An ornicopter is a helicopter without a tail rotor, but with wings that flap like bird wings, as shown in Fig. 4(i). The name, ornicopter is a contraction of the words ornithopter and helicopter. In other words, ornicopter is a helicopter that flaps its wings like a bird to get into the air. Aeronautical engineers at Delft University of Technology thought that by flapping a helicopter's main rotor blades like the wings of a bird, they can dispense with the tail rotor and avoid the drawbacks of the NOTAR (NO TAil Rotor) system and increase the freedom of movement by flapping like a bird.

Cyclocopter µUAVs

The cyclocopter or cyclogyro are µUAVs that use cycloidal rotors which consist of airfoils rotating around a horizontal axis to generate lift and thrust forces, as shown in Fig. 2.7(j). They can take off, land, vertically, and hover like a helicopter. The cyclocopter wing resembles a paddle wheel, with airfoils replacing the paddles [71]. Bin et al. [72] from the National University of Singapore first built a cyclogyro µUAV that could hover and turn on the end of a tether.

Classification of MAVs

MAV airplanes are micro planes usually with a length smaller than 100 cm and a weight lower than 2 kg. These drones are grouped into nine categories: fixed wing, flapping wing, VTOL, rotary wing, tilt-rotor, ducted fan, helicopter, ornicopter, and unconventional types. These drones can carry visual, acoustic, chemical, and biological sensors, as shown in Fig. 2.8. Different types of micro air vehicles are attracting various disciplines including aerospace, mechanical, electrical, and computer engineering. The Defense Advanced Research Projects Agency (DARPA) program limits these air drones to a size less than 150 mm in length, width, or height and weighing between 50 and 100 g [7,76], but after the advent of NAVs and PAVs, the definition for MAV was changed. Therefore, in this review, the dimensions of these drones are considered between 15 cm to 100 cm and weight between 50 g to 2 kg. The smaller dimension of MAVs, compared to UAVs, provides them with the broader performance range.

MAV airplanes are micro planes usually with a length smaller than 100 cm and a weight lower than 2 kg. These drones are grouped into nine categories: fixed wing, flapping wing, VTOL, rotary wing, tilt-rotor, ducted fan, helicopter, ornicopter, and unconventional types. These drones can carry visual, acoustic, chemical, and biological sensors, as shown in Fig. 2.8. Different types of micro air vehicles are attracting various disciplines including aerospace, mechanical, electrical, and computer engineering. The Defense Advanced Research Projects Agency

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Fig. 2.8. Different types of MAVs, (a) fixed wing, (b) flapping wing, (c) fixed/flapping-wing, (d) rotary wing , (e) VTOL, (f) ducted fan, (g) tilt-rotor, (h) helicopter, (i) unconventional, (j) ornicopter.

The first comprehensive research on MAV was performed in 1993 at RAND Institute [77,78]. In the past decade, due to the quick advances in microtechnology, MAVs have drawn a great deal of attention. As a result, in subsequent years, several research investiga-tions were carried out on the micro planes [79,80]. In addition to their small sizes, these types of planes are capable to fly at low speeds.

MAVs are mainly flying at low altitudes for various applications, such as monitoring of dangerous locations, tracking of the specific targets, or mapping. Flying of MAVs at low altitude places them within the atmospheric boundary layer, a particularly turbulent regime which makes them sensitive to these atmospheric disturbances [81].

Therefore, design and fabrication of these air drones should be accurately carried out. Conceptual design of micro air vehicles usually differs from that of conventional UAVs design due to nontraditional flight missions and decreased time required for design, production, and evaluation of these drones [82].

As for VTOL, tilt-rotor, ducted fan, helicopter, ornicopter, and unconventional MAVs, they are similar to μUAV models but have smaller size and weight compared to them, as shown in Fig. 2.8(e), (f), (g), (h), (i), and (j), respectively. The features of a few of the MAVs shown in Fig. 5 are indicated in Table 2.7.

Table 2.7

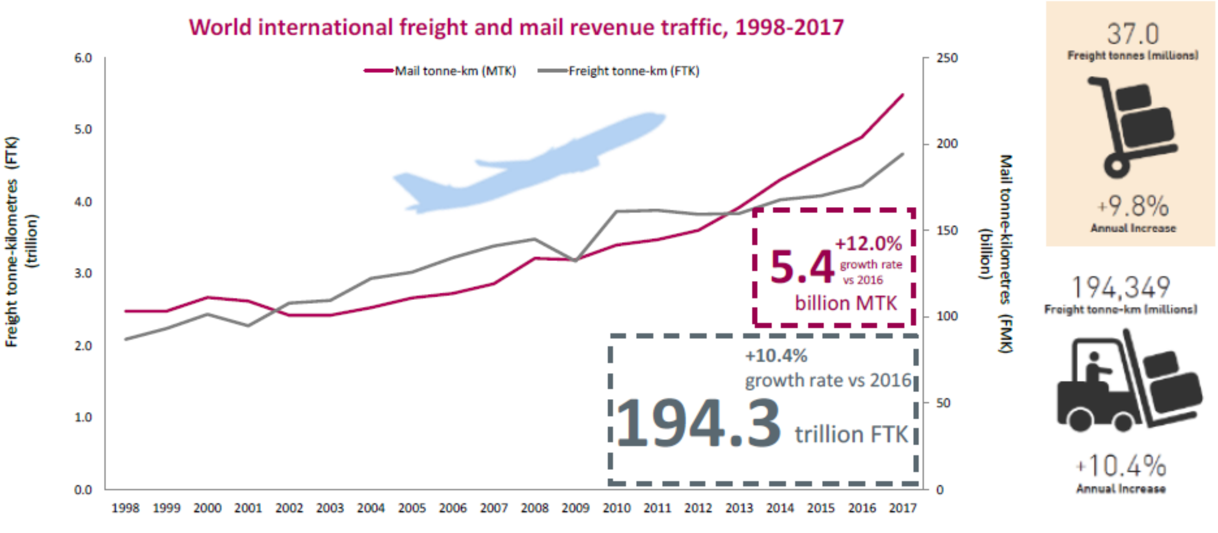
The characteristics of different types of MAVs

Name	Manufacturer	Weight	Wing span
[a] Inverse Zimmerman	Isfahan University of Technology	430 g	43.2 cm
[b] Thunder I	Isfahan University of Technology	350 g	70 cm
[c] NPS flapping-wing	Naval Postgraduate School	14 g	23 cm
[d] Apollo	IdeaFly	1200 g	35 cm
[e] VTOL UAS	Cranfield Aerospace Solutions	–	–
[f] GFS 7	JL Naudin	526 g	60 cm

2.3. Worldwide air cargo analytics: facts & figures

Air cargo or freight refers to any property, other than mail, stores and passenger baggage, carried on an aircraft. The term air cargo is also used in a broader sense by the airline industry to mean any property (freight, express and mail) transported by air except baggage. An all-cargo service is an air service that carries only cargo, whether scheduled or non-scheduled.

Economic growth and globalization drive air cargo demand. Today, air cargo retains its vital role in economic expansion, with emphasis on developing markets. As a trade facilitator, air cargo increases the global reach of businesses, allowing them to bring goods and products to distant markets in a more cost-effective and faster way. 2017 was an exceptional rebound year for air cargo performance, resulting from improved global economic conditions, world trade and increased import and export activity. Over the past two decades, the annual average growth rate of Freight Tonne Kilometer (FTK) was 4.1% while Mail Tonne Kiloemter (MTK) was 4.05%.



Source: ICAO

Fig. 2.9. World international freight and mail revenue traffic, 1998-2017

In terms of freight tonnes, there was a growth of 9.8 per cent, with a total load of 37.0 million tonnes during 2017, while there were 33.7 million tonnes loaded in 2016.

In 2017, demand (FTKs) grew 10.4 per cent, totaling 194.3 billion.

Air cargo carries a diversity of goods: high-value, consumer, heavyweighted and outsize goods, live animals, and temperature sensitive. A high proportion of air freight is business-to-business and pre-consumer in the supply chain. Components, machinery and spare parts for products may not be intrinsically of high value, but they are process critical in the supply chain and the air linked assembly line. Air cargo enhances the productivity of several industries by cutting costs for storage, inventory, and production.

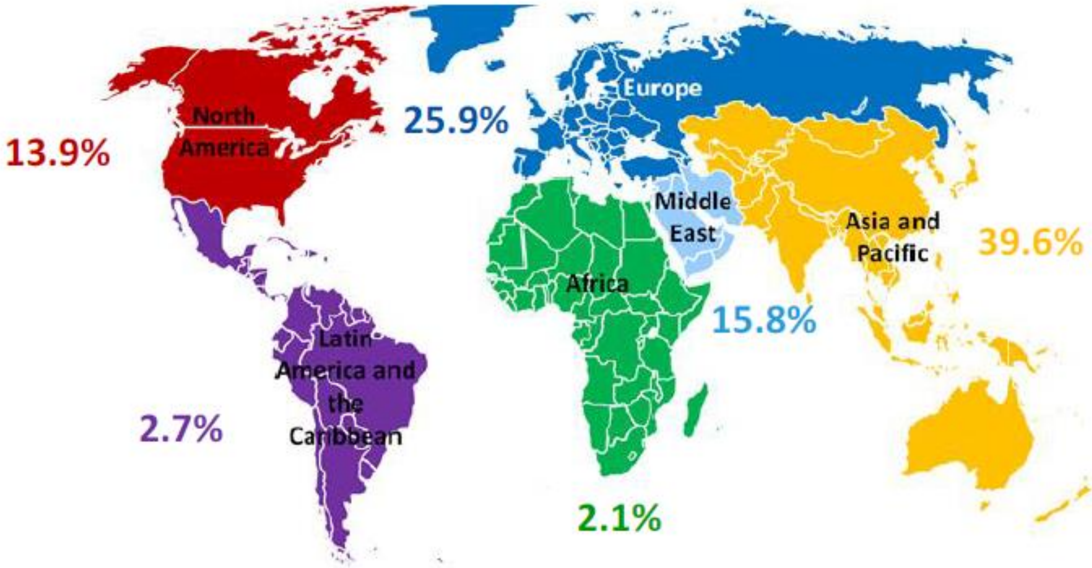


Fig. 2.10 Share of International Freight Tonne-Kilometres by region, 2017.

Asia-Pacific was the most dynamic region in 2017 in terms of FTK , at 38.8 percent of total global traffic. This represents more than 86.7 billion of FTKs compared to 80.3 billion in 2016, which represents a 2017 growth rate of 7.9 percent in. Air cargo growth rate followed the strong expansion in world trade: 4.7 per cent. This outperformance was a result of strong global demand for manufacturing exports and a re-boost in consumers' confidence.

Air cargo or freight refers to any property, other than mail, stores and passenger baggage, carried on an aircraft. The term air cargo is also used in a broader sense by the airline industry to mean any property (freight, express and mail) transported by air except baggage. An all-cargo service is an air service that carries only cargo, whether scheduled or non-scheduled. . During the same period, mail recorded 3.8 million tonnes which represents a growth rate of 6.5 per cent. It is important to underline, that North America.

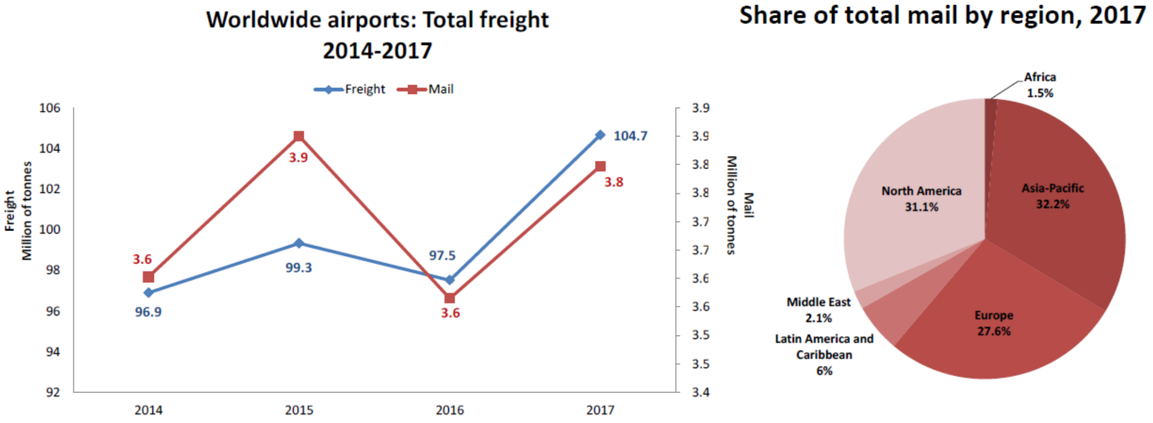


Fig. 2.11. Worldwide airports: Total freight Share of total mail by region, 2017

The good 2017 for air cargo is also reflected in airports performance. During 2017, 104.7 million tonnes were transported throughtout airports across the world, where 69 per cent represented international freight. Total freight (loaded and unloaded) grew 7.3 per cent in comparison with 2016. During the same period, mail recorded 3.8 million tonnes which represents a growth rate of 6.5 per cent. It is important to underline, that North America and Asia Pacific regions captured 63.3 per cent of the total mail, totaling 2.4 million tonnes.

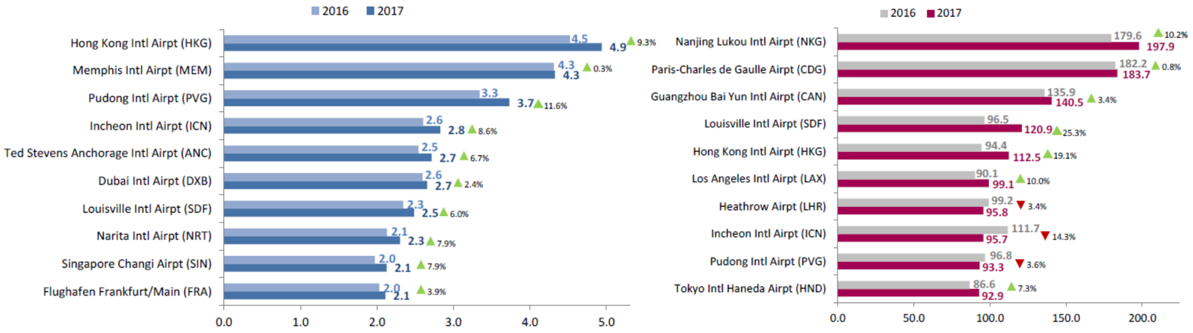


Fig. 2.12. Top ten airport ranking in freight tonnage / Top ten airport ranking in mail tonnage

The airport rankings in freight and mail tonnage confirm the performance abovementioned. Related to the airport ranking in freight tonnage, these 10 airports capture the 27 per cent of the worldwide freight tonnage. From these ten airports 5 are located in Asia Pacific, 3 in North America and one in the Middle East and Europe, respectively.

Related to airport ranking in mail tonnage, these 10 airport represent the 37 per cent of the total mail tonnage. From these ten airports 5 are located in Asia Pacific, 2 in North America and 3 in Europe. Changi airport growth in cargo flows were for cargo segments such as e-commerce, perishables and pharmaceuticals. Also, Changi is the major pharmaceutical hub in the Asia Pacific region.

Embracing new technologies, new platforms… new ways of thinking

As online retail boosts demand for parcel delivery services worldwide, e-commerce has become one of the main drivers for the air cargo industry,. According to the Cross-Border E-Commerce Shopper Survey 2017 by the International Post Corporation (IPC), consumers are shopping more than ever online and are most active in China, Korea, India and the United States. The most popular device used to shop online was a laptop (34%), followed by desktop (30%) and smartphone (24%). When comparing countries, smartphones were most popular in China (53%), India (51%), the US (43%), Brazil and Korea (both 36%). Also, the volume of cross-border light weight packets continues to grow, with packets becoming lighter (51% of the goods purchased cross-border weighed less than 500g) and the value of goods decreasing (39% of the goods purchased cross-border cost less than €25). With regards to the platforms used for on-line shopping, Amazon, eBay and Alibaba/AliExpress accounted for 56% of the most recent cross-border e-commerce items purchased.

This performance is reflected in the figures deployed by the international mail tonne-kilometer performed (MTK) in 2017, with a growth of 12 percent reaching 5.5 billion in 2017, compared to 6.7 billion in 2016.. This explains the dynamic synergy between e-commerce and air cargo traffic.

Differente size, different nature…different needs

Depending on geographical location, infrastructure sophistication and economic framework, each economy might be more or less use-extensive in air cargo transport system for international trade.

As the chart shows, in economies such as the United Kingdom, air transport accounts for 47.5 percent by value, while in Germany it accounts for 21.3 percent.

Landlocked countries have difficulty in accessing global markets, even by air. This is reflected in the share of total 2017 international trade value where countries such as Paraguay captured 15.3 percent and Bolivia 10.8. Mainly as a consequence of hard and soft infrastructure deficit. According to the World Bank2 almost all the capital cities of landlocked countries are now linked to ports with paved infrastructure in fair or good condition.

However, transport prices remain extremely high for most operators based in landlocked countries. Other problems include border delays, cartels in the trucking industry, multiple clearance processes, and bribe-taking, all of which keep transport costs artificially high.

In other countries the low share may be explained by the strong competition among the various modes of transportation, as well as a consequence of rules effectively constraining air cargo operational and market opportunities. Other causes include common regulatory challenges that cargo operators may encounter. Examples are airport curfews and limitations on airport slots, especially at congested airports where all-cargo operations are often given lower priority than passenger services.

Table 2.8.

Air transport share of total international trade value (%)

Economies	Air transport share of total international trade value (%)
United Kingdom/3	47.5%
Japan	40.0%
EU-28	26.5%
Malaysia	29.3%
United States	27.5%
Germany	21.3%
Dominican Republic	19.0%
Turkey	13.1%
Paraguay	15.3%
Qatar	12.1%
Canada	11.7%
Colombia	11.7%
Kuwait	10.8%
Bolivia/2	8.9%
Uruguay	8.1%
Mexico	7.0%
Azerbaijan	5.0%

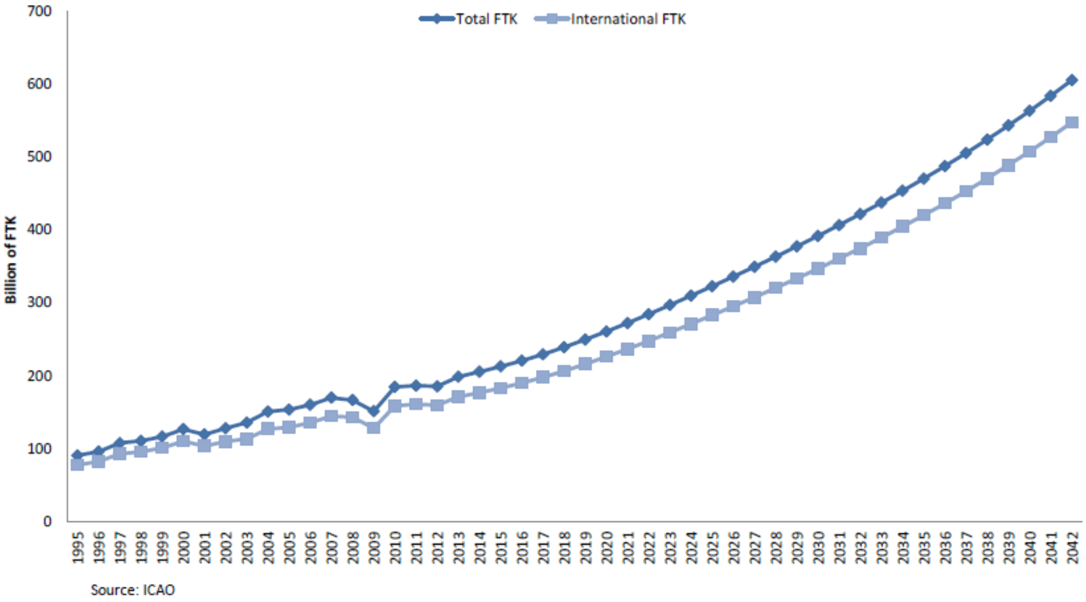


Fig. 2.13. Forecasting air cargo demand

Air cargo industry battled against the global economic downturn in 2008 and 2009. After an eager comeback in 2010, air cargo fought again, against the standstill from 2011 to 2012. The first signs recovery were in 2013 and 2014, when total FTK grew 0.4 and 4.7 per cent, respectively. These elements were key encouraging signs for expected recovery of the industry. However during 2015 air cargo slowdown the pace as a consequence of the weakness reflected by the trade growth in Europe and Asia-Pacific. The strong growth rate appeared in 2016, when the total FTK grew at 3.6 per cent, that was nearly double than 2015 growth rate. This result was a positive output from a strong recovery in the export orders. Finally 2017 has been the best year since 2010.

Air cargo traffic gathered strength during 2016 and 2017, and is projected to return to sustainable trend growth by 2018. The development of the air cargo industry depend mainly of the following economic variables: Gross Domestic Product (GDP) growth rate, performance of international trade and the relationship of air freight demand to goods trade. Air cargo also is facing some threats and challenges such as rising interest rates, trade protectionism, and international conflict, along with operational restrictions. However, new oppportunities show in the international framework such as: e-commerce and pharmaceuticals. ICAO has forecasted the air cargo demand measured in Freight Tonne Kilometers (FTK). Taking 2017 as the baseline for the estimation of the annual component growth rate, it is estimated that the total FTK may grow at 4.5 per cent in the coming decade and 10.7 per cent in the next 25 years. The International FTK is expected to grow at 2.9 per cent in the next ten years and 6.2 per cent in the next 25 years.

Conclusion

During 2017, air cargo traffic took-off and showed a recovery as a result of the improvement of global economic conditions, strong boost of e-commerce and the robust expansion of the world trade. Even though air cargo moves an average of 0.5 per cent of the total volume of the worldwide international trade, for some economies, the value of the merchandises may represent from 47.5 per cent to 5.0 per cent depending on how use-extensive that economy is from its air transport systems as well as the various geographical, infrastructural and economic factors.

Air cargo plays a vital role in the network economies supporting just-in-time supply chain management that is beneficial to cut storage and inventory costs. Air cargo retains and even expands its vital role because businesses consider it as a crucial link in the supply chain. Security and reliability of air freight as well as the speed are the key decision factors for this choice in mode of transport. ICAO is collaborating with its Member States as well as other International Organizations to enhance security, facilitation and liberalization of air cargo. Its goal is to develop a sustainable, global air cargo network that is a vital component of the global supply chain and complements other modes through appropriate connectivity. ICAO is also showcasing the importance of air cargo as a key element in infrastructure development and the alleviation of poverty, as well as a technology trigger and a means to empower both least developed and developing economies so they might effectively participate in the global marketplace.

2.4. Warehouse automation facts analysis

Warehouse automation stats show that automation is making a big impact on warehouses and distribution centers. There are many driving forces behind the automation trend, from rising labor costs to rapid growth in ecommerce sales and a growing demand for rapid order fulfillment, such as two-day and even same-day delivery. Labor availability is also a concern, as well as workplace safety.

As technology awareness grows, more warehouses and DCs turn to automation to adapt to the changing landscape. Below, we’ve rounded up 50 compelling statistics to shed some light on the driving forces behind warehouse automation and the impact automation has on the industry.

General warehouse industry statistics
Warehousing costs & revenue statistics
Warehouse efficiency statistics
Labor statistics in the warehousing industry
Automation adoption in the warehousing industry
Warehouse performance metrics

Warehouse automation stats: General warehouse industry statistics

Warehouse automation stats: The number of private warehouses is growing. According to data from the U.S. Bureau of Labor Statistics, there are 18,182 private warehousing establishments as of 2018, up from 15,203 in 2008.

1. The number of private warehouses is growing. According to data from the U.S. Bureau of Labor Statistics, there are 18,182 private warehousing establishments as of 2018, up from 15,203 in 2008.

2. Warehouses are increasing in size, as well. The average size of warehouses in 2000 was about 65,000 square feet, compared to about 181,370 square feet in 2017, according to a 2017 report from Westernacher Consulting. According to the report, “The increase in size helps warehouses to cope with higher volumes and a growing number of SKUs. However, rising costs and long traveling distances in

large warehouses are making size expansion less effective in addressing operational challenges.”

Warehouse automation stats: A growing number of DCs have multiple buildings. Among distribution centers with three or more buildings, 28% had six or more buildings in 2016, 22% had six or more buildings in 2017, and 27% had six or more buildings in 2018, according to Logistics Management.

3. A growing number of DCs have multiple buildings. Among distribution centers with three or more buildings, 28% had six or more buildings in 2016, 22% had six or more buildings in 2017, and 27% had six or more buildings in 2018, according to Logistics Management.

4. Distribution centers are growing in size. The average square footage of distribution centers in 2016 was 539,000, increasing to 473,400 in 2017 and 672,080 in 2018. The median square footage of distribution centers was 240,410 in 2016, 176,600 in 2017, and 305,000 in 2018.

Warehouse automation stats: Distribution centers are expanding vertically, as well. According to Logistics Management, the average clear height of distribution centers was 32.7 feet in 2018, an increase from 31.1 feet in 2016.

5. Distribution centers are expanding vertically, as well. According to Logistics Management, the average clear height of distribution centers was 32.7 feet in 2018, an increase from 31.1 feet in 2016.

6. Ecommerce demand drives up U.S. domestic revenue for UPS. According to a 2017 press release from UPS, “The Domestic segment benefited from strong demand for ecommerce deliveries and revenue was up 5% over Q1 2016. The U.S. consumer continues to transform retail consumption due, in part to the simplicity, personal convenience and reliable delivery solutions offered by UPS.”

Warehouse automation stats: The demand for warehouse space drives up prices. Westernacher Consulting explains, "As warehouses demand more space, this naturally pushes up price. In fact, between 2011 and 2015, warehouse renting rates were up by a whopping 28.7%. This trend is likely to continue as the US Industrial Space vacancy rate falls to 5.3% in Q1 2017, the lowest since 2008."

7. The demand for warehouse space drives up prices. Westernacher Consulting explains, “As warehouses demand more space, this naturally pushes up price. In fact, between 2011 and 2015, warehouse renting rates were up by a whopping 28.7%. This trend is likely to continue as the US Industrial Space vacancy rate falls to 5.3% in Q1 2017, the lowest since 2008.”

8. Average warehouse capacity utilization among manufacturers is about 68%. “However, 15% reported that they were at 100% capacity, while 19% were at 81% to 99% capacity. Looking forward for the next two years, 53% expect increased utilization, while only 5% expect a decrease,” according to a 2018 survey by Logistics Management and Peerless Research Group (PRG).

Warehouse automation stats: More warehouses and distribution centers are investing in automation and robotics thanks to a positive economic outlook. "Peerless Research Group’s (PRG) annual survey, conducted in January of this year, found that 42% of respondents were proceeding with investments given the state of the economy, up from a 35% response to the same question in early 2017. Similarly, only 9% said they were 'holding off' on investments, well under the 16% in 2017," the report explains.

9. More warehouses and distribution centers are investing in automation and robotics thanks to a positive economic outlook. “Peerless Research Group’s (PRG) annual survey, conducted in January of this year, found that 42% of respondents were proceeding with investments given the state of the economy, up from a 35% response to the same question in early 2017. Similarly, only 9% said they were ‘holding off’ on investments, well under the 16% in 2017,” the report explains.

10. Vacancy and availability rates are on the decline. “CBRE’s third-quarter 2018 industrial and logistics indicators were over-performing nationwide, in most markets, both primary and secondary. The overall availability rate declined 10 basis points to 7.1 percent, the lowest level since the fourth quarter of 2000. This marked the 34th consecutive quarter of positive net absorption, the longest streak since 2001. The national vacancy rate edged down to 4.3 percent, the lowest level

since at least 2002. Vacancy rates in key transportation hubs and seaport cities were even lower,” according to a report from JOC.com.

Warehouse automation stats: Net asking rents continue to rise, as well. According to JOC.com's report on CBRE's findings, net asking rents rose to $7.21 per square foot in Q3 2018. It's the highest level since CBRE started tracking rents in 1989. Since 2012, rents have increased by 5.6% annually.

11. Net asking rents continue to rise, as well. According to JOC.com’s report on CBRE’s findings, net asking rents rose to $7.21 per square foot in Q3 2018. It’s the highest level since CBRE started tracking rents in 1989. Since 2012, rents have increased by 5.6% annually.

12. Suppliers face pressure under rising ecommerce sales. “As U.S. e-commerce sales continue to grow at over 15% annually, suppliers feel the pressure to satisfy e-commerce customers by delivering a variety of goods in smaller sizes at a faster pace,” Westernacher Consulting explains.

Warehouse automation stats: Warehousing costs & revenue statistics

Warehouse automation stats: Companies with high-performing supply chains benefit from higher revenue growth. According to a Deloitte analysis of supply chain leadership, "79% of companies with high-performing supply chains achieve revenue growth superior to the average within their industries."

13. Companies with high-performing supply chains benefit from higher revenue growth. According to a Deloitte analysis of supply chain leadership, “79% of companies with high-performing supply chains achieve revenue growth superior to the average within their industries.”

14. Distribution costs can impact profitability. In fact, according to Logistics Bureau, “up to 12% of companies are unprofitable after distribution costs are taken into account.”

Warehouse automation stats: Ecommerce sales of physical goods are skyrocketing. "In 2018, online sales of physical goods amounted to 504.6 billion US dollars and are projected to surpass 735 billion US dollars in 2023," according to Statista.

15. Ecommerce sales of physical goods are skyrocketing. “In 2018, online sales of physical goods amounted to $504.6 billion and are projected to surpass $735 billion in 2023,” according to Statista.

16. Most warehouses and distribution centers take actions to lower operating costs. According to Logistics Management’s 2018 Warehouse / Distribution Center Survey, “Respondents took a range of actions to lower operating costs, including improving processes, improving warehouse information technology (IT), improving inventory control, and leveraging a 3PL. While 98% took actions of some type, one type of action that increased sharply was to improve warehouse IT, which climbed from 38% last year to 50% this year. Using a 3PL also climbed to 15%, while a new option, ‘adding automated equipment to processes,’ also drew a 15% response.”

Warehouse automation stats: Warehouse efficiency statistics

Warehouse automation stats: Travel time in a warehouse or distribution center accounts for up to half of total picking time. Amware Fulfillment explains that in a fulfillment warehouse, walking is "the enemy of efficient order picking. In fact, it can comprise as much as 50% of the picking process – and up to half of your warehousing labor cost. Without the right system-aided picking process, you’re paying order pickers to walk, not to pick."

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18. Less than one in ten DCs handle only full pallets for outbound shipping. “According to the 2016 Warehouse Operations Survey, only 9% of DCs now handle only full pallets during outbound. Most DCs (46%) now handle a mixture of pallets, cases and split cases. While it still could be time-efficient to deliver pallet orders using traditional labor, it might not be so for cases and split cases.

Therefore, many warehouses are turning to case conveyors and robotic picking arms for help. In general, many warehouses found that optimizing piece & case picking gave them the highest ROI," explains Westernacher Consulting.

Warehouse automation stats: Warehouses are handling an ever-increasing number of SKUs. According to Westernacher Consulting, "Just in 2015, the average number of SKUs in warehouses increased by 18% in the U.S. Next year, 38% of companies plan to handle even more SKUs based on PRG's Research."

19. Warehouses are handling an ever-increasing number of SKUs. According to Westernacher Consulting, "Just in 2015, the average number of SKUs in warehouses increased by 18% in the U.S. Next year, 38% of companies plan to handle even more SKUs based on PRG's Research."

20. More SKUs can be handled with automation solutions. "For 2018, the average number of SKUs in a warehouse reached 13,985, up from 13,130 last year. Additionally, when asked roughly what percentage of SKUs are conveyable or could be handled robotically, respondents' average answer was 43%, up from 29% last year," explains Logistics Management.

Warehouse automation stats: Labor statistics in the warehousing industry

Warehouse automation stats: Labor comprises 50% to 70% of a company's warehousing budget. According to Kane is Able, labor comprises the largest portion of a warehouse's total operating budget, making finding the right people and optimizing warehouse productivity priorities for most warehouses.

21. Labor comprises 50% to 70% of a company's warehousing budget. According to Kane is Able, labor comprises the largest portion of a warehouse's total operating budget, making finding the right people and optimizing warehouse productivity priorities for most warehouses.

22. Warehouses have a high injury rate (about 1 in 20). According to data from the U.S. Bureau of Labor Statistics (BLS), the rate of recordable illness and injury cases in the warehousing and storage sector was 5.1 out of every 100 workers in 2017.

Warehouse automation stats: Hourly wages in the warehousing and storage sector are on the rise. Data from the BLS shows that hourly wages in the warehousing and storage subsector rose by more than 20% between 2008 and 2017.

23. Hourly wages in the warehousing and storage sector are on the rise. Data from the BLS shows that hourly wages in the warehousing and storage subsector rose by more than 20% between 2008 and 2017.

24. Hiring and retaining a qualified workforce is a prominent challenge for warehouse managers. “In 2016, a staggering 41% of warehouse managers reported an ‘inability to attract and retain quality hourly workforce’ as one of their top concerns,” according to Westernacher Consulting.

Warehouse automation stats: A typical warehouse spends millions of dollars in labor expenses annually. Westernacher Consulting explains, "A typical warehouse with 100 employees costs more than $3.5 million in labor expenses per year (an average production and nonsupervisory employee earns $15.81 per hour at an average of 42.9 hours per week as of 2016). This is not considering health insurance, seasonal labor spikes and overtime adjustments."

25. A typical warehouse spends millions of dollars in labor expenses annually. Westernacher Consulting explains, “A typical warehouse with 100 employees costs more than $3.5 million in labor expenses per year (an average production and nonsupervisory employee earns $15.81 per hour at an average of 42.9 hours per week as of 2016). This is not considering health insurance, seasonal labor spikes and overtime adjustments.”

26. Temporary workers comprise more than 13% of a warehouse’s workforce, on average, during normal demand periods. According to Logistics Management, the average percent of workers who are temporary during average volume periods is 13.5% of the workforce. During peak volume periods, temporary workers comprise an average of 19.1% of the total workforce.

Warehouse automation stats: Labor scarcity is a top concern among warehouse managers. According to Logistics Management's 2018 Warehouse /

Distribution Center Survey, "This year, 55% of respondents named labor scarcity as the top issue, an increase from last year’s 49%. In descending order, the other top issues for 2018 are insufficient space (44%); outdated storage, picking or material handling equipment (38%); and inadequate information systems (32%). Only on this last issue of IT system capabilities did respondents rank it lower than they did last year, when it drew a 36% response."

27. Labor scarcity is a top concern among warehouse managers. According to Logistics Management’s 2018 Warehouse / Distribution Center Survey, “This year, 55% of respondents named labor scarcity as the top issue, an increase from last year’s 49%. In descending order, the other top issues for 2018 are insufficient space (44%); outdated storage, picking or material handling equipment (38%); and inadequate information systems (32%). Only on this last issue of IT system capabilities did respondents rank it lower than they did last year, when it drew a 36% response.”

Warehouse automation stats: Automation adoption in the warehousing industry

28. Human error is the most frequent cause of inventory and fulfillment issues. “Humans are not computers. They make mistakes. 62% of respondents reported human error from manual process management as the #1 root cause of inventory fulfillment issues. The key phrase here is ‘manual process management.’ When employees are repeatedly performing manual tasks which require perfect precision – such as entering shipping addresses or SKUs – they will inevitably make mistakes,” explains Stitch Labs.

Warehouse automation stats: Just 10% of warehouses reported using sophisticated warehouse automation technology in 2016. Westernacher Consulting predicts that the percentage of warehouses leveraging sophisticated automation technologies will grow within the next five years.

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30. Innovation is important for growth. According to Deloitte, “96% of industry leaders identify innovation as ‘extremely important’ to growth (vs. 65% of followers).” Leaders are defined as organizations with superior supply chain capabilities, while followers are organizations with lower-performing supply chains.

Warehouse automation stats: High-performing supply chain companies use analytics extensively. "75% of leaders utilize optimization software (vs. 34% of followers), visualization software (67% vs. 28%), mobile technologies (75% vs. 30%), and radio frequency identification tags (65% vs. 27%)," according to Deloitte.

31. High-performing supply chain companies use analytics extensively. “75% of leaders utilize optimization software (vs. 34% of followers), visualization software (67% vs. 28%), mobile technologies (75% vs. 30%), and radio frequency identification tags (65% vs. 27%),” according to Deloitte.

32. Seven out of 10 decision makers plan to increase their technology investments by 2020. According to a study conducted by Zebra Technologies, “51% of those surveyed expected increased investment in real-time location systems that track inventory and assets throughout the warehouse last year, but this number escalates to 76% of respondents in 2020.”

Warehouse automation stats: AS/RS, order picking and fulfillment systems, mezzanines, and conveyor/sortation systems top the list of investment considerations. "When asked which type of systems and equipment respondents are considering during the next 12 months, growth categories included AS/RS (up to 14% from 7% last year), order picking and fulfillment systems (up to 17% from 13%), as well as mezzanines (up by 4% this year versus last), and conveyor/sortation (up by 3%)," Logistics Management reports.

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which type of systems and equipment respondents are considering during the next 12 months, growth categories included AS/RS (up to 14% from 7% last year), order picking and fulfillment systems (up to 17% from 13%), as well as mezzanines (up by 4% this year versus last), and conveyor/sortation (up by 3%)," Logistics Management reports.

34. More than three out of 10 warehouses and distribution centers are currently using or considering robotics. "When asked about current robotics use and whether they will evaluate robotics during the next 24 months, 16% said that they currently use robotics, while 15% are evaluating robotics, for a total of 31% now either using or considering robotics. That's up from last year, when 9% said they use robotics and 13% were considering robotics," explains Logistics Management.

Warehouse automation stats: Warehouses and distribution centers increasingly leverage robotics for pick and place, parts transfer, pick to cart, order fulfillment, truck loading and transportation. As Logistics Management explains, "For applications, using or considering robotics for pick and place or parts transfer climbed by 8% to reach 41%, while using or considering robotics for palletizing declined by 8%. Use or consideration of robotics for pick to cart, order fulfillment (picker to part), truck loading, and transportation also were on the upswing."

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36. Nearly five out of 10 warehouses and DCs track order cycle times manually. "Currently only 35% of respondents have an automated means of tracking order cycle times, 46% track them manually, and 19% don't track them. However, when asked how they'll be gauging cycle time performance in two

years, 57% expect they will have an automated means of tracking cycle times, 29% expect they’ll be tracked manually, and those that don’t track cycle time drops to 14%,” according to Logistics Management.

Warehouse automation stats: Worldwide warehousing and logistics robot shipments are increasing. "Tractica forecasts that worldwide warehousing and logistics robot unit shipments will increase from 40,000 in 2016 to 620,000 units annually by 2021. The market intelligence firm estimates that global market revenue for the sector reached $1.9 billion in 2016 and anticipates that the market will continue to grow rapidly over the next several years, reaching a market value of $22.4 billion by the end of 2021."

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38. System-directed work is increasingly used to automate decision-making. “Moving up are warehouses that use system-directed work to automate decision-making. Here, a Warehouse Management System (WMS) is used to make decisions on where to put away/pick items and manage processes such as deconsolidation, VAS (Value Added Services) and quality inspection. It also optimizes decisions on when to perform the tasks, and who should perform the tasks. System Automation usually involves using Mobile RF (Radio Frequency) Technologies or Voice-directed Technologies to confirm and send stock information to the WMS in real time. In general, most companies observe around a 25% gain in overall productivity, a 10-20% improvement in space utilization, and a 15-30% reduction in safety stock when moving from a paper-based system to this level of automation,” explains Westernacher Consulting.

Warehouse automation stats: In 2018, WMS adoption exceeded 90% for the first time. "Not only was 2018 the first year WMS adoption topped 90%, but use of paper-based picking systems dropped from 62% last year to 48% this year—the first time that use of paper-based picking dropped below 50%," according to Logistics Management.

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40. More warehouses are adopting voice-directed picking solutions. Logistics Management explains, “Other picking technologies and methods on the rise include RF-assisted with scanning, up by 9% versus 2017, and voice assisted with scanning, which reached 12%, up from 7% last year. Voice systems with no scanning came in at 10%, so this year 22% are using some form of voice-directed solution.”

Warehouse automation stats: Less than 30% of commercial transportation companies leverage advanced digitization. "Commercial transportation companies lag in digitization efforts, with just 28% reporting advanced levels of integration and digitization in 2017," explains PwC.

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Warehouse automation stats: Warehouse performance metrics

42. Capacity and quality top the list of priorities for warehouse operators. According to Material Handling & Logistics, “Operations are prioritizing quality and capacity, with the top five metrics being:

Order Picking Accuracy (percent by order)
Average Warehouse Capacity Used
Peak Warehouse Capacity Used

On-time Shipments

Inventory Count Accuracy by Location”

Warehouse automation stats: Higher perfect order rates lead to greater profitability. According to a white paper by Intermec by Honeywell and Supply Chain Services, "Companies with perfect order rates (a popular metric that measures customer orders that arrive complete, on time, undamaged, and with an accurate invoice) of 80 percent or higher are three times more profitable than companies with perfect order rates of 60 percent, a separate AMR Research study found."

43. Higher perfect order rates lead to greater profitability. According to a white paper by Intermec by Honeywell and Supply Chain Services, “Companies with perfect order rates (a popular metric that measures customer orders that arrive complete, on time, undamaged, and with an accurate invoice) of 80 percent or higher are three times more profitable than companies with perfect order rates of 60 percent, a separate AMR Research study found.”

44. On-time shipments below 94% indicate an opportunity for improvement. Avery Weigh-Tronix explains, “…if your on-time shipment performance is below 94% then this falls in the bottom quintile (20%) of the results and would indicate there is a major opportunity for improvement. However, if on-time shipments are above 99.8% then this would fall within the top quintile of the results and can be considered best-in-class. The median performance for on-time shipment data is 98.20%.” These statistics are based on data from the ‘DC Measures 2018 Trends and Challenges’ report from the Warehousing Education and Research Council (WERC).

Warehouse automation stats: Best-in-class operations ship more than 99.87% of shipments on time. On-time shipments is the percentage of orders shipped at the planned time, meaning the shipment is off the dock and in transit to the destination.

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46. Best-in-class operations pick orders with an accuracy of 99.84% or better. This metric measures the accuracy of order picking based on errors identified prior to order shipment, such as during packaging.

Warehouse automation stats: Best-in-class operations have dock-to-stock cycle times under two hours (dock-to-stock). "The dock-to-stock cycle time equals the time, typically measured in hours, required to put away goods. The cycle time begins when goods arrive from the supplier and ends when those goods are put away in the warehouse and recorded in the inventory management system," according to Yale's Top 10 Warehouse Operational Metrics.

47. Best-in-class operations have dock-to-stock cycle times under two hours (dock-to-stock). “The dock-to-stock cycle time equals the time, typically measured in hours, required to put away goods. The cycle time begins when goods arrive from the supplier and ends when those goods are put away in the warehouse and recorded in the inventory management system,” according to Yale’s Top 10 Warehouse Operational Metrics.

48. Best-in-class operations have internal order cycle times under 3.8 hours. This metric reflects the average time between the supplier receiving an order and shipping it.

rehouse automation stats: Total order cycle times average less than seven hours among best-in-class operations. This metric reflects the average cycle time between order placement and final receipt of the order by the end customer.

49. Total order cycle times average less than seven hours among best-in-class operations. This metric reflects the average cycle time between order placement and final receipt of the order by the end customer.

50. Automated, efficient warehouses benefit from better inventory accuracy, reduced labor costs and prompt shipping. “Automated and efficient warehouses in the survey were 76% more likely to boost inventory accuracy to 99% or higher, 36% more likely to have reduced labor costs an average of 3% per year, and 40% more likely to consistently ship within one day of an order’s placement,” according to Robotics Business Review.

3. DESIGN PART

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3.1. Design of airport warehouse control system for real time management

Warehouse Control System (WCS) provides an integrated interface to a broad range of material handling equipment. It is able to collect equipment information and control equipment in real time. The state-of-the art WCS is expected to have versatility, integrity, information-visibility with variety of function for supporting warehouse control and material flow [25].

We analysed key functions and limitations of existing WCS and suggest a new architecture for WCS which provide plug and play equipment interface and also provide the result of communication test between pilot system and material handling equipment using new architecture.

Conventionally, warehouse is operated by manual operation such as forklift, conveyor and cart, etc. However, due to time critical orders and low profit caused by manual operation, automated facilities such as Automatic Guided Vehicle (AGV), Automated Storage and Retrieval System (AS/RS) are widely getting more attention by big players such as Amazon.

The control of automatic facilities require control software such as Warehouse Control System (WCS), Material Flow Controller (MFC), Equipment Management System (EMS) or Equipment Control System (ECS). Even though, the objectives of WMS and WCS are quite different, many software providers use those terms in the mixed ways. WMS focused on the management of an order and generally interfaced with ERP system whereas WCS is more focused on the controlling of machines and deals with dynamic data with shorter timing (close to real time). It is rather focused on the monitoring of machine status and controlling machines. From the functional point of view, WCS consist of the following functions: interfacing equipment; collecting equipment data; executing and control material flow; and monitoring & controlling equipment. In this paper, we define that WCS is a system that controls all equipment/facilities in the warehouse.

WCS is currently under development by a few vendors. We have compared WCS of five companies such as Dematic (2014), Daifuku (2014), SSI-Schaefer (2014), Bastian Solution (2014) and QC software (2014).

From the review of eight companies, we found that most companies typically do not provide generic interface for third parties. Also most of companies do not provide flexible user interface (UI) and functionality for lifecycle management of equipment. It is considered that warehouse control system should provide such capabilities with generic capabilities.

PnP starts when WCS/HMI-ECS is updated. When updating is completed, it is switched then the updated one replace existing one (After this process, the existing WCS/HMI-ECS could be updated).

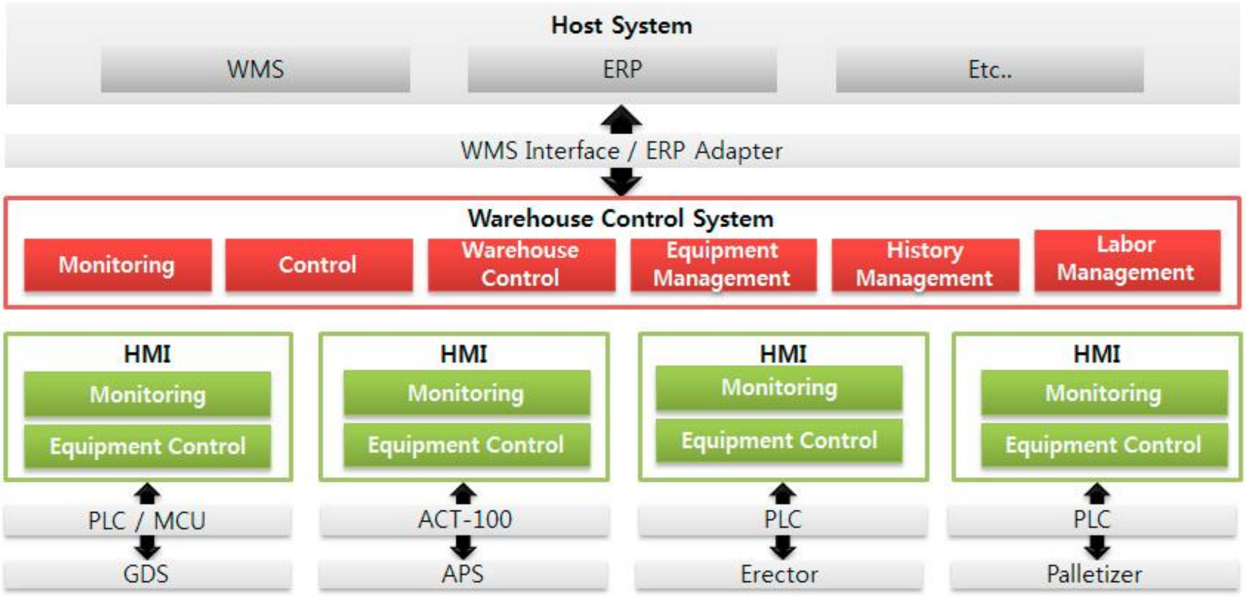


Fig. 3.1. WCS Concept of WCS and HMI-ECS

Fig 3.1 shows the concept of this system. Human Machine Interface (HMI) is also called as Human Machine Interface-for Equipment Control System (HMI-ECS). It is a system installed in the individual equipment and user can control individual equipment using HMI. As in the figure, key function of HMI (or HMI-ECS) is control and monitoring. A WCS can control many HMI-ECS and it provides monitoring of equipment in the warehouse and controls actions if required. A WCS can provide a good grip of equipment in the warehouse to the manager.

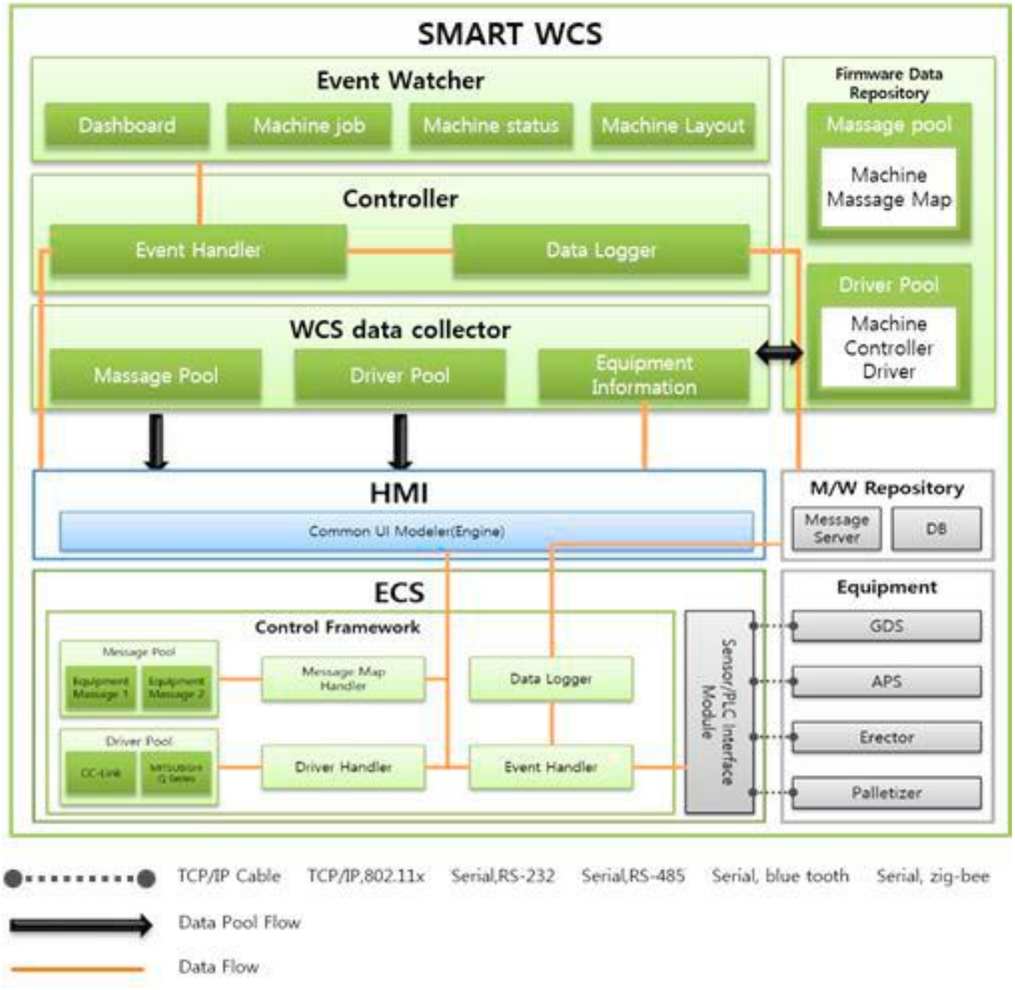


Fig 3.2. Smart WCS/HMI-ECS

Fig 3.2 shows control framework of ECS for real time handling of machine event. ECS consists of control framework and Sensor/PLC interface module. Sensor & PLC interface module defines sensor and PLC Interface. ECS Control framework consists of event handler, driver handler, message map handler, and data logger.

Common UI module (Engine) manages the characteristics of each type of equipment. The UI generates event according to user operation, and transmits related data to event handler of control framework.

WCS/HMI-ECS contains firmware data to improve generality of WCS. Using firmware data, the users can connect equipment regardless of the brand of equipment manufactured. The system also supports dynamic plug and play (PnP), connection and the management of equipment. Dynamic PnP is a unique function to identify different types of equipment when it is hook up to the WCS/HMI-ECS system without system re-booting. Such capability is possible because of its pre-built in PLC and protocol information in the system. To make this, WCS/HMI-ECS is structured for duplication using imaginary fault tolerance tool. Dynamic WCS data collector registers equipment data to embody dynamic PnP of WCS/HMI. Driver Pool and Message Pool receive and store the Vender Drive data and the Message Map data of specific equipment which is managed by WCS and also transmit and manage Driver and Message Map of equipment to HMI. Kyusakov et al (2013) researched a new approach for making operation systems using SOA based wireless sensor and actuator nodes with Web Service Description Language. SOA is using WSDL form to send and to receive data. In our research the message map of massage pool is applied instead of WSDL. Message map describes the information on the memory address of the PLC Program. And the system uses the message map for communicate to equipment. Equipment information is equipment data available for user to input and to adjust. It can be used to construct various application including machine monitoring screen. Controller works based on WCS data collector and includes Event handler and Data Logger. Event handler transmits an order from event data collected from HMI and provides the information to users. Data Logger transforms all event data collected from Event Handler into Log data and it is stored in the database. Event watcher provides integrated information to users. It provides equipment information such as Machine Job, Machine Status, machine Layout graphically to users.

3.2. Drone Automation in Warehouse 4.0

The technology, of course, plays a central role in driving revenue, profit margin, and safety improvements for warehouses, across numerous use cases such as [1]:

- Inventory search & reconciliation
- Cycle counting & audits
- Roof inspection Security & surveillance
- Worker safety & productivity
- Item marking & recognition
- 2D/3D space optimization
- Order picking optimization
- Empty & full slot detection
- Yard management
- Forklift guidance
- In-warehouse transport

Most of the above involve tasks that are laborious, tedious, risky, redundant and expensive. They require shutdowns, slowdowns, and downtime that result in lost revenue, inaccurate inventory counts, and harm or loss of life. Warehouses have hence been early adopters of technologies that help continuously locate, identify, store, count, secure and/or protect their valuable inventory.

Table 3.1 Technologies description in warehouses

Current Solution	Manual	Automated Guided Vehicles	Radio Frequency Identification
Limitations	Costly, inefficient and tedious	High captial investments	Not compatible with materials such as liquids, metals

Continue Table 3.1

	Prone to human error	Decreased flexibility of operations	Prone to interference
	Risk to human life	Routine maintenance & occasional repair	Lack of global standards

Drones (unmanned autonomous vehicles) are an essential ingredient in the digital transformation of warehouses. They are inherently advantageous given their ability to carry payloads, operate at heights, fly autonomously, scale via fleets, and survey assets & premises. Drones can reach narrow storage areas, localize hard-to-find items, and send real-time data via the cloud, for easy integration into warehouse management systems. By augmenting the existing technologies adopted by warehouses, drones help improve the RoI on existing infrastructure, yet offer capabilities and insights unimaginable to date.

Advantages:

Automatic cycle counting & real time inventory

Improved safety & operations reliability

Stable drone navigation in narrow warehouse aisles

Minimal cap-ex and infrastructure investments

The business benefits of UAVs are rapidly realizable for warehouse applications – given minimal capital expenditure, simpler regulatory requirements and immediate access to data & insights resulting in short time-to-value. Warehouse drones thus represent the logical extension that integrates virtual information processes with physical warehouse processes.

Airspace and aircraft regulators across the world remain wary of commercial drone applications that involve a) flying over crowds, b) flying at night and c) flying beyond the visual line of sight.

Warehouse 4.0 has the unique advantage of being able to leverage the existing UAV laws for full-fledged drone adoption - without awaiting regulatory progress on the above three restrictions.

By improving inventory data integrity, drone adoption by digitally transformed warehouses immediately improves KPIs such as cycle time, cycle counting frequency, employee turnover rate, on-time deliveries, inventory and fulfillment.

Based on numerous proof-of-concept and pilot projects executed at modern warehouses across the world, it is estimated that billions of dollars of revenue, cost and safety benefits are realizable via large scale adoption of commercial drones by stakeholders across the supply chain industry.

Fig. 3.3. Barcode Scanning Using The Drone And Computer Vision

For example, inventory audits using drones could save more than 50% time of worker time, e-commerce click-to-ship times can be reduced by up to 75%, and inventory per square-foot can be increased by as much as 50% since drones can navigate in tighter spaces. UAVs also offer governance benefits to warehouses in the form of (auditable) geolocation data, (AI-based) item verification, and continuous surveillance of staff, inventory and infrastructure. By directly improving worker quality-of-life, drones can mitigate employee turnover, stress and injury risks for warehouses.

Challenges to widespread drone adoption in Warehouse 4.0 fall into 4 categories:

1. Capital expenditure on drone hardware and batteries, given expensive proprietary drones and short battery.
2. Coordination of drone fleets and missions without having to rely on skilled, certified UAV pilots.
3. Safe operation of drones in a warehouse environment with static (e.g. storage racks, conveyors) and dynamic (e.g. forklifts, workers) elements.
4. Integration with existing warehouse workflows and information systems.

Fortunately, commercial drone software is poised to provide robust, scalable solutions to these challenges in the immediate future.

Computers and smartphones provide a perfect analogy for commercial drone hardware. This segment is being disrupted by DJI, which has brought drones to the market at a featureprice combination that is 10X better than proprietary drones built for specific industrial applications. By building a fleet of small, light-weight COTS drones, complemented with a few high-end application-specific ones, warehouse operators and system integrators can drastically lower both the upfront and operating costs of large-scale UAV adoption.

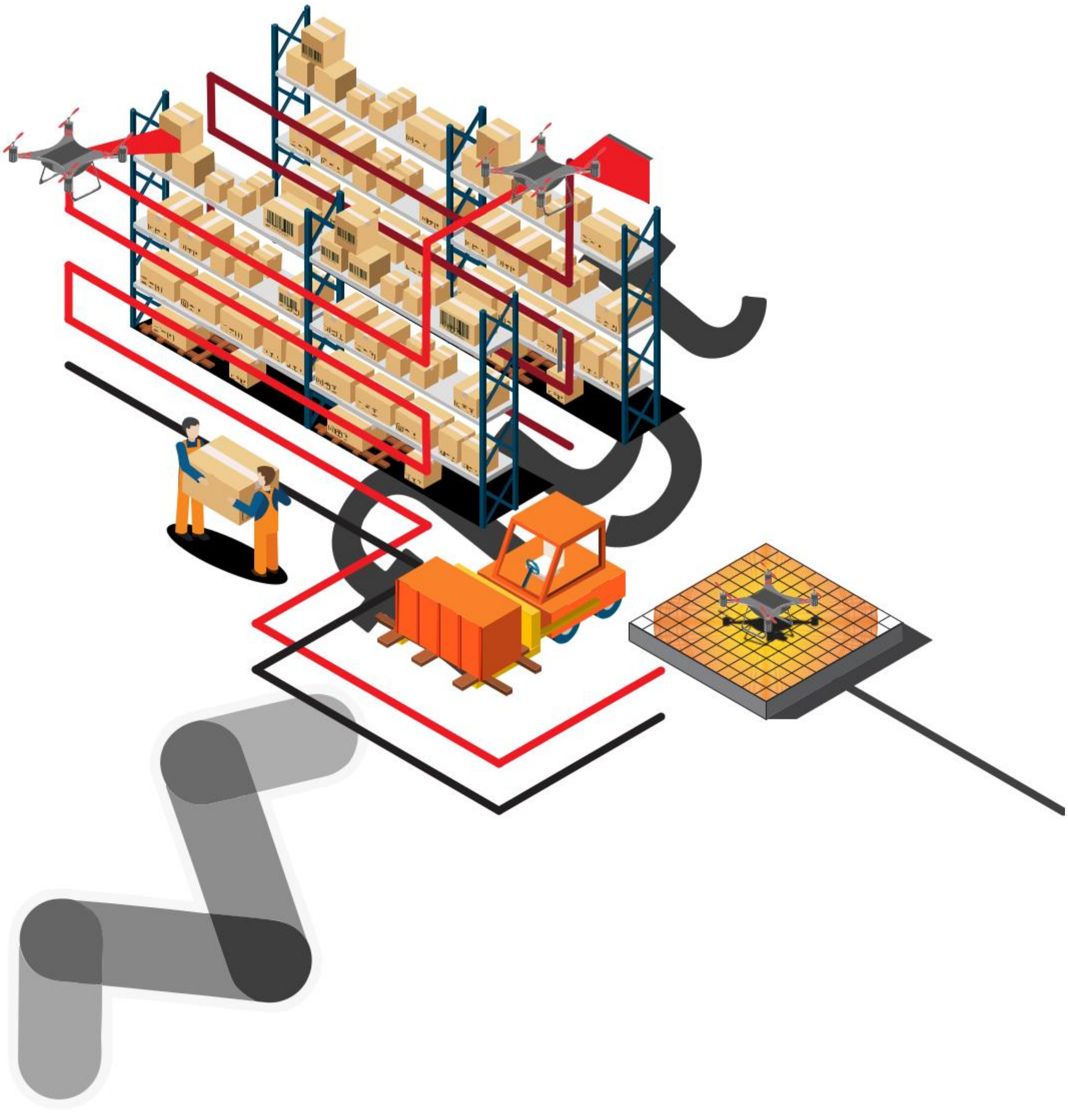


Fig. 3.4. Automated Warehouse Management Using Drones

Integrated with affordable charging pads and docking stations, drones can fly for hours inside a warehouse, by automatically recharging their batteries at strategically placed charging stations. Of course, this requires the software stack to be not only hardware agnostic, but also enable software developers and system integrators to rapidly build intelligent plug-ins at the edge and cloud layers of the drone technology stack. This, in turn, enables autonomous flights of fleets of drones – without any dependence on pilot-operated UAVs. In fact, coordinating a set of complex, repeatable missions involving dozens of drones, while ensuring no collisions take place, is possible only via software automation.

In very large - or outdoor - warehouse applications, the drone fleets may have to operate beyond the visual line of sight – facilitated by telepresence over 4G/5G communication channels. The flight path planning, takeoff, precision landing, return-to-home and obstacle avoidance capabilities must be entirely software-driven for warehouses to transition from drone PoC projects and pilot programs to enterprise-wide

Problems:

- Indoor Autonomous Navigation
- Collision Avoidance
- Automated Drone Fleet Management

The choice of drones matters a great deal for warehouse safety; heavy proprietary drones can be safely operated only in restricted areas, whereas small lightweight drones (with shrouded propellers) can be used in human proximity. Drones can be programmed with fallback mechanisms such as automatically climbing to heights, returning to home, or circling around obstacles to ensure worker safety. Equipped with sirens, flashlights and other warning devices, drones can not only make workers aware of their presence but also augment warehouse evacuation efficiency in case of fire or other emergencies.

From a business point of view, data plays a central role in such digital transformation of warehouses. With a large amount of near-real-time data streaming in from drones, logistics executives and hub managers need to seamlessly integrate such data into the existing information systems and workflows. This high-volume data can be analyzed using AI to provide new insights for better decision-making related to inventory management, responsiveness to supply chain demand, security & safety.

Characteristics:

- Hardware Agnostic
- Auto Charging using Precision Landing
- Integrate with WMS

Again, software plays a central role – APIs at appropriate layers in the stack allow for easy integration of drones into legacy warehouse workflows as well as application-specific workflows such as empty slot detection, automatic item recognition, narrow aisle navigation, etc.

Drone Program for Warehouse 4.0

The following best-practices will accelerate the success of drone adoption for warehouse applications:

1. Minimize CapEx budgets and infrastructural changes by building a fleet of (primarily) COTS drones, complemented by charging pads and docking stations.
2. Opt for cloud-connected drone fleets powered by intelligent automation, complemented by certified pilots who focus on supervisory and regulatory aspects.
3. Ensure that drone hardware and software both have collision avoidance capabilities that can be continuously improved.
4. Leverage high-quality image, video capture and recording capabilities of UAVs to build a rich, real-time view of warehouse operations.
5. Involve a comprehensive set of stakeholders (such as inhouse R&D teams, innovation leaders, system integrators, warehouse managers, IT staff, drone operators, and technology consultants) early on to prioritize use cases
6. Start with a couple of medium complexity use-cases involving up to three drones, especially applications where case studies of successful drone PoCs and pilots already exist.
7. Validate the business case (investment, payback period, RoI, impact on KPIs) for these use cases within weeks, and grow the fleet to ten or more drones for validation of additional use-cases.
8. Use customized, cloud-based dashboards to coordinate missions across stakeholders i.e. warehouse workers, drone operations management, subject-matter experts and senior executives.

9. Leverage software APIs to seamlessly integrate drone mission control and data collection into Warehouse 4.0 management systems.

10. Adopt cloud-based SaaS offerings, instead of on-premise enterprise software, wherever possible – to benefit from rapid scalability, continuous upgrades, prompt technical support, and flexible pricing.

Inventory Management

In the area of inventory management, drones can be used for the following tasks: inventory audit, inventory management, cycle counting, item search, buffer stock maintenance, and stock taking [2]. Stock taking is the physical verification of the quantity of items stored in warehouses. Stock taking is often done annually or by the end of the fiscal year. Whereas cycle counting describes the process of counting a partial amount of a warehouse’s inventory on a more frequent basis [7]. This task is usually performed daily or weekly by a small trained team of inventory control staffs. They walk or drive to a designated location in the warehouse, scan the barcode of the item, count the units and move on to the next location following their schedule. Even though this method increases the inventory accuracy compared to the annual one-time inventory checks, there are still several downsides. Among others, cycle counting is slow (manual task), labor-intensive (several inventory staffs are needed), dangerous (risky operations due to working in high altitudes), expensive (labor costs) and error-prone (highly repetitive tasks). Drones can add value to optimize this process [8]. The main objectives of using drones for inventory management are to increase the inventory accuracy, decrease labor costs, and minimize dangerous tasks for the workforce.

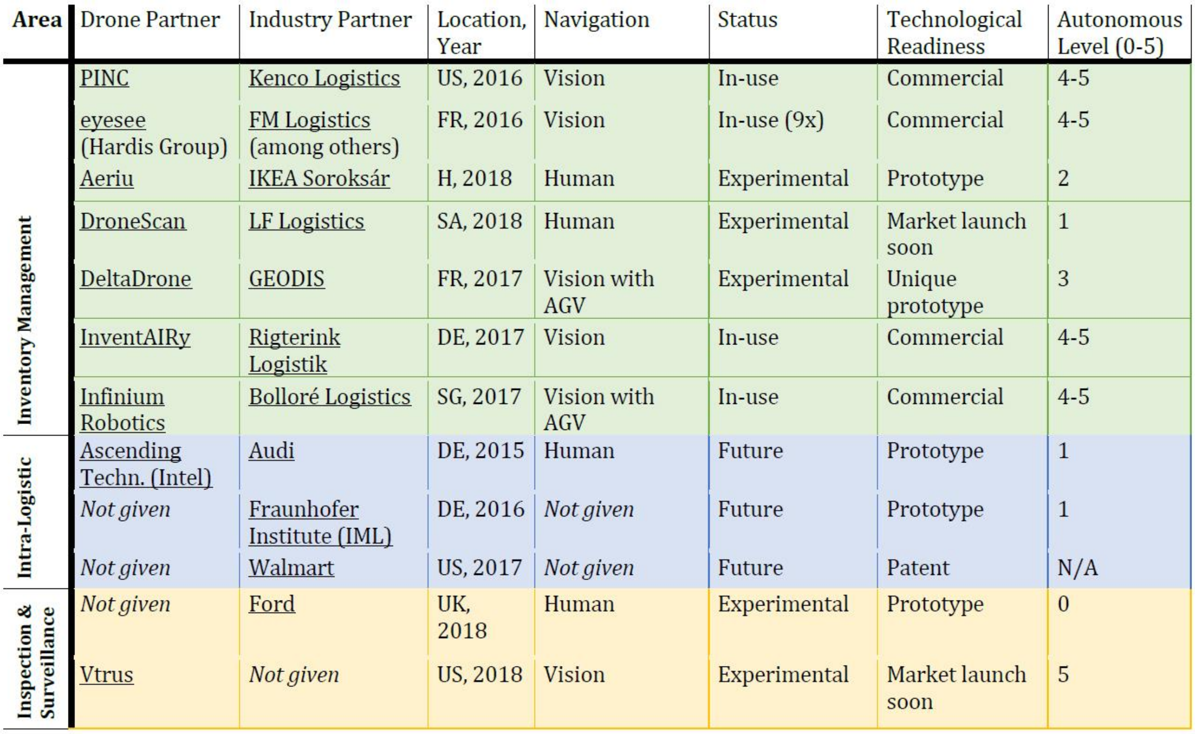
Intra-Logistics

Drones can also be used for intralogistics. For instance, they can transport parts from warehouses to workshops in factories. The ability of drones to follow pre-defined flight paths and carry items show good potential for indoors such as on-site express delivery of tools and spare parts as well as lubricants. However, significant limitations for intralogistics is payload, gripping/placing movements and navigation [9].

Inspection & Surveillance

Drones can be a viable alternative to replace manual inspection and surveillance operations in warehouses. Drones are already used for inspection in many industries such as construction, petrochemical, oil and gas, and power generation. Indoor use cases of drones for inspection is also growing. In warehouses, drones can for example inspect roofs, racks, pallet placements, walls, and ceilings. The growth of warehouse operations and customer demand makes inspection processes expensive and difficult. Indoor inspection tasks often require skilled inspectors and sometimes work is obstructed during inspections. Indoor drones are a perfect fit for tasks that require monitoring and inspection in dangerous areas or high altitudes [10]. Drones can also be used for regular surveillance routes to prohibit theft and other unwanted behavior.

Table 3.2. Areas of drones use in warehouses

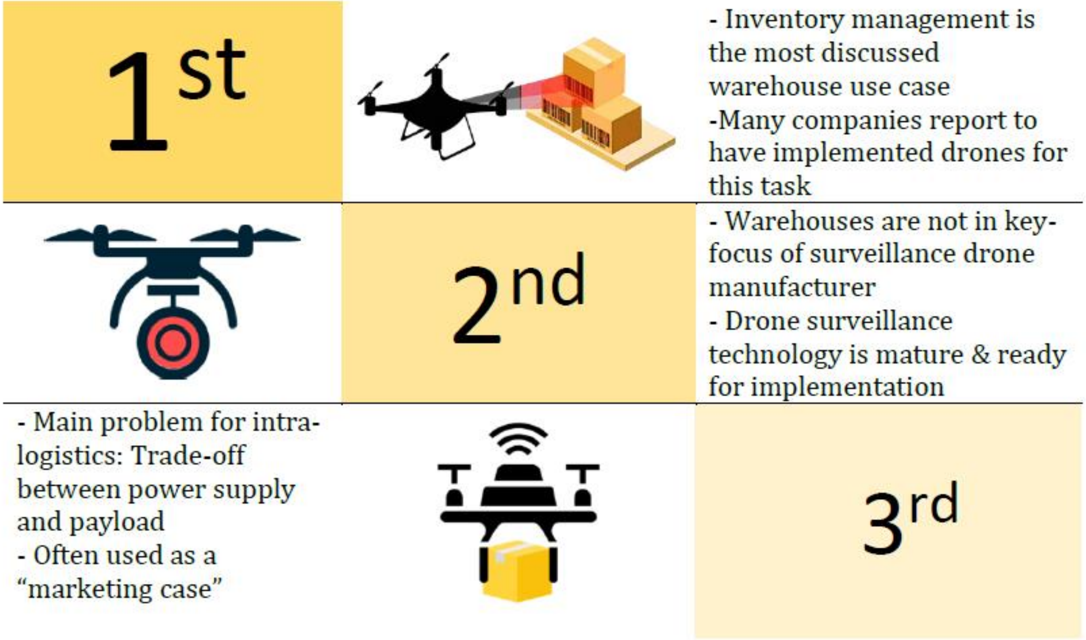


Area	Drone Partner	Industry Partner	Location, Year	Navigation	Status	Technological Readiness	Autonomous Level (0-5)
Inventory Management	PINC	Kenco Logistics	US, 2016	Vision	In-use	Commercial	4-5
	eyesee (Hardis Group)	FM Logistics (among others)	FR, 2016	Vision	In-use (9x)	Commercial	4-5
	Aeriu	IKEA Soroksár	H, 2018	Human	Experimental	Prototype	2
	DroneScan	LF Logistics	SA, 2018	Human	Experimental	Market launch soon	1
	DeltaDrone	GEODIS	FR, 2017	Vision with AGV	Experimental	Unique prototype	3
	InventAIRy	Rigterink Logistik	DE, 2017	Vision	In-use	Commercial	4-5
	Infinium Robotics	Bolloré Logistics	SG, 2017	Vision with AGV	In-use	Commercial	4-5
Intra-Logistic	Ascending Techn. (Intel)	Audi	DE, 2015	Human	Future	Prototype	1
	Not given	Fraunhofer Institute (IML)	DE, 2016	*Not given*	Future	Prototype	1
	Not given	Walmart	US, 2017	*Not given*	Future	Patent	N/A
Inspection & Surveillance	*Not given*	Ford	UK, 2018	Human	Experimental	Prototype	0
	Vtrus	*Not given*	US, 2018	Vision	Experimental	Market launch soon	5

Highest Potential Use Case

Inventory management applications appear to have the highest potential for use in warehousing operations. Seven of the 12 use cases fall into this category and they are also the ones that (reportedly) have beyond testing phase in some companies. To date, using drones for intra-logistics seem to be difficult due to technological challenges, namely power supply and payload. There is limited evidence for successful inspection & surveillance applications in warehouses.

Several drone solution providers are gearing up to enter the drone inventory management market. For instance, Corvus Robotics claimed to launch their new autonomous warehouse inventory solution in the beginning of 2019 [11]. In addition, Linde Material Handling, the leading European company in warehouse optimization, stated at the LogiMAT trade fair in Stuttgart in 2017, that the market launch of their inventory checking solution “Flybox” is scheduled for 2018 at earliest [12]. Verity Studios is also testing prototypes in their lab while elaborating a strategy of how to potentially enter the drone inventory market [7, 13].



- Inventory management is the most discussed warehouse use case
-Many companies report to have implemented drones for this task

- Warehouses are not in key-focus of surveillance drone manufacturer
- Drone surveillance technology is mature & ready for implementation

- Main problem for intra-logistics: Trade-off between power supply and payload
- Often used as a “marketing case”

Fig. 3.5. Drones use in warehouses

State of Drone Technology

The most challenging part to reach full automation (level 5) is concerned with indoor navigation. Due to insufficient navigation accuracy, drones are not likely to fly autonomously in any of the application areas in the next few years. Yet, recent advances of promise that drones will achieve high precision for indoor navigation in the near future.

Vision based algorithms provide a promising way to achieve 100% accuracy. To date, one of the most advanced visual SLAM algorithm achieves an accuracy of 5cm. Yet, visual based SLAM outperforms other localization technologies such as Ultrawide-Band (UWB). The radio frequency based technology is often used for the tracking of floor conveyors such as forklifts or pallet trucks with relatively low accuracy of 10-30cm, which is not a suitable alternative for indoor localization of drones. Other emerging technologies can potentially increase the accuracy of visual based SLAM. For instance, light detection and ranging (LiDAR) technology has high potentials for indoor navigation. It is a method with high-precision and measures distance to a target by illuminating the target with pulsed laser light. Leica Geosystem co-developed a drone with DJI [14] using a combination of LiDAR sensors and cameras. The so called “Aibot” achieves an accuracy of 2.5cm over an area of 10ha (100’000 square meters). However, the weight of drone is almost 10 kilograms that impose constrains for indoor environments.

An example of an advanced available technology for high precise navigation for indoors is the technology of Vtrus [15]. This technology combines 3D depth sensors and 3D scanner with 360° wide-angle cameras to achieve the highest possible accuracy. Their vision based simultaneous localization and mapping algorithm (SLAM) is processing millions of camera pixels in parallel, as often as 30 times per second. In addition, they are able to reproduce a 3D map and locate the drone inside the map. The indoor navigation solutions from PINC [16], inventAIRy [17] and eyesee [18] are also vision based and are similar to the Vtrus’s technology. For example, PINCs solution is not only able to check inventory but also to localize it. InventAIRy states that their software is capable of vision-based inspection providing information on packaging quality, pallet quality and possible damages on goods. Mastering the challenge of indoor navigation is the key to success for indoor drone implementation in warehouses but also for other indoor environments.

To further increase the localization accuracy, Geodis/DeltaDrone and Infinium Robotics combine drones with an automated ground vehicle (an AGV) with a mounted calibration board on top. The tethered (wired) drones are physically attached with a cable to a ground vehicle, which also increases battery lifetime. Therefore, the air time of such a technology is up to four hours, whereas technologies without automated ground vehicle can be up to ca. 30 minutes (e.g. inventAIRy). Yet, using wired drones reduces the hovering and maneuverability of drones and makes the integration in warehouses rather difficult.

Favorable Warehouse Characteristics

Warehouses with the following characteristics have a high potential for drones:

✓ Relatively large size >10’000 square meters

✓ High shelfs (>5 meters) (Dangerous tasks for operators)

✓ Long corridors (>50 meters) (Long walking distances increase time needed to accomplish tasks)

✓ Single deep pallet rack (Barcode scanning not possible for double deep storage principle)

Drones “fly high” in warehouses. We expect to see a high number of new tests and implementations of drones in warehouse operations in the next years.

This development is likely to be driven by companies in high-cost countries, but it doesn’t have to. For instance, Indian media released a news in December 2018 that the Indian Ministry of Civil Aviation has legalized the use of drones after a four year long prohibition phase [21]. In October 2014, the Director General of Civil Aviation (DGCA) had banned the use of drones due to privacy and security concerns and lack of regulation [21]. Mahindra Logistics, an Indian based logistics giant, already stated on May 19, 2019 that they are awaiting further indoor regulatory approvals before starting to use drones for inventory management [22]. That said, the legalization in India is boosting the potential for additional indoor drone applications.

Despite difficulties of intra-logistics for indoors, two big German companies have recently tested outdoor intra-logistics drone flights. ZF was the first company in Germany that received approval for the automated drone flights delivering spare parts on factory premises . By the end of 2018, the first test flight was successfully accomplished. The second company, Thyssenkrupp Steel, announced in May 2019 its first on site drone delivery flight delivering laboratory samples. These two recent applications are important milestones for the intra-logistics applications of drones in Europe. Although the use cases are outdoors, it shows that there is potentials for indoor experiments in the near future.

3.3. Description and design the drone system for airport warehouse logistics and inventory

UAVs have been the focus of intense study for a decade. Many start-up companies as well as existing enterprises are investigating the opportunities that aerial drones present. Fig. 3.6 plots the Teal Group’s forecast of the fast-growing global aerial drone market. They estimate that by 2024, annual spending on aerial drones, including both civilian and military applications, will be more than US$ 12 billion. They believe that the civilian side of the market will grow more rapidly, though from a very low base (Teal group, 2015).

UAVs are used in various civil fields such as communication relay, delivery, environmental monitoring and disaster relief. Among them, UAV delivery is one of the emerging areas of UAV applications. Whereas ground vehicles encounter many obstacles on the delivery path and also require support to cross otherwise impassable areas such as seas, UAVs are unimpeded on the flight path to the destination. In fact, a delivery company, DHL, uses a UAV known as the Parcelcopter to serve customers on islands or in mountainous areas. In these ways, UAVs provide savings in time, effort and cost. Furthermore, as UAVs can effectively avoid traffic congestion, they are used in urban areas to provide quick and precision delivery service. Alibaba tested a UAV delivery service in Beijing, Shanghai and Guangzhou. Amazon developed Amazon Prime Air to provide quick, within-30-min delivery service (maximum range: 16 km). Fig. 3.hows the delivery UAVs of two prominent international companies.

Also, UAVs can be used for relief delivery to disaster areas, many of which are inaccessible to ground vehicles or even rescuers on foot.

However, with respect to UAV delivery service enhancement, one of the most important issues is how UAVs can be used in an efficient way beyond the development of service components. The vehicle routing problem (VRP), for example, has been studied over the past several decades. The much newer, Unmanned Aerial Vehicle Routing Problem (UAVRP) has, relative to the usual ground vehicle routing, the following unique characteristics. Commercial UAVs have fundamental limitations on their flight duration and loadable capacity; therefore, they cannot conduct long-duration delivery service without replenishing consumables, which is to say fuel (battery charge) and de-livery products. (2) The flight time of UAVs delicately depends on the amount of loaded product; therefore, the relationship between the weight of the loaded product and the flight time must be addressed in the UAVRP. (3) UAVs should not be allowed to stay on the ground during idle time between tasks, as this might cause loss of or damage to UAVs and delivery products. For real-world use of UAVs, the UAVRP needs to address these issues. We propose a UAV delivery logistics system and mathematical model for scheduling of UAVs based on consideration of their fundamental properties. In the proposed system, UAVs share multiple service stations (these can be the distribution centers of a delivery company) distributed across the field of operation. Thus, they can visit any service station to recharge and re-load products. Afterwards, they return to delivery service, and achieve long-duration service in this manner. The flight time of a given UAV between certain points is a function of the amount of loaded product carried during the flight. Also, for prevention of product loss or damage, UAVs are not permitted to land between take-offs and landings at designated service stations. The proposed ideas and limitations are considered to be essential for persistent UAV delivery logistics.

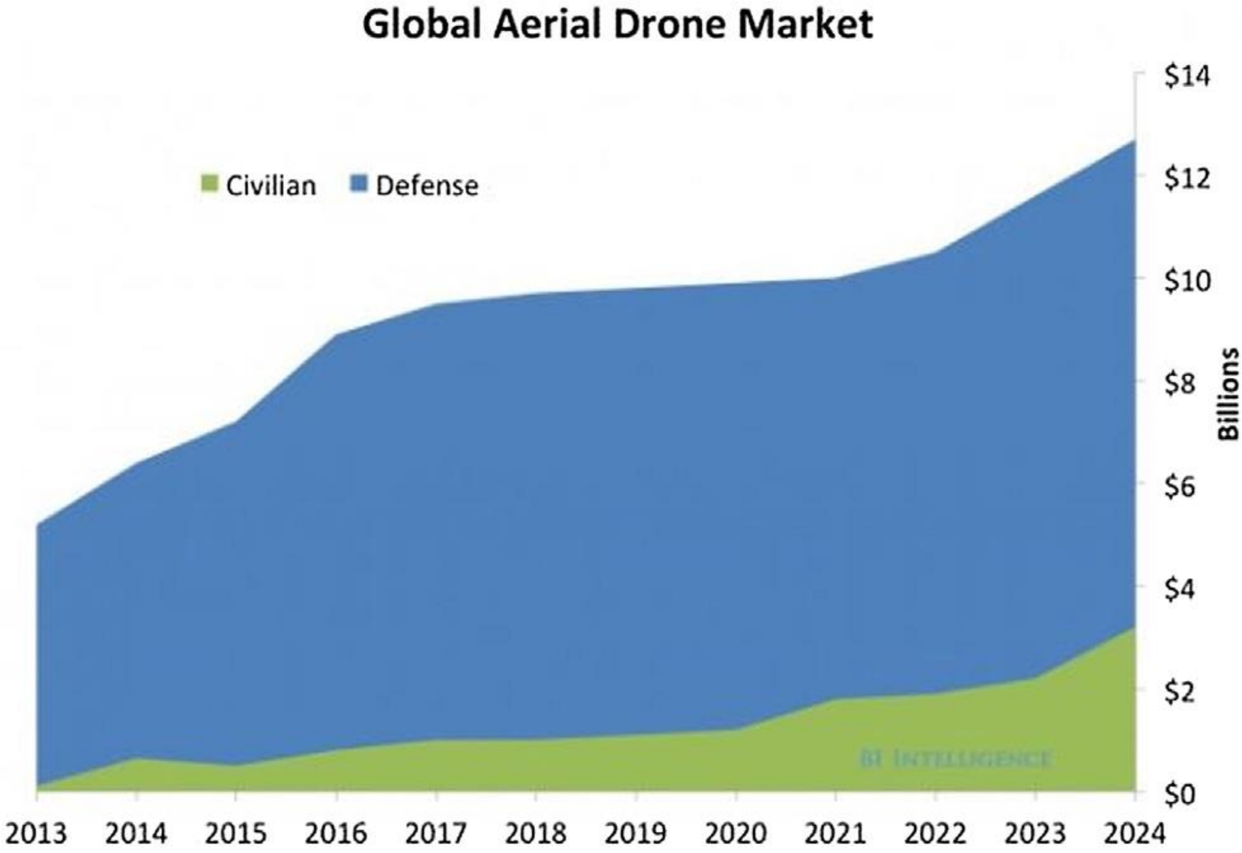


Fig. 3.6. Forecast global UAV market.

In this section, we review the research on the VRP for delivery logistics. As noted in the Introduction above, the VRP for delivery efficiency has been continually studied over the past several decades. The first such investigation was that of Dantzig and Ramser (1959), who introduced the truck-dispatching problem for multiple different-capacity vehicles and multiple products as a special case of the traveling salesman problem (TSP) and proposed a procedure for finding the near-optimal solution. According to Eksiogly, Vural, and Reisman (2009), routing with uncapacitated vehicles is a very common problem configuration through the 1990s, for example in the research of Jaillet (1988) and Letchford and Eglese (1998). However, after the introduction of faster heuristics, more complex and realistic problems with capacitated vehicles became the common approach. In the capacitated VRP (CVRP), all customers correspond to deliveries, the demands are deterministic, known in advance and unsplitable, and identical, capacitated vehicles are based at a single depot. Toth and Vigo (2002) re-viewed the branch-and-bound algorithm developed for the CVRP with either a symmetric or asymmetric cost matrix, showing the change of the solvable boundary. Lysgaard, Letchford, and Eglese (2004) developed, for the CVRP, the branch-and-cut algorithm, which uses cutting planes and describes separation algorithms for inequalities. In some cases, contrary to the classical VRP, the demand of each customer can be greater than the vehicle capacity, and each customer can be visited more than once. This is called the split delivery VRP. Archetti, Speranza, and Hertz (2006) and Archetti, Speranza, and Savelsbergh (2008) proposed, respectively, a tabu search algorithm and an optimization-based heuristic for split delivery capacitated VRP. Gulczynski, Golden, and Wasil (2012) considered the minimum de-livery amount on the split delivery VRP in order to mitigate split-de-livery-incurred customer inconvenience. Yu, Lin, Lee, and Ting (2010) combined the location problem with capacitated VRP and solved both simultaneously.

In early 1980s, the concept of the time window was added to the VRP, which problem is referred to as the VRP with time window (VRPTW). In the VRPTW, each demand point should be visited within a given time interval. The time window concept was introduced to the TSP by Christofides, Mingozzi, and Toth (1981), who proposed a branch-and-bound algorithm for the small-scale problem. Cheshire, Malleson, and Naccache (1982) applied time constraints to the vehicle scheduling problem and presented a heuristic for its solution. Braysy and Gendreau (2005a, 2005b) conducted surveys on the VRPTW in terms of route construction, local search heuristics and metaheuristics. Figliozzi (2012) presented time-dependent VRPs with hard or soft time windows and a solution algorithm. In this research, the author tested the proposed algorithm with a benchmark problem and demonstrated the computation power and solution quality. A study with link capacity also was conducted. Ma, Cheang, Lim, Zhang, and Zhu (2012) introduced the single-depot VRP with time window and link capacity constraints. In their study, each arc represents a road segment and has a link capacity by which the load of a passing vehicle is restricted.

All of the above-noted studies assumed a single depot in the system. However, since the 1980s, some researchers have investigated multiple-depot VRPs (MDVRPs). In the MDVRP, there are several depots instead of one, and each vehicle belongs to a certain depot and finishes its journey there. The goal is to derive vehicle routes to serve every customer in the system. Laporte, Nebert, and Taillefer (1988) examined an asymmetrical multi-depot VRP and location routing problems, deriving an optimal solution via the branch-and-bound algorithm in small-scale problems. Renaud, Laporte, and Boctor (1996) and Ho, Ho, Ji, and Lau (2008), to address the computational complexity of the MDVRP, developed tabu search and a genetic algorithm, respectively. Tu, Fang, Li, Shaw, and Chen (2014) suggested a bi-level Voronoi diagram-based metaheuristic for a large-scale MDVRP. Suzuki (2012) investigated a multi-depot VRP based on a limited charge supply for disaster relief logistics.

Now we turn our attention to the UAVRP literature. Due to the huge potentials of UAVs, numerous studies have been published during the past decade. We will focus herein on the issue of persistent UAVRP that allows a UAV to conduct missions persistently. In persistent UAVRP, UAVs perform missions and return to the station (depot) to replenish their consumables; they then take off and perform other missions. In this manner, UAVs can overcome their flight-duration limitation and conduct long-duration missions persistently. Sundar and Rathinam (2014) suggested a mathematical model and algorithm for UAVRP with the presence of refueling depots. In the study, a UAV visits refueling depots for refueling and conducts missions persistently. However, this approach is able to generate routes for only a single UAV, which restricts its potential applicability to real-world problems.

The persistent UAVRP with heterogeneous UAVs was treated by Kim, Song, and Morrison (2013), Kim and Morrison (2014) and Song, Kim, and Morrison (2016). In those studies, UAVs share multiple service stations distributed in the field of operation. After recharging, they return to service.

Fig. 3.7. Amazon Prime Air (left) and DHL Parcelcopter (right).

A long-duration monitoring and patrolling mission is divided into a set of split tasks, and UAVs cooperate to provide uninterrupted service. However, none of the above studies included delivery context, which meant that UAVs were not constrained by loading capacity and were limited only by the flight duration. Some research focuses on the UAVRP for delivery in order to resolve UAV limitations regarding loadable products and flight duration. Murray and Chu (2015) suggested a flying sidekick approach for UAV parcel delivery. The authors resolve UAV limitations by launching a UAV from a delivery truck, which UAV serves a single task per flight. In this way, the UAV and delivery truck cooperate to perform last-mile parcel delivery. However, the authors do not consider multiple depots or heterogeneous UAVs and trucks. Ferrandez, Harbison, Weber, Sturges, and Rich (2016) extend the truck-UAV parcel delivery system by optimizing the locations of multiple launch sites and the number of UAVs per truck. Studies such as this one have proposed approaches whereby UAVs can be utilized in the delivery context. However, to date, the research supporting the potentiality of UAV delivery remains scanty and insufficient.

In the present study, the problem of persistent UAV operation with respect to delivery logistics is addressed. Heterogeneous UAVs are limited by loading capacity as well as flight duration. To overcome such limitations, they are allowed to share multiple stations to replenish their consumables. Also, this study delicately controls for UAV-operational limitations for real-world delivery scenarios. Indeed, in real-world UAV implementations, the flight capabilities of UAVs are hugely affected by the amount of loaded product. By considering those cap-abilities in deriving UAV schedules, the proposed study can make a significant contribution to realistic delivery operations. Furthermore, each UAV can serve multiple customers as its fuel and loaded products allow. An efficient heuristic called the RHTA as well as a mathematical formulation is developed to derive the optimal or near-optimal delivery schedule in a reasonably short time. To our knowledge, ours is the first study to intensively focus on UAV delivery logistics in their theoretical and practical aspects.

In this section, we describe the proposed UAV logistics system and its fundamental properties. Also, we suggest a possible real-world application of UAV

Commercial UAVs have fundamental flight-duration and loadable-capacity limitations. As such, they cannot continue long in service be-fore having to be recharged and reloaded with new delivery products. In the proposed system, UAVs share multiple service stations distributed in the field of operation for recharging and product-reloading purposes. In this manner, UAVs can provide long-duration logistics service. Fig. 3.8 describes the persistent UAV logistics system. A UAV starts its delivery service from service station 1. After done its job, it returns to service station n for recharging and reloading, preparatory to serving additional customers. In this way, the UAV can serve customers persistently. A control center integrates system in-formation such as UAV locations, charge and product loads, and delivery requests. With this information, the control center derives UAV delivery schedules, controls UAVs and monitors the overall the drone system.

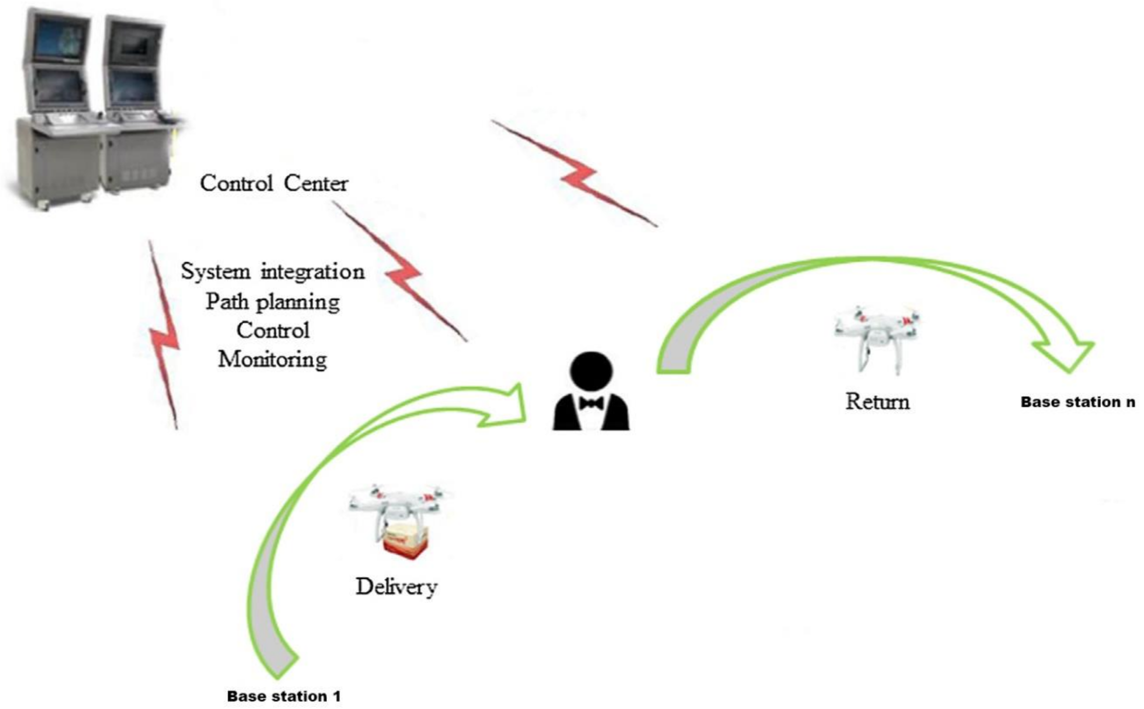


Fig. 3.8. UAV logistics system.

The flight time of a UAV critically depends on the amount of loaded products. In fact, without consideration of the effect of loaded products, a UAV delivery schedule might not be implementable in real situations. In this study, we developed and applied a weight function to the UAV flight time based on the amount of loaded products. Using this weight function, the proposed mathematical model can derive practical UAV schedules that can be smoothly applied in real-world UAV delivery service situations.

An important additional issue in the use of UAVs in logistics is that of inter-task idle time. In the case of conventional logistics using ground vehicles, idle time between two connected tasks might not cause any issues, as the vehicle just remains on the ground. However, in the case of UAVs, this could potentially cause loss of or damage to UAVs and/or delivery products. To prevent such problems, it is preferable to keep UAVs flying during inter-task idle time, which approach is the one followed in the proposed system.

3.4. Development, implementation and technical support of the drone system for Airport warehouse

Total development, implementation and maintenance costs of the drone system at airport warehouse:

$$TC_{di} = \sum C_{dv} + \sum C_{im} + \sum C_{mt}, \tag{3.1}$$

where $\sum C_{dv}$ – total development costs of the drone system at airport warehouse, $\sum C_{im}$ – total implementation costs of the drone system at airport warehouse.

Total development costs of the drone system at airport warehouse:

$$\sum C_{dv} = C_{doc} + \sum C_{dv\,hard} + \sum C_{dv\,soft}, \tag{3.2}$$

where C_{doc} – project of the system documentation development costs, $\sum C_{dv\ hard}$ – total development costs of the hardware components of the drone system at airport warehouse, $\sum C_{dv\ soft}$ – total development costs of the software components of the drone system at airport warehouse.

Total development costs of the hardware components of the drone system at airport warehouse:

$$\sum C_{dv\,hard} = C_{c\,hard} + C_{fea\,hard} + C_{tes\,hard}, \tag{3.3}$$

where $C_{c\ hard}$ – hardware components of the system costs, $C_{fea\ hard}$ – system hardware features development costs, $C_{tes\ hard}$ – system hardware testing costs.

Total development costs of the software components of the drone system at airport warehouse:

$$\sum C_{dv\,soft} = C_{cod} + C_{fea\,soft} + C_{tes\,soft}, \tag{3.4}$$

where C_{cod} – system software code development costs, $C_{fea\ soft}$ – system software features development costs, $C_{tes\ soft}$ – system software testing costs.

Total maintenance and technical support costs of the drone system at airport warehouse:

$$\sum C_{mt} = C_{sch} + C_{unsch}, \tag{3.5}$$

where C_{sch} – system scheduled maintenance and technical support costs, C_{unsch} – system unscheduled maintenance and technical support costs.

For the first year total costs for development, implementation and technical support of the drone system at airport warehouse:

$$TC_{1y} = \sum C_{dv} + \sum C_{im} + \sum C_{mt} . \tag{3.6}$$

For the next years:

$$TC_{(2+)y} = \sum C_{mt} . \tag{3.7}$$

1. Hardware components of the drone system at airport warehouse

We propose the next hardware configuration the drone system at airport warehouse:

1. Drones;
2. Stations for the drones;
3. Control servers;
4. Wi-fi stations.

Figure 3.9. Drone used in this study

Drone Specifications

Table 3.3.

Element	Specification
Dimensions	437 mm × 402 mm × 553 mm with propellers, frame arms (excluding landing gear)
Weight (with six TB47S batteries)	9.5 kg
Weight (with six TB48S batteries)	10 kg
Max takeoff weight recommended	15.5 kg (drone together with delivered goods)
Hovering accuracy	Vertical: ±0.25 cm, Horizontal: ±0.5 cm
Max ascent speed	5 m s^{-1}
Max descent speed	3 m s^{-1}
Max service ceiling above sea level	2170R propellers: 2500 m 2195 propellers: 4500 m
Max speed	65 km h^{-1} (no wind)
Hovering time* (with six TB47S batteries)	No payload: 32 min, 6 kg payload: 16 min
Hovering time* (with six TB48S batteries)	No payload: 38 min, 5.5 kg payload: 18 min
Flight control system	A3 Pro
Propulsion system	Motor model: DJI 6010 Propeller model: DJI 2170R
Operating temperature	–10 to 40° C
Energy use per package per kilometer	0.093 MJ

The basic designs in this study are as follows:

Drones can last up to 30 min

Drones can carry products up to 5 kg

Drones’ s cargo box dimension is 30.48 cm×30.48 cm×25.4 cm

Drones can be used in inventory

Project of the system documentation development costs C_{doc} can be calculated based on hourly project development cost:

$$C_{doc} = C_{h\,doc} \cdot h_{doc}, \tag{3.8}$$

where $C_{h\,doc}$ – project development cost development rate in \$ per hour, h_{doc} – total hours spend for details agreement with consumer. Minimum, average and maximum project details agreement with consumer costs:

$C_{doc\,\min} = 75\$/\text{hour} \cdot 50\text{hours} = 3750\$$;

$C_{doc\,\text{ave}} = 100\$/\text{hour} \cdot 50\text{hours} = 5000\$$;

$C_{doc\,\max} = 125\$/\text{hour} \cdot 50\text{hours} = 7600\$$.

Total development costs of the hardware components of the drone system at airport warehouse

Hardware components of the system costs $C_{c\,hard}$ can be calculated as

$$C_{c\,hard} = \sum_{i=1}^{k} C_{comp\,k}, \tag{3.9}$$

where k – number of the hardware components of the system, $C_{comp\,k}$ – component cost of the system.

According to our assumption, (3.9) can be rewrite as:

$$C_{c\,hard} = \sum_{i=1}^{4} C_{comp\,k} = n_{drones}C_{drone} + n_{stations}C_{station} + n_{wifi}C_{wifi} + n_{cont\,serv}C_{cont\,serv} \tag{3.10}$$

where: n_{drones} – number of drones for the warehouse; C_{drone} – single drone cost; $n_{stations}$ – number of stations for drones; $C_{station}$ – single station for drone cost; n_{wifi} – number of wi-fi stations; C_{wifi} – single wifi station cost; $n_{cont\,serv}$ – number drones' control servers; $C_{cont\,serv}$ – single drones' control server cost.

Variables n_{drones}, $n_{stations}$, n_{wifi} and $n_{cont\,serv}$ depend on warehouse area.

For our project we consider:

$n_{drones\,min} = 2$, $n_{drones\,ave} = 4$, $n_{drones\,max} = 8$;

$n_{stations\,min} = 2$, $n_{stations\,ave} = 4$, $n_{stations\,max} = 8$;

$n_{wifi\,min} = 20$, $n_{wifi\,ave} = 40$, $n_{wifi\,max} = 80$;

$n_{servers\,min} = 1$, $n_{servers\,ave} = 1$, $n_{servers\,max} = 2$.

Cost of special drone with all necessary equipment: $C_{drone} = 4000\$$.

Cost of drone charging station: $C_{station} = 500\$$.

Cost of single wifi station: 70$.

Cost of single drones' control server: 10000$.

Therefore:

$C_{c\ hard\,\min} = 2 \cdot 4000\$ + 2 \cdot 500\$ + 20 \cdot 70\$ + 1 \cdot 10000\$ = 20400\$;$

$C_{c\ hard\,\mathrm{ave}} = 4 \cdot 4000\$ + 4 \cdot 500\$ + 40 \cdot 70\$ + 1 \cdot 10000\$ = 30800\$;$

$C_{c\ hard\,\max} = 8 \cdot 4000\$ + 8 \cdot 500\$ + 80 \cdot 70\$ + 2 \cdot 10000\$ = 61600\$.$

System hardware features development costs $C_{fea\ hard}$ can be calculated based on hourly project development cost:

$$C_{fea\ hard} = C_{h\ \ fea\ hard} \cdot h_{fea\ hard}, \tag{3.11}$$

where $C_{h\ fea\ hard}$ – system hardware features development rate in \$ per hour, $h_{fea\ hard}$ – total hours spend for system hardware features development. Minimum, average and maximum system hardware features development costs:

$C_{fea\,hard\,\min} = 100\$/\mathrm{hour} \cdot 15\mathrm{hours} = 1500\$;$

$C_{doc\,\mathrm{ave}} = 100\$/\mathrm{hour} \cdot 30\mathrm{hours} = 3000\$;$

$C_{doc\,\max} = 100\$/\mathrm{hour} \cdot 45\mathrm{hours} = 4500\$.$

System hardware testing costs $C_{tes\ hard}$ can be calculated based on hourly project development cost:

$$C_{tes\ hard} = C_{h\ tes\ hard} \cdot h_{tes\ hard}, \tag{3.12}$$

$C_{tes\,hard\,\min} = 75\$/\mathrm{hour} \cdot 20\mathrm{hours} = 1500\$;$

$C_{doc\,\mathrm{ave}} = 75\$/\mathrm{hour} \cdot 40\mathrm{hours} = 3000\$;$

$C_{doc\,\max} = 75\$/\mathrm{hour} \cdot 60\mathrm{hours} = 4500\$.$

Total development costs of the software components of the drone system at airport warehouse

System software code development costs C_{cod}, system software features development costs $C_{fea\ soft}$ and system software testing costs $C_{tes\ soft}$ can be calculated using basic equation:

$$C_{i\ soft} = C_{i\ h\ soft} \cdot h_{i\ h\ soft}, \tag{3.13}$$

where $C_{i\,h\,soft}$ – system software development rate for i-th component in \$ per hour, $h_{i\ h\ soft}$ – total hours spend for software component system hardware features development.

Minimum, average and maximum system software code development costs:

$C_{cod\,\min} = 60\$/\text{hour} \cdot 200\text{hours} = 12000\$$;

$C_{cod\,\text{ave}} = 80\$/\text{hour} \cdot 200\text{hours} = 16000\$$;

$C_{cod\,\max} = 100\$/\text{hour} \cdot 200\text{hours} = 20000\$$.

Minimum, average and maximum system software features development costs:

$C_{fea\,soft\min} = 60\$/\text{hour} \cdot 40\text{hours} = 2400\$$;

$C_{fea\,soft\text{ave}} = 80\$/\text{hour} \cdot 40\text{hours} = 3200\$$;

$C_{fea\,soft\max} = 100\$/\text{hour} \cdot 40\text{hours} = 4000\$$.

Minimum, average and maximum system software testing costs:

$C_{tes\,soft\min} = 40\$/\text{hour} \cdot 40\text{hours} = 1600\$$;

$C_{tes\,soft\text{ave}} = 60\$/\text{hour} \cdot 40\text{hours} = 2400\$$;

$C_{tes\,soft\max} = 80\$/\text{hour} \cdot 40\text{hours} = 3200\$$.

Total maintenance and technical support costs of the drone system at airport warehouse:

We consider system scheduled maintenance and technical support costs C_{sch} as follows (per each year):

$C_{sch\min} = 1000\$/\text{year}$;

$C_{sch\text{ave}} = 2000\$/\text{year}$;

$C_{sch\max} = 4000\$/\text{year}$.

We consider unscheduled maintenance and technical support costs C_{unsch} based on linear deterioration of the drone system at airport warehouse equals to 5% year-per-year of the hardware system costs.

For first year:

$$C_{unsch1y\,\min} = 20400\$ \cdot 0{,}05 = 1020\$;$$

$$C_{unsch1y\,\text{ave}} = 30800\$ \cdot 0{,}05 = 1540\$;$$

$$C_{unsch1y\,\max} = 61600\$ \cdot 0{,}05 = 3080.$$

For fifth year:

$$C_{unsch5y\,\min} = 20400\$ \cdot 0{,}25 = 5100\$;$$

$$C_{unsch5y\,\text{ave}} = 30800\$ \cdot 0{,}25 = 7700\$;$$

$$C_{unsch5y\,\max} = 61600\$ \cdot 0{,}25 = 15400\$.$$

Total minimum, average and maximum development costs of the system (according to equation 3.2):

$$\sum C_{dv\min} = 3750\$ + 20400\$ + 1500\$ + 1500\$ + 12000\$ + 2400\$ + 1600\$ = 43150\$$$

$$\sum C_{dv\text{ave}} = 5000\$ + 30800\$ + 3000\$ + 3000\$ + 16000\$ + 3200\$ + 2400\$ = 63400\$;$$

$$\sum C_{dv\max} = 7600\$ + 61600\$ + 4500\$ + 4500\$ + 20000\$ + 4000\$ + 3200\$ = 105400\$.$$

Ways to Reduce Inventory Costs in Airport Warehouse:

- Reduce Labor Costs;
- Eliminate Picking and Putaway;
- Limit Storage Space Needs.

We consider the scenarios in which we reduce labor costs by replace workers by drones for each variant of the system. Therefore number of drones = number of workers.

Let us build the model to determine self-payment period of the system.

Aging effect of the system is calculated based on scheduled and unscheduled maintenance costs (see above). For simplify the model we suppose that scheduled and unscheduled maintenance costs are uniformly distributed along 12 months per each year.

Note. This model does not include the *personnel certification* costs.

For each *i*-th month the cumulative sum of scheduled and unscheduled maintenance costs of the drone system:

$$C_{mt\_m} = \frac{C_{sch\_y}}{12} \cdot i + \sum_{r}^{h-1} C_{sch\_c} + \frac{\sum C_{c\,hard}}{12} \cdot k_y \cdot i + \sum_{r}^{h-1} \left(\frac{\sum C_{c\,hard}}{12} \cdot k_{y\_pr} \right), \quad (3.14)$$

where C_{mt_m} – cumulative month-per-month sum of scheduled and unscheduled maintenance costs of the drone system; i – sequential number of considered month (with 12 month - year period), C_{sch_y} – value of scheduled maintenance costs of the drone system for considered year h, C_{sch_c} – cumulative sum of scheduled maintenance costs of the drone system for years from r to h-1, k – coefficient which characterize deterioration (aging) of the system depends on service year and equals to 5% (0,05) year-per-year of the hardware components system costs $C_{c\ hard}$ (k_y – coefficient for considered year, k_{y_pr} – coefficient for past years):

$$C_{unsch} = \sum C_{c\,hard} \cdot k. \quad (3.15)$$

Cumulative labor reducing costs for each month can be calculated by the equation:

$$C_{lr} = n_{\text{workers}} \cdot C_{sal} \cdot v, \quad (3.16)$$

where n_{workers} – number of workers, C_{sal} – worker salary, v – sequential number of considered month (with all period of analysis).

For each scenario we consider that number of drones = number of workers and the worker salary equals to 800$ per month.

According to these models and assumptions we build graphs for three scenarios for the drone system at airport warehouse - minimum, average and maximum system costs and consider constant cumulative labor reducing costs based on equality number of drones and number of workers for each system (figures 3.10 - 3.12).

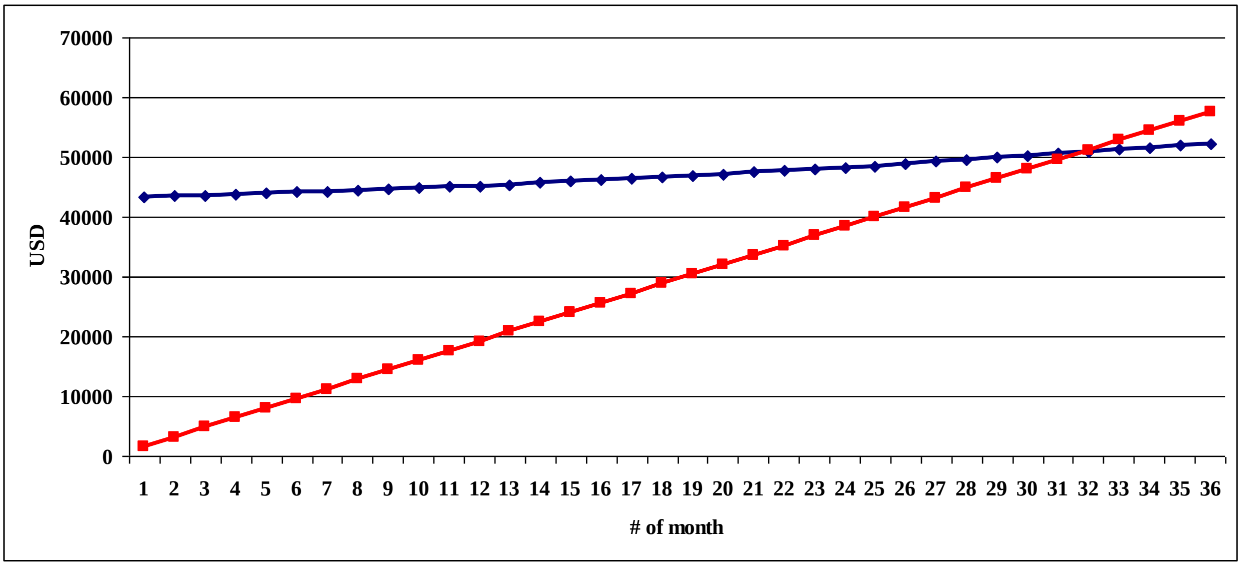


Figure 3.10. Cumulative labor reducing costs (red line) and minimum cost scenario of the drone system development, implementation and maintenance (blue line) for 36 months period ($n_{\text{workers}} = 2$)

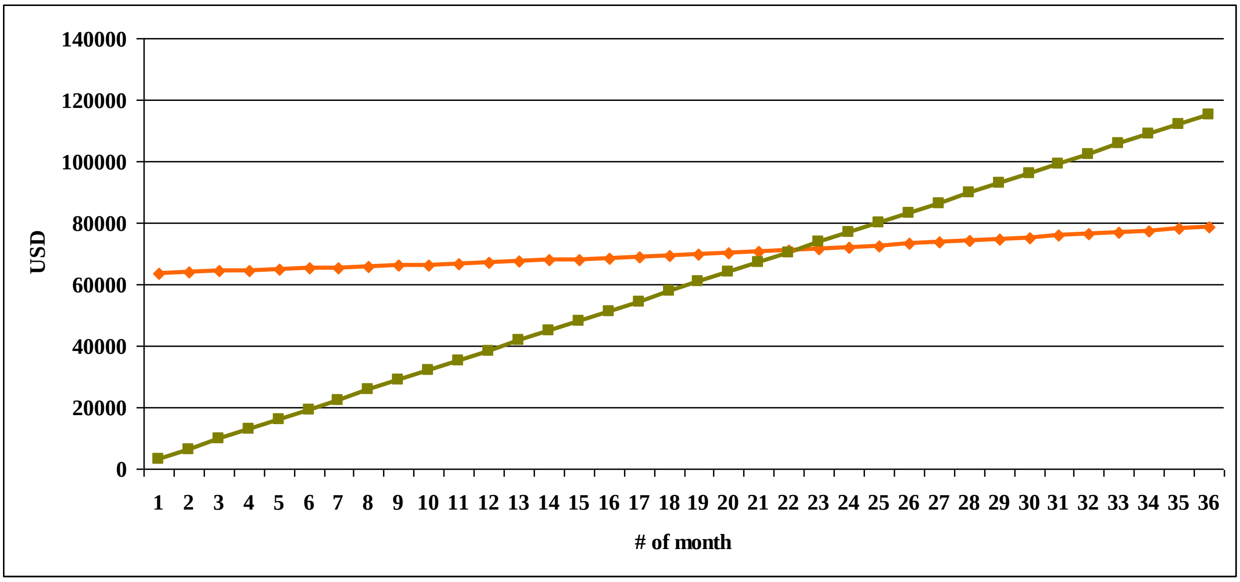


Figure 3.11. Cumulative labor reducing costs (green line) and average cost scenario of the drone system development, implementation and maintenance (orange line) for 36 months period ($n_{\text{workers}} = 4$)

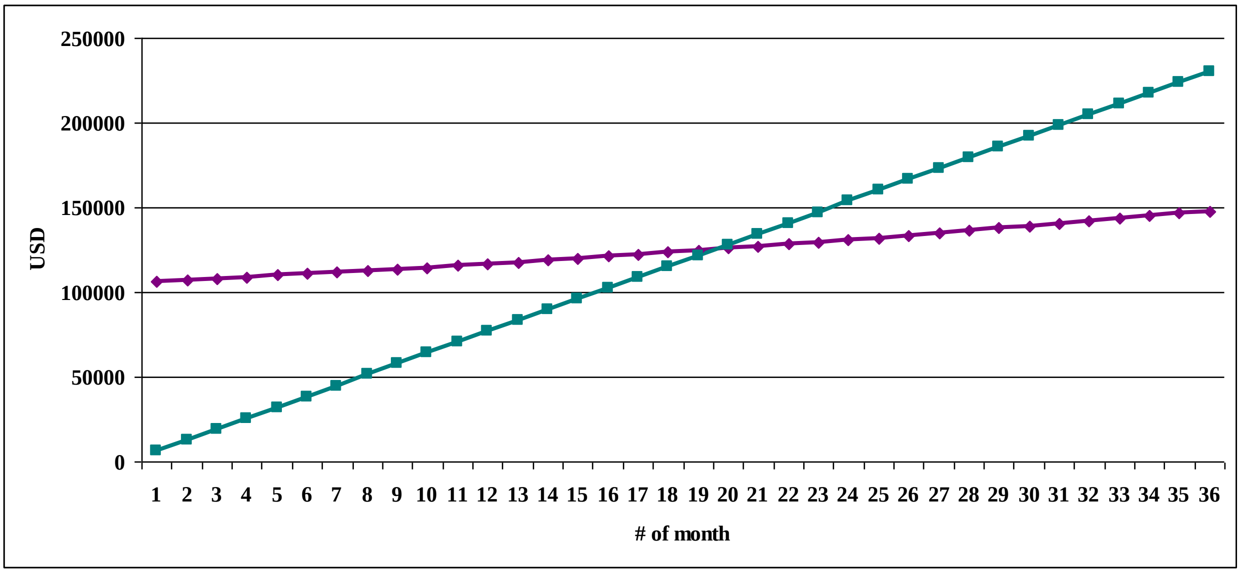


Figure 3.12. Cumulative labor reducing costs (green line) and maximum cost scenario of the drone system development, implementation and maintenance (violet line) for 36 months period ($n_{\text{workers}} = 8$)

According to graph presented on figure 3.10, self-repayment period for minimum cost of the system scenario is approximately 32 months (cross point of red and blue lines on the graph). As for average cost of the system scenario (figure 3.11), self-repayment period is approximately 22 months (cross point of green and orange lines on the figure) and for maximum cost of the system scenario (figure 3.12) is approximately 20 months (cross point of green and violet lines in the figure).

CONCLUSIONS

<table>
<tr><td colspan="4">Air Transportation Management Department</td><td colspan="6">NAU 19. 09. 00. 300EN</td></tr>
<tr><td>Done by</td><td>Kopin O.</td><td></td><td></td><td rowspan="4">CONCLUSIONS</td><td colspan="3">Letter</td><td>Sheet</td><td>Sheets</td></tr>
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<tr><td>Head of the Dep.</td><td>Yun G.</td><td></td><td></td></tr>
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Drones at airport warehouses can be used for:

- Inventory Management
- Intra-Logistics
- Inspection & Surveillance

Warehouses with the following characteristics have a high potential for drones:

- Relatively large size >10’000 square meters
- High shelfs (>5 meters) (Dangerous tasks for operators)
- Long corridors (>50 meters) (Long walking distances increase time needed to accomplish tasks)
- Single deep pallet rack (Barcode scanning not possible for double deep storage principle)

We proposed the next hardware configuration the drone system at airport warehouse:

1. Drones;
2. Stations for the drones;
3. Control servers;
4. Wi-fi stations.

According to our calculations, total minimum, average and maximum development costs of the system:

$$\sum C_{dv\,\min} = 43150\$$$

$$\sum C_{dv\,\mathrm{ave}} = 63400\$;$$

$$\sum C_{dv\,\max} = 105400\$.$$

We consider the scenarios in which we reduce labor costs by replace workers by drones for each variant of the system. Therefore number of drones = number of workers.

Three scenarios for costs – minimum, average and maximum costs and consider cumulative labor reducing costs growth for all scenarios were taken into consideration.

According to these models and assumptions we build graphs for three scenarios for the drone system at airport warehouse - minimum, average and maximum system costs and consider constant cumulative labor reducing costs based on equality number of drones and number of workers for each system.

Self-repayment period for minimum cost of the system scenario is approximately 32 months (cross point of red and blue lines on the graph). As for average cost of the system scenario, self-repayment period is approximately 22 months (cross point of green and orange lines on the figure) and for maximum cost of the system scenario is approximately 20 months (cross point of green and violet lines in the figure).

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