TESTING AUTONOMOUS CARGO VEHICLES AT AIRPORTS – AN ANALYSIS OF THE BASIC REQUIREMENTS FOCUSING ON STAFF-RELATED HUMAN FACTORS

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ABSTRACT

The air cargo industry is increasingly turning towards autonomous handling vehicles. Research so far has not fully explored how these vehicles affect human staff at airports. This paper presents a mixed-methods study, utilizing a three-stage approach including process analysis and expert interviews, followed by merging both thematic analyses in an adapted SHELL model. The SHELL model is found to be an effective tool for analysing the various types of interaction between the human factors and autonomous vehicles in their distinct environment. The conclusion of the paper emphasizes the importance of considering human factors, including change management, process optimization, resilience, and others, to successfully integrate autonomous vehicles into airport operations. For instance, the application of the SHELL model highlights that autonomous vehicles require an adapted environment with advanced road infrastructure for effective communication and navigation. These changes may impact daily work routines, dispatch procedures, communication protocols, emergency response plans, and operational processes.

KEYWORDS

air cargo; autonomous driving; human factors; airport automation; change management; aviation logistics

1. INTRODUCTION

The air cargo industry is experiencing a significant rise in the testing and deployment of autonomous cargo vehicles at airports. In Table 1 of Appendix 1, we present a comprehensive (not exhaustive) list of 32 publicly known cases from 13 countries (see Figure 1 for an example). This compilation serves to underscore the escalating interest and acknowledgement of automation potentials among industry stakeholders, as evidenced by the increasing number of prototypes and solutions introduced by an expanding range of manufacturers.

Figure 1. Exemplary test solution from UK-based manufacturer Aurrigo at East Midlands Airport (Aurrigo 2023)

However, so far, the scientific literature has not extensively examined the challenges faced by new users and their interactions with automation and autonomisation within the airport environment. No specific contributions were identified that systematically address the human factors of autonomous vehicles in the context of air cargo.

In other logistical fields, research on human factors of autonomous vehicles is more advanced. Liu (2021) points out obstacle avoidance approaches for unstructured human environments. Klumpp et al. (2019) focus on human-computer-interaction in automated production facilities, whereas Carsten and Martens (2019) discuss human machine interface principles for automated cars. In contrast, it appears that the current focus of researchers exploring airport automation is more generic, considering air cargo as one among many potential application fields, rather than delving into specific tasks and processes.

Only a limited number of research articles have covered autonomous air cargo vehicles. Notably, Bierwirth et al. (2019) and Mehrtens and Uhing (2021) discuss a specific demonstration conducted as part of a research project at Frankfurt Airport in Germany. Edlinger et al. (2022) present research findings from testing various autonomous functions using a remotely controlled robot platform at Linz Airport in Austria. Den Heijer (2020) analyses the potential of autonomous dolly transports at Amsterdam Airport in the Netherlands. Additionally, Mehrtens et al. (2023) outline a current research project that aims to demonstrate autonomous air cargo vehicles at multiple German airports. The presence of these specific papers instils confidence in the relevance of our research field for stakeholders within the air cargo industry.

Several contributions in the field of airport automation have adopted high-level approaches to assess its potential. For instance, Tabares et al. (2021) propose a mathematical approach for evaluating the feasibility of automating airport ground handling operations. Similarly, Hájnik et al. (2021) view autonomous vehicles as an innovative addition to airport electrification projects.

In contrast, other authors have contextualized selected air cargo solutions within non-cargo focused areas such as passenger services, luggage handling, and specific aviation-related tasks like Foreign Object Debris (FOD) runway checks. Carosio et al. (2019), for example, analyse the potential of electrified autonomous transport systems for various tasks at the apron. Although their work only partially focuses on air cargo processes, it provides valuable insights and relevant requirements that we will incorporate into our paper.

Meanwhile, Chen (2022) proposes a categorization of solutions into robots for parking services, terminal passenger service robots, terminal luggage handling robots, and outdoor transportation robots. However, it is important to note that air cargo processes at airports encompass both handling and transportation, taking place in both outdoor and indoor environments. Therefore, for a comprehensive approach, it is necessary to consider all solutions that align with either of these characteristics.

While industrial stakeholders are actively advancing in this area, researchers have yet to significantly support this technological progress. Therefore, our contribution aims to contribute filling this research gap within the air cargo industry by compiling and defining the major challenges from a user's perspective. By referring to "users," we encompass organizations that employ autonomous vehicles, including airport operators, cargo handlers, and cargo forwarders. We analyse the basic requirements for testing and demonstrating the technological potential. Hereby, we focus on human factors by utilizing established aviation research methodology and we address the following questions along our qualitative methodological approach (Q1-4):

a. Q1: Which specific workplace conditions, equipment, or procedures shall be established to enhance human factors in the system and support safe and efficient operations with autonomous vehicles?
b. Q2: How can the human-machine interface be designed to ensure effective communication and control between humans and autonomous vehicles?
c. Q3: What are the specific areas of interaction between humans and autonomous vehicles in an airport ground operations environment?
d. Q4: How will the role of humans change, which new types of human interaction will occur between operators of autonomous vehicles and other staff?

2. BACKGROUND

2.1. HUMAN FACTORS

Our research specifically focuses on conducting a systematic assessment of the role human factors play when introducing autonomous vehicles into the airside system of airports. Human factors, in the context of our research, refer to the study and understanding of the human-related aspects of a system. This includes the interactions, behaviour, capabilities, limitations, and performance of individuals within the airport system (Salas et al., 2010). In the case of introducing autonomous vehicles in the airport airside system, human factors encompass the employees and management personnel involved, such as equipment operators, system designers, operations dispatchers, managers at all levels, and front-line personnel.

One crucial aspect of our study revolves around examining the interactions between humans and autonomous vehicles within the unique airport environment. Although the vehicles themselves may operate autonomously, human involvement is necessary for tasks such as planning, management, and dispatching of these vehicles. This underscores the significance of understanding the dynamics of human-machine interaction and establishing specific measures to ensure safe and efficient operations at the airport (Muecklich et al., 2023). Each potential interaction between humans and vehicles must be meticulously assessed in order to determine where these interactions may occur and what safety and efficiency considerations need to be taken into account (McFadden & Towell, 1999). While the implementation of autonomous vehicles may mitigate safety risks in certain operational areas by reducing human error, there may also be new safety risks arising from the interaction with autonomous vehicles or the potential for human error in this new context. Managing human factors is crucial for maintaining safety, efficiency, and effectiveness in ground operations at airports (Muecklich et al., 2023; Ek & Akselsson, 2004; ICAO, 2018).

In the realm of assessing human factors in a system, various models have been developed, with many of them primarily centred around analysing potential human error. Among the widely accepted models in this domain are the Human Factors Analysis and Classification System (HFACS) (Shappell & Wiegmann, 2000), the Systems-Theoretic Accident Model and Processes (STAMP) (Patriarca et al., 2022), or the Human Factors Integration (HFI) Model (Tainsh, 2004).

However, for our specific research, we have chosen to utilize the SHELL model (see Figure 2), which provides a relatively simplistic framework for examining human factors interactions in a system. The SHELL model is a widely accepted framework for assessing human interactions in the workplace (Dumitru & Boscoianu, 2015; ICAO, 2018; UK CAA, 2002). It consists of four dimensions: Liveware (human operators and lifeware as other humans in the system), Software (procedures and policies), Hardware (equipment and technologies), and Environment (physical and social conditions) to assess how these factors interact and influence human performance and safety within the system (ICAO, 2018).

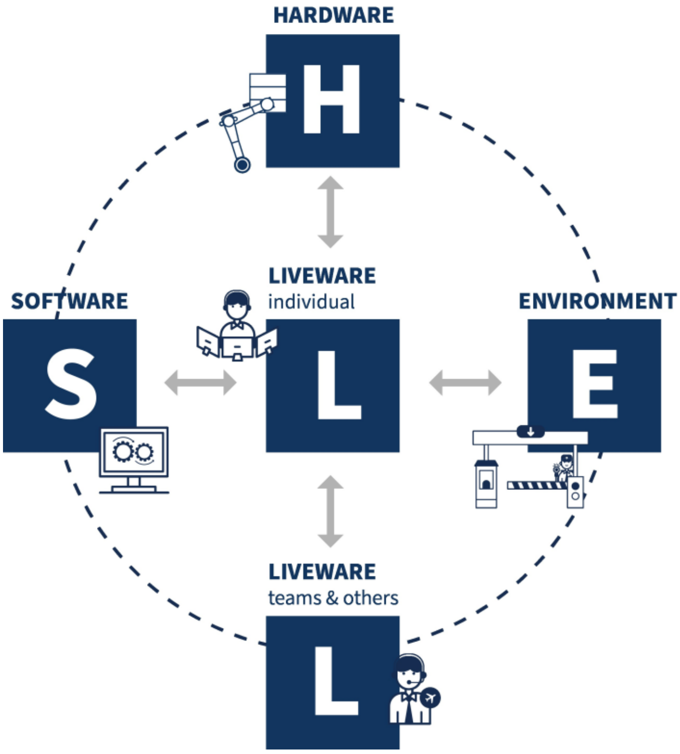


Figure 2. The SHELL model based on ICAO (2018)

By analysing each dimension of the SHELL model, aviation researchers and professionals can identify potential sources of error or hazards and develop strategies to mitigate risks and improve overall safety. In addition, the model can also be used to identify interactions, to optimise processes, improve communication, and improve planning of all SHELL components.

It is important to recognize that while the overall benefits of implementing autonomous vehicles in airport ground operations may be significant, any operational change must be thoroughly considered and properly managed. This includes the human-machine interface and ensuring that the working environment, tasks, and actions are well-aligned to support safe and efficient operations. Certain factors in the environment, such as specific workplace conditions, equipment, and procedures, can be managed to enhance the overall human factors in the system (Liu & Wang, 2014; ICAO, 2018).

The application of potentially timeless research knowledge on human factors originating to the 1970s is still relevant, especially in the context of the airport and the relatively new technology of autonomous driving. For example, the Human Factors Training Manual, published in 1998, is still commonly used and discussed. It can be helpful in designing autonomous vehicles in airport operations. It provides valuable insights and recommendations to enhance human-machine interface and safety in the airport context (ICAO, 1998).

2.2. PROCESS FOCUS

To facilitate better analysis, visualisation, and understanding, we have developed a sample process that showcases the application of our methodology (described in Chapter 3). This sample process serves as a practical example to demonstrate how our approach can be implemented and utilized effectively. By using this sample process, stakeholders can gain a clearer understanding of our methodology and its potential benefits for their own operations. The process is described below.

Figure 3. Exemplary test solution from France-based manufacturer Charlatte Autonom at Frankfurt Airport (Fraport AG, 2023)

For our assessment, we are specifically focusing on outdoor transportation activities that occur at the apron area of an airport. Our main area of interest is the movement of Unit Load Devices (ULDs), which are air cargo units, from aircraft positions to warehouses (and vice versa). This transportation is carried out using specialized wagons called dollies, which can be connected to each other using drawbars. These connected dollies are then towed by a vehicle known as a tractor or tug (see Figure 3). We have chosen this part of the process chain because it has been extensively tested at various airports, including Frankfurt, Stuttgart, Paris, Amsterdam, London, Linz, and several Asian airports. Additionally, we have collaborated with industry experts through a series of workshops to prepare for a test that shall take place at Stuttgart airport in 2024. While our focus is on a specific aspect of air cargo ground operations, we believe that our approach is comprehensive enough to provide valuable insights for stakeholders involved in the entire process chain and beyond cargo operations (DTAC, 2023). Figure 4 illustrates a simplified representation of the current manual process, while Figure 5 depicts a simplified version of the process utilizing an autonomous towing tractor instead of manual handling.

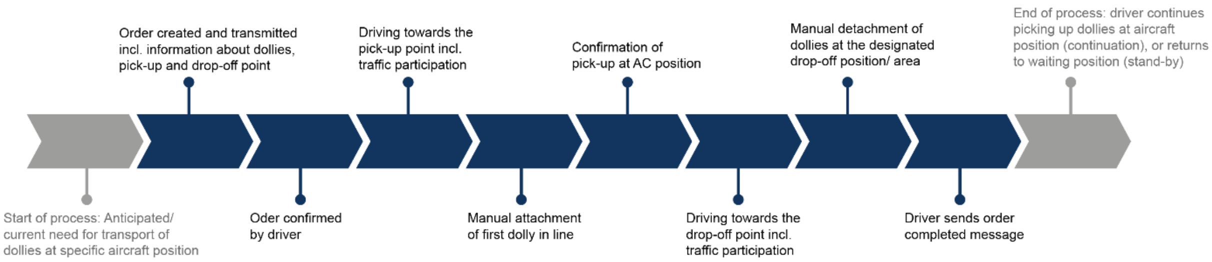


Figure 4. Simplified representation of the current manual process

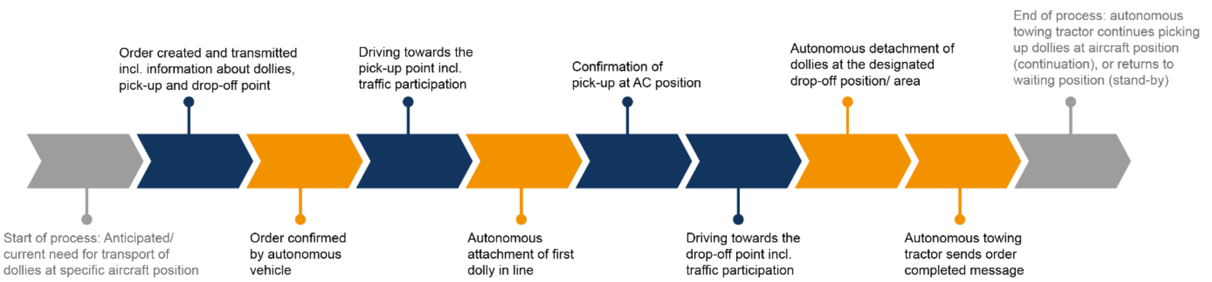


Figure 5. Simplified version of the process utilizing an autonomous towing tractor instead of manual handling

For clarification, as well as for further research purposes, we suggest dividing autonomous air cargo projects in four phases, based on our project and research experience in airport innovation (see Figure 6). These phases are user centric. They apply, when for example airport operators or cargo handlers wish to add autonomous cargo vehicles into their non-autonomous fleet.

Phase 1, the identification of use cases, includes status-quo and potential analyses, as well as the selection of one (or more) use case(s) for project execution. For our paper, we consider this phase as already completed, as human factors usually play just a minor role in the case selection process.

Phase 2, our focus-phase, is called testing & demonstration. One or more selected solutions are being integrated into existing systems and processes. Human factors play an important role, as test vehicles are operating in a mixed-traffic environment with plenty of human interaction, often for the first time in the history of the airport.

Phase 3 and 4, which are implementation & operations as well as scaling-up & optimization, we see as potential for further research. On the one hand, most known airport cases so far have not yet reached these stages. New potential users, on the other hand, might have had use cases in their minds for a long time, but might at the same time be hesitating to start phase 2 due to a lack of available objective knowledge.

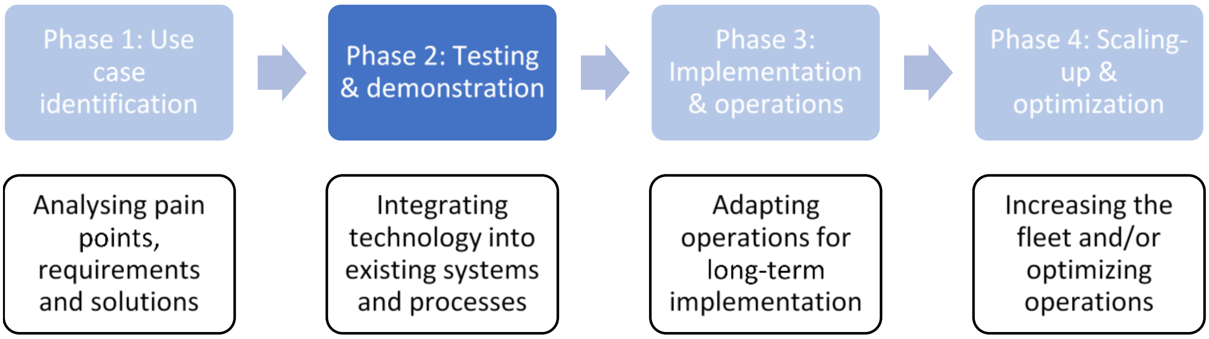


Figure 6. Testing and demonstration phase in the context of a 4-phase approach towards the implementation of autonomous air cargo vehicles at airports

Although we are aware that there is some confusion with regard to terminology (i.e. autonomy, full and partial automation, Automated Guided Vehicle (AGV), Autonomous Mobile Robot (AMR) and so on), we do not wish to address this issue in our work. Several authors, for example Fottner et al. (2021), suggest clear definitions and technology stages, which can be applied on all industries. It is apparent, though, that this terminology confusion exists even in other, more mature application fields, such as automotive production facilities and distribution centres. As Ullrich and Albrecht (2023) note, certain terms can be misleading and easily be used for marketing purposes. We are convinced that users always strive for the best available technology. For air cargo research, thus, we see the need to first structure and access this relatively new research field regardless of the automation level. This is why we do not distinguish between automation and autonomy in the following.

3. METHODOLOGY

The methodology employed in this study involved a sequential qualitative approach consisting of process analysis, categorization of expert interviews, and a synopsis of the first two stages within the SHELL model (see Figure 2). At this early stage of a human factor analysis for new airport technology, qualitative research and the qualitative application of the respective models has proven valuable. Figure 7 displays the three-stage approach.

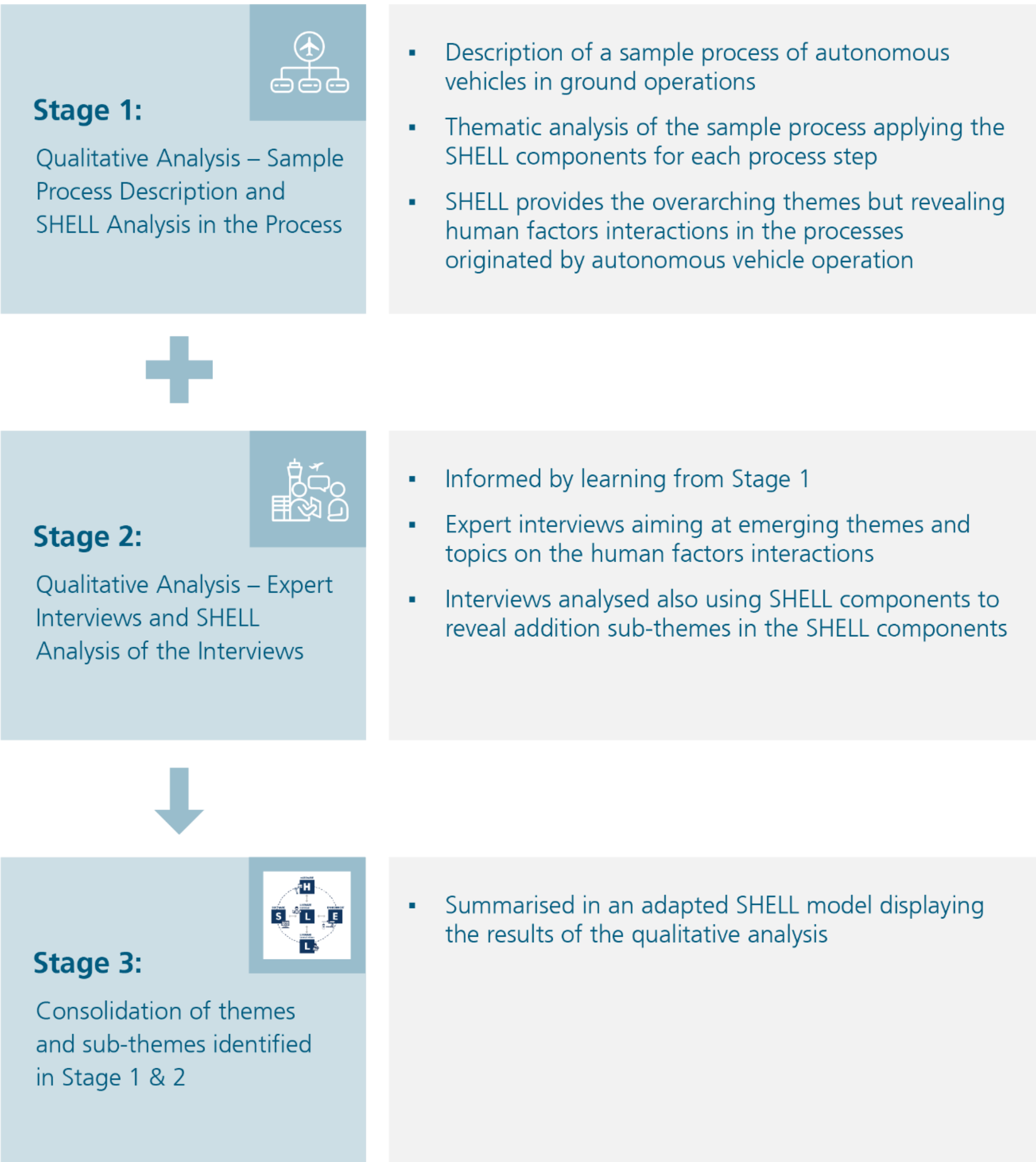


Figure 7. Three staged qualitative methodological approach

In the first stage, a process analysis of a sample process, as described in Chapter 2, was conducted to examine the specific components and workflows affected by the presence of autonomous vehicles in ground operations. The SHELL model was used to identify the S H E L L components within the process (Dumitru & Boscoianu, 2015; ICAO, 2018). This analysis provided a detailed understanding of how autonomous vehicles impact various aspects of the ground operations process. The thematic analysis of the sample process revealed S H E L L categories that were condensed into broader themes, revealing the impact on human factor interactions originated by autonomous vehicle operation.

Following the process analysis, expert interviews were conducted in the second stage (Interview Guide provided in the Appendix 2). These interviews aimed to gather additional insights and perspectives from experts in the field. We interviewed an airport's Head of Project, responsible for one of the demonstrations mentioned in Chapter 1, as well as another airport's Head of Project, who is planning a demonstration in 2024, which is not yet publicly known. The third interviewee was a project grant coordinator responsible for a number of innovation projects at four European airports. The interview guide was structured into four parts: Introduction, Challenges for Demonstrations, Human Factors (questions classified using SHELL), and Other relevant Aspects. The information gathered from the interviews complemented the findings from the first stage and provided further validation for the study. The interview data was categorized based on relevant themes and topics that emerged from the discussions (Leedy & Ormrod, 2015). These categories were then further analysed to identify their alignment with the different aspects of the SHELL model.
Please note that only three expert interviews were conducted, which may restrict the depth and diversity of perspectives obtained. Additionally, the use of convenience sampling with industry contacts may introduce bias and limit the generalizability of the findings. Therefore, the results should be interpreted with caution and may not fully capture the range of opinions and experiences in the field.

In a third stage, the themes and categories from the process analysis and from the interview analysis were consolidated and summarised in content to visualise an adapted SHELL model for the autonomous vehicle operation in a ground operations context.

By systematically analysing the process, categorizing interview data, and applying it within the SHELL model, this methodology provided a comprehensive understanding of the implications of autonomous vehicles on the human-machine interface and the ground operations staff. This approach allowed for a first assessment of the challenges and opportunities associated with the integration of autonomous vehicles in ground operations. Thus, the four questions raised in Chapter 1 relate to the four categories of the SHELL model, as depicted in Figure 8.

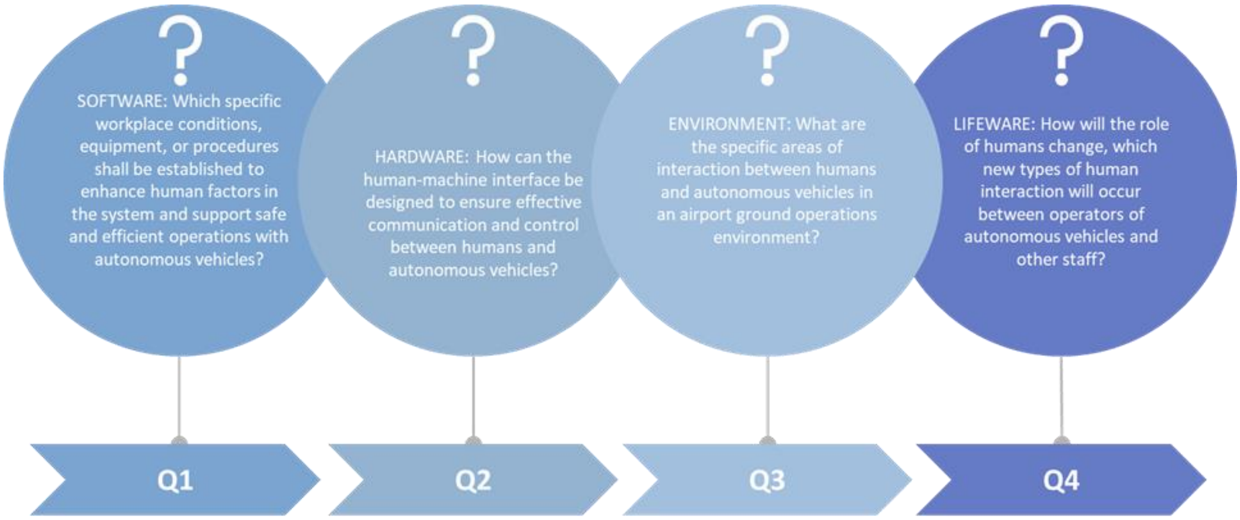


Figure 8. SHELL model assessment in the research approach

However, it is important to note that this study has limitations, and further research is needed to expand upon the findings and implications. The research outlook suggests that this study serves as a first step towards a deeper understanding, and further assessments are necessary. The implications for further research and for practitioners are discussed in the conclusion section, providing directions for future investigation in this field.

4. RESULTS & DISCUSSION

4.1. PROCESS ANALYSIS

The following tables (see Tables 1 - 5) provide an overview of the exemplary process analysis and the potential interactions of the SHELL components. A short description of the physical or digital interactions is added, or specific links between the components. From these descriptions we derived categories to be considered when planning the autonomous vehicle tests and demonstrations.

Table 1. Exemplary process analysis – Process Step 1

Process Analysis **Process Step #1: Need Anticipation & Order Creation**		
		
SHELL	**Physical / Digital / Link**	**Categories**
Lifeware-	- Ramp agents, unloading process (keep	- Ramp Agents

Lifeware	the aircraft position safe, enable efficient operations) - Humans in AGV control station and dispatch station (have to monitor fleet) - Confirmation with air traffic / ground control that aircraft is ready to be unloaded	- AGV Control Stations - Dispatch Station Operators - Communication with Air Traffic Control / Ground Control
Lifeware-Software	- Dealing with damaged cargo - Sequence and destination of ULDs in unloading process (transfer ULDs to the right customers or onward flights)	- Digital Communication - Management Software
Lifeware-Hardware	- Preparation of single dollies to be picked-up - Linking of dollies (considering state-of-the-art solutions, this task still needs to be done by humans) - AGV drives towards aircraft position - Order creation and confirmation for autonomous vehicle - Data based preparation, predictive analytics, resource planning (how to efficiently use AGV fleet) - AGV accepts order	- Dolly - Autonomous Vehicle
Lifeware-Environment	- Dolly position accessible for pick-up - Overview of vehicles and tasks at aircraft position	- Dolly position - Apron

Table 2. Exemplary process analysis – Process Step 2

<table>
<tr><th colspan="3">Process Analysis
Process Step #2:


</th></tr>
<tr><th>SHELL</th><th>Physical / Digital / Link</th><th>Categories</th></tr>
<tr><td>Lifeware-Lifeware</td><td>- AGV operator confirms operations with other operators (ramp agent, air traffic control, etc.)</td><td>- AGV operator communication with other operations personnel (ramp agents, ATC, etc.)</td></tr>
<tr><td>Lifeware-Software</td><td>- Safety issue prior to the vehicle leaving the position (no humans must be in-between the dollies in the sensor blind spots)</td><td>- Safety issue considered in the software development</td></tr>
<tr><td>Lifeware-Hardware</td><td>- AGV approaches pick-up point
- AGV sensors recognize position / dollies
- If applicable, reversing to approach dollies
- If applicable, releasing the break of the dollies (human assistance might be necessary)</td><td>- AGV operations functions
- AGV sensors and recognition</td></tr>
</table>

	- Linking vehicle and first dolly - Autonomous identification of designated dollies	
Lifeware-Environment	- Manoeuvring at the aircraft position (pedestrians, also other vehicles, obstacles, restricted areas) - harmonization with other aircraft turnaround processes	- Aircraft turnaround environment, incl. aircraft position

Table 3. Exemplary process analysis – Process Step 3

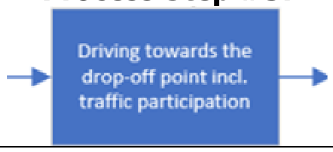
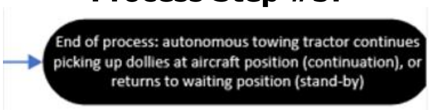
Process Analysis **Process Step #3:** 		
SHELL	**Physical / Digital / Link**	**Categories**
Lifeware-Lifeware	X	X
Lifeware-Software	X	X
Lifeware-Hardware	- Dealing with human driving behaviour - Dealing with speeding and/or dangerous situations caused by humans	- AGV functions considering human driving behaviour, incl. monitoring and intervention mechanisms - Hardware System Safety, e.g. incl. collision avoidance mechanisms and emergency braking systems
Lifeware-Environment	- Traffic participation with other vehicles (and pedestrians) - Control points, humans might check vehicle	- Traffic Participation: Interaction and coordination with other vehicles and pedestrians in the surrounding environment - Control Points: Designated areas or checkpoints where humans may need to check or inspect the AGV or its operations

Table 4. Exemplary process analysis – Process Step 4

Process Analysis **Process Step #4:**  		
SHELL	**Physical / Digital / Link**	**Categories**
Lifeware-Lifeware	- AGV operator confirms operations with other operators (warehouse manager)	- AGV Operator Communication and coordination
Lifeware-Software	- Notification to disposition	- Software system that generates and sends notifications or alerts
Lifeware-Hardware	- AGV approaches drop-off point - AGV sensors recognize designated position - Unlinking vehicle and first dolly - If applicable, secure dolly (human assistance might be necessary) - Autonomous identification of designated drop-off point	- AGV operations - AGV sensors and recognition - Dolly handling
Lifeware-Environment	- Manoeuvring near the drop-off point / at the warehouse (pedestrians, also other vehicles, obstacles, restricted areas) - harmonization with other warehouse processes	- Warehouse manoeuvring and process harmonisation

Table 5. Exemplary process analysis – Process Step 5

Process Analysis **Process Step #5:**  		
SHELL	**Physical / Digital / Link**	**Categories**
Lifeware-Lifeware	x	x
Lifeware-Software	- Decision making how to use vehicle next	- Control station decision making
Lifeware-Hardware	- Charging status to be considered	- Charging status
Lifeware-Environment	x	x

<u>Note:</u> There are concepts for autonomous vehicles that do not work with linked dollies as it is usual in the current non-automated process. Instead, single ULDs are transported. These single-unit solutions appear to be more flexible because each ULD can be delivered individually. However, more vehicles are necessary to transport the same amount of ULDs. As we are focusing on stage 2 (see *Figure 3* in Chapter 1), we find the dolly tug approach based on the status-quo more natural for the process analysis in this early research phase.

4.2. EXPERT INTERVIEWS

The qualitative content analysis of the interviews has revealed several themes within each SHELL category. These themes reflect the recurring ideas, opinions, and perspectives expressed by the experts. Using the SHELL categories, the analysis has been organized into distinct sections to provide a comprehensive overview of the findings. Each shell category represents a specific aspect or topic discussed during the interviews. By categorizing the data, it becomes easier to identify common patterns and trends within the expert responses. It is important to note that the analysis of expert interviews is an iterative process and involves careful consideration of the context, nuances, and limitations of the data. The findings presented in this analysis (see *Tables 6-9*) are based on the information provided by the interviewed experts and should be interpreted within the scope of the study.

In this analysis, we explore the various aspects related to the feasibility and integration of a test vehicle into airport operations. The analysis focuses on several overarching categories, each of which plays a crucial role in ensuring the success.

4.2.1. LIFEWARE-LIFEWARE

Table 6. Results Expert Interviews - LIFEWARE-LIFEWARE

LIFEWARE-LIFEWARE	
Category	**Description**
Communication	Digital and personal communication: Adequate, open, and honest communication strengthens employee trust and fosters a supportive environment for the test operations. Effective communication is essential to address any concerns, provide necessary information, and ensure smooth collaboration between employees and the test vehicles.
Employee Engagement and Support	Emphasizing that the introduction of autonomous vehicles is not about job reduction but rather about relieving employees of certain tasks and making their roles more engaging. Providing support to employees during the transition period and beyond is crucial. This can be achieved by offering training, ensuring clear communication channels, and actively involving employees in the testing and evaluation process.
Humanizing the System	Humanizing the autonomous vehicle system can help create a sense of familiarity and trust among employees. Giving names to the vehicles or using other human-like characteristics can make the system more

	relatable and reduce potential resistance or fear of automation.
Familiarization and Testing	Allowing employees sufficient time to familiarize themselves with the test vehicles in real traffic situations is vital. Providing a few days of adjustment and training helps build confidence and ensures employees understand the capabilities and limitations of the vehicles. Actively involving employees in testing, particularly in areas such as the braking function, enables them to have first-hand experience and contribute to the evaluation process. Dangerous situations during the operations of the vehicles should be used as examples to actively explain critical functionality and weaknesses of the system to the staff. A statistical analysis of the operations, including dangerous situations, can help reduce irrational fears.
Change Agents	Act as a bridge of knowledge and support for employees, answering questions, addressing concerns, and facilitating a smooth transition.
Works Council	Coordination and active communication with the works council is key for acceptance and successful change management through Change Agents. The very present fear of losing jobs due to automation can be addressed and discussed rationally through the council representatives.

In addition to the categories evolving from the analysis, a few key points said by the interviewees are worth mentioning here:

"The topic of 'humanizing the system' is very important to me. This is a central change management topic. It requires a team of people which get to grips with the system and carry the findings into the organization. These change agents have to make sure that the others follow suit." (IW#2)

"Operations really need long for implementing changes. There's a lot of resistance to change things. For cargo, it's actually even worse. Because stakeholders in cargo have even more limited resources than airlines, and there's not much time, not much money to invest in change." (IW#3 on the resistance to change and potential limitations to overcome)

4.2.2. LIFEWARE-SOFTWARE

Table 7. Results Expert Interviews - LIFEWARE-SOFTWARE

LIFEWARE-SOFTWARE	
Category	**Description**
Feasibility Testing and Demonstrations	These activities assess the vehicle's capabilities, performance, and compatibility with existing airport systems. By conducting rigorous testing, potential issues or limitations can be identified and addressed, ensuring a smooth integration process.
Integration into Existing Processes and Procedures	Thorough analysis of how the vehicle fits into the existing infrastructure, workflows, and regulations. Evaluating the impact on operations, safety protocols, and communication channels is necessary to ensure a seamless transition without disruptions.
Change Management	Strategies and approaches needed to manage and facilitate the transition. By understanding the concerns and resistance to change, appropriate change management techniques can be applied to ensure employee buy-in and smooth adoption of the new technology.
Safety Driver as a Link	Link between the test vehicle and employees. Examination of the role of the safety driver in overseeing and monitoring the vehicle's operations. The analysis includes identifying the necessary qualifications, responsibilities, and training required for safety drivers to ensure safe and efficient testing.
Safety Procedures	Many links and handovers are due to safety procedures and regulations, i.e. security checks between apron and restricted cargo areas. Both all vehicles and all humans are subject to inspection every time when entering the apron. An autonomous vehicle, however, could potentially register any kind of manipulation automatically (comparable to modern cars) and pass through checkpoints without stops, thereby reducing the total amount of vehicles and the total transport times.
Insurance	In terms of insurance, specific cover for Aviation-specific damage is crucial. This includes, amongst others, damaging aircrafts and ground support equipment (GSE) as well as injuries and death potentially caused by the vehicles. Additionally, liability insurance cover must

	be higher than most general policies (in Germany, a total of 100 million Euro must be covered according to the German Ground Handling Service Regulation ("BADV")).
Control Centre	Role of the Control Centre as a central hub connecting the test vehicle's software with other airport systems. Exploring how the Control Centre optimises operations by coordinating and managing the vehicle's activities in alignment with other stakeholders and systems. It highlights the importance of seamless communication and integration for efficient operations.
Regulatory Hurdles and Stakeholder Communication	Understanding and navigating the regulatory landscape to ensure compliance and obtain necessary approvals. Additionally, effective communication with stakeholders, including airport authorities, airlines, and ground personnel, is essential to address concerns, gain support, and foster collaboration.
Training and Skill Development	Exploring the training programs required to familiarize employees with the test vehicle and its functionalities. It also considers the integration of digital offerings as complementary tools to enhance training effectiveness and knowledge transfer.

"The fundamental insight from this test was feasibility: It is feasible to map the process with an autonomous test vehicle, albeit the limitations. We are much closer [to successful implementations] as we were 10 years ago. It is becoming more and more realistic to use such systems at airports." (IW#2)

"I assume that the right autonomous vehicles will be available for every package size and for every load carrier in the future. In the best-case scenario, our IT system reports that, for example, a certain pallet size weighing 6 tons needs to be transported from point A to point B, with an order being automatically created for the matching autonomous vehicle." (IW#1)

"With regards to autonomous project at airside, it turned out that airlines are very concerned, or actually their insurance companies are concerned on incidents because it's not very clear at the moment who is responsible when an autonomous vehicle bumps into whatever." (IW#3 on the regulatory constraints/unclarities that stakeholders involved are facing)

4.2.3. LIFEWARE-HARDWARE

Table 8. Results Expert Interviews - LIFEWARE-HARDWARE

LIFEWARE-HARDWARE	
Category	**Description**
System Reliability	Reliability of the autonomous vehicle system. It encompasses the overall performance and dependability of the system in carrying out its intended functions.
Functions	- Override Capability: presence of a stop button and the ability to override the autonomous system. It involves the ability for a human operator or user to take control of the vehicle if necessary. - Speed: importance of speed in the given mixed traffic environment. It focuses on the need for the autonomous vehicle to be perceived as neither an obstacle nor a danger by other road users. - Brake Function: emphasizing the importance of a brake function that operates even outside of the human field of vision. It ensures that the vehicle can detect and respond to potential hazards or obstacles.
Equipment & Features	Equipment and features of the autonomous vehicle that contribute to its visibility and communication with other road users. It encompasses items such as a flashing light, stickers, and audible warning signals.
Connectivity	The need for an LTE connection and a nearby cellular tower for the autonomous vehicle's communication and data transfer needs. These categories capture the main aspects mentioned in the provided information.

“In one situation, a person unexpectedly came into the field of vision, and therefore also into the sensor field. The braking was tight, admittedly. But the test vehicle braked, extremely hard, which was not necessarily pleasant for me as a safety driver. But it did brake, and we were all very surprised.” (IW#2 on their experiences in a safety critical situation)

4.2.4. LIFEWARE-ENVIRONMENT

Table 9. Results Expert Interviews - LIFEWARE-ENVIRONMENT

LIFEWARE-ENVIRONMENT	
Category	**Description**
Infrastructure	Seamless integration of the autonomous vehicle into the existing infrastructure of the environment. Limit infrastructure adaptions necessary for testing & demonstration
Apron	Complex intersection situations, reverse driving, push-back, taxiways, and other aircraft/airport-specific situations
Warehouse	Intersections to the warehouse, transfer points, handover areas
Control Centre	Working environment designed for the dispatchers planning the ramp operation Including the deployment of the autonomous vehicle

"Another advantage was that this system basically does not require any infrastructure adjustments or new infrastructure. (...) We were able to integrate the vehicle into our charging infrastructure; we could park it in the parking lots just like our other vehicles. It seamlessly fit into the existing workflows almost everywhere. It looked different, but it was harmonious." (IW#2 on the infrastructure requirements for AGVs)

4.3. APPLIED SHELL MODEL

The adapted SHELL model visualisation (see Figure 9) incorporates the categories derived from the initial two research steps and provides a comprehensive visualisation of the key components that need to be considered. By utilizing this model, researchers and practitioners can identify research fields and plan and execute informed demonstrations of autonomous vehicles.

The adapted SHELL model serves as a valuable resource for researchers, guiding their investigations into specific areas of interest and contributing to the growing knowledge on the implementation and impact of autonomous vehicles in airport operations. Practitioners can also benefit from this model, using it to inform their decision-making processes and assess the potential implications, challenges, and opportunities associated with introducing autonomous vehicles on the airport ramp.

Furthermore, the discussion chapter of this study presents further implications resulting from the application of the SHELL model. It offers insightful recommendations for both researchers and practitioners, highlighting areas for further exploration and considerations in the demonstration of autonomous vehicles.

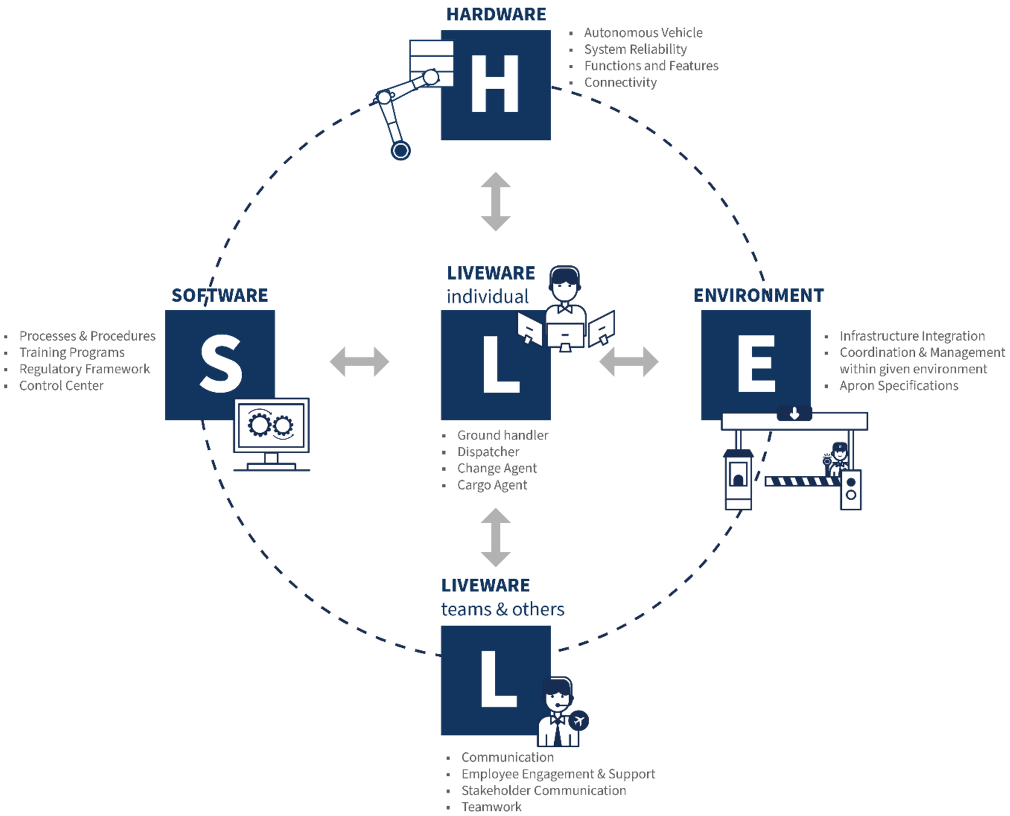


Figure 9. Applied SHELL Model

5. DISCUSSION

The results of this study indicate that in the context of the relationship of humans (LIFEWARE) with SOFTWARE and HARDWARE, as well as of humans with the ENVIRONMENT, the topic of New Work becomes prominent. People are increasingly working in control stations, where they are responsible for error management and fleet monitoring. However, in certain individual processes, such as operating dolly brakes, people still need to perform manual work. Similar considerations arise in the relationship between LIFEWARE and ENVIRONMENT.

Initially, autonomous test vehicles may be seen as foreign elements in a well-functioning system of manual handling and transportation. The interactions involved in their introduction represent a sensitive and critical aspect for the successful implementation of such systems.

An important question that arises is how the infrastructure can be designed to facilitate the safe and efficient collaboration between humans and autonomous vehicles. This calls for a holistic safety concept that considers the unique requirements of both parties.

The infrastructure should be designed in a way that allows for clear separation of responsibilities and tasks. This includes defining specific areas where humans and AGVs can operate and ensuring proper signage and markings to guide their movements. Clear communication channels should be established to facilitate effective coordination and information exchange between humans and AGVs.

Safety measures such as sensors, cameras, and warning systems should be implemented to detect potential hazards and prevent accidents (Boehning, 2014). Additionally, training programs should be developed to educate both humans and AGV operators about the safe practices and protocols to follow when working together. Furthermore, the infrastructure should be flexible and adaptable to accommodate the changing needs and advancements in technology. This may involve integrating smart technologies and automation systems that can enhance the overall safety and efficiency of operations.

The application of the SHELL model highlights the emergence of new relevant work forms for airport personnel in relation to autonomous test vehicles. This includes tasks such as operating the test vehicles, monitoring them from a control centre, managing orders, considering the ongoing non-autonomous operations, and intervening in case of errors. These personnel also act as a bridge to the existing workforce, serving as competent and approachable contacts and playing a crucial role in the change management approach.

6. CONCLUSIONS

This analysis shed light on the impact of autonomous vehicles on the human-machine interface, including factors such as workload, communication, decision-making, and training requirements. It also provided insights into the implications for ground operations staff, including changes in job roles, skills, and overall work processes.

By applying the shell model on a sample process, we defined 19 categories to structure the focus interactions between LIFEWARE, SOFTWARE, HARDWARE and ENVIRONMENT. These categories serve as a first structured approach to assess human factors in the context of autonomous cargo vehicles at airports.

Regarding Q1 (see Chapter 3), we see a particular need to transfer more detailed change management theory and to connect it with the findings from our interviews. It seems valuable to explore the role of change agents in air cargo organisations more and to design generic training programs for the operative staff at airports. Thus, human factors can be enhanced while supporting safe and efficient operations.

Approaching Q2, we suggest a deep dive into the design of autonomous cargo vehicles and robots. The human-machine interface shall reduce fear and allow for seamless integration into mixed environments. Researchers and practitioners can explore haptic, visual and acoustic features, especially comparing autonomous and non-autonomous systems.

With regard to Q3, it seems necessary to focus on complex, aviation-related traffic situations which don't occur in other industries and, therefore, have not been fully addressed in the air cargo context yet. This includes, for example, the crossing of taxiways, manoeuvring at or near aircraft positions including push-back processes, the passing of checkpoints and the handover points between stakeholders. Quantitative analyses could hereby lead to a deeper understanding of the specific challenges. For example, process times, safety protocols and process quality KPI's could be offset for both autonomous and traditional transport and handling.

Lastly, Q4 could be further investigated by classifying the new roles and tasks of human workforce, as remote monitoring and error management are likely to become more important tasks than operating vehicles. Thereby, it seems essential to also explore the interaction between the new (remote) autonomous vehicle controllers and other traffic coordinators at airports. For example, the (future) interaction between air traffic controllers and autonomous vehicle controllers could be key to harmonise aircraft and autonomous ground vehicle traffic.

However, future research is necessary to address limitations and explore further implications in this field. In the discussion part, we point out several implications for both researchers and practitioners. The application of the SHELL model has proven valuable as an initial method for this new research field. More complex models from the human factor theory can now be applied for more detailed insights and suggestions.

6.1. IMPLICATIONS FOR FURTHER RESEARCH

Future research should focus on key implications for integrating autonomous vehicles on airport ramps to enhance understanding and inform decision-making. Further research is needed to explore the role of human factors in interacting with autonomous vehicles, including behaviour, decision-making, trust, and potential for error.

Strategies to enhance collaboration and communication between humans and autonomous vehicles should be explored, with a focus on training programs and skill development to increase efficiency. Identifying competencies, evaluating training methods, and assessing impact on job performance and satisfaction are important. Additionally, research should consider the social and ethical implications of autonomous vehicles, including public perceptions, data privacy concerns, and ethical considerations related to decision-making and job displacement.

Research should also delve into process optimization by evaluating how autonomous vehicle integration can optimize ramp processes such as dispatch, fuelling, and maintenance. This includes analysing efficiency, resource allocation, and overall workflow optimization. Case studies can provide insights into the potential of process optimization with autonomous vehicles (Fusic et al., 2019). Stakeholder acceptance and new vehicle concepts like autonomous ULD movers and robotic swarms should be investigated (Pigeon et al., 2021; Kugler et al., 2021).

Evaluating the economic viability and cost-effectiveness of integrating autonomous vehicles on airport ramps is another important area for research. Assessing return on investment, potential cost savings, and financial implications for airport operations will provide valuable insights.

Lastly, it is crucial to assess the long-term impact of integrating autonomous vehicles. Research should evaluate effectiveness, efficiency, and safety over extended periods, identifying unforeseen challenges and benefits. The 4-phase model introduced in chapter 2 can help structure research outcomes and transfer knowledge from other application fields (see, for example, Eberlein et al., 2018; Fragapane et al., 2022; D'Andrea & Wurman, 2008). By addressing these research areas, we can deepen our understanding of integrating autonomous vehicles on airport ramps and optimize operations in collaboration with human factors.

6.2. IMPLICATIONS FOR PRACTITIONERS

The introduction of autonomous vehicles on an airport ramp brings significant changes for practitioners. They must adapt to these changes by understanding the purpose, scope, and requirements of autonomous tests and demonstrations. The integration of autonomous vehicles affects daily work routines, tasks, and overall workflow (Bierwirth et al., 2021). Practitioners are recommended to assess how to collaborate and communicate effectively with these vehicles. They should also evaluate the potential impact on job roles, skill requirements, and operations such as equipment dispatch and maintenance. Recognizing the benefits of autonomy, practitioners can increase efficiency, effectiveness, and safety. (Carosio et al., 2019) Establishing clear roles and responsibilities, developing an emergency plan, and implementing cybersecurity measures are crucial for successful integration. (Reithner et al., 2021) By considering these factors, practitioners can navigate the integration and ensure safe and efficient ramp operations.

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Additionally, the research on human factors in airport ground handling is part of research conducted for a doctoral dissertation at the University of West London.

APPENDICES

Appendix 1: List of publicly known autonomous cargo vehicle tests

Table 1: List of publicly known cases of autonomous cargo vehicles at airports worldwide in chronological order (as per December 2023)

Year*	Airport	Manufacturer	System**	User	Status	Source
2024	Amsterdam (NL)	Lödige	Unknown	dnata	Planned	Link
2023	East Mid-lands (GB)	Aurrigo	Auto-Cargo	UPS	Planned	Link
2023	Frankfurt (DE)	Charlatte Autonom	Autonom Tract AT135	Fraport AG	Test completed	Link
2023	Munich (DE)	Fraunhofer IML	evoBOT	Cargogate Munich Airport GmbH	Test completed	Link
2023	Barcelona (ES)	Linde	R-Matic	Worldwide Flight Services (WFS)	Test ongoing	Link
2023	Barcelona (ES)	MOVVO	Unknown	Worldwide Flight Services (WFS) and Aena	Test completed	Link
2023	Kansai (JP)	EasyMile	TractEasy	Unknown	Test completed	Link
2022	Frankfurt (DE)	Lödige Industries	5 ft FTS / 10 ft FTS	Swissport	Test ongoing	Link
2022	Dubai (AE)	AeroVect	Driver	dnata	Test ongoing	Link
2022	San Francisco (US)	AeroVect	Driver	GAT	Test completed	Link
2022	Zhengzhou (CN)	Jaten	unmanned forklift system	Unknown	Implemen-ted	Link
2022	Singapore (SG)	Aurrigo	Auto-Dolly baggage vehicle	Changi Airport Group	Test ongoing	Link
2022	Singapore (SG)	Aurrigo	Auto-Dolly Tug	Changi Airport Group	Test ongoing	Link
2022	Guangzhou (CN)	UISEE	Unknown	Baiyun Airport	Unknown	Link
2022	Linz (AT)	REFORM	Metron RC48	Linz Airport, DHL	Test completed	Link
2021	Cincinatti (US)	ThorDrive	Autonomous Driving System	Unknown	Test completed	Link
2021	Paris (FR)	OROK	Demokart	ADP Group (Air France-	Test completed	Link

				KLM Martinair Cargo)		
2021	Amsterdam (NL)	EasyMile	TractEasy	Royal Schiphol Group	Test completed	Link
2021	Stuttgart (DE)	Volk Fahrzeugbau GmbH	SmartFleet-Schlepper	Flughafen Stuttgart GmbH	Test completed	Link
2021	Tokyo (JP)	Toyota Industries	Unknown	All Nippon Airways	Test completed	Link
2020	Chubu (JP)	Toyota Industries	Unknown	All Nippon Airways	Test completed	Link
2020	Singapore (SG)	EasyMile	TractEasy	Changi Airport Group	Implemented	Link
2019	Frankfurt (DE)	KAMAG	Smart Air Cargo Trailer	Fraport AG	Test completed	Link
2019	London (GB)	Aurrigo	Auto Dolly	British Airways	Test completed	Link
2019	Tokyo (JP)	EasyMile	TractEasy	Japan Airlines and Narita International Airport Corporation	Test completed	Link
2019	Tokyo (JP)	ZMP Inc.	Unknown	Narita International Airport Corporation	Test completed	Link
2019	Saga (JP)	Toyota Industries	Unknown	All Nippon Airways	Test completed	Link
2018	Hong Kong (HK)	Teksbotics	Autonomous Electric Tractor (AET)	Airport Authority Hong Kong	Implemented	Link
2018	London (GB)	Gaussin	AAT (Autonomous Airport Transporter)	Siemens Postal, Parcel & Airport Logistics	Test completed	Link
2017	Singapore (SG)	Unknown	Unknown	Changi Airport Group	Test completed	Link
2017	Munich (DE)	Dimos	INTRAC	Unknown	Test completed	Link
1996	Paris (FR)	Alstef Group	CM – Powered conveyor	Air France Cargo	Implemen-ted	Link

*Year of first test at that airport with that manufacturer. If unknown, the earliest year of publication of articles mentioning this particular case is stated.
** We did not consider luggage robots, people mover, service robots, and other vehicles used for specific aviation-related tasks, just air cargo handling and transportation systems.

Appendix 2: Interview Guide

Interview Guide

Interviewee:

Interviewers:

Type: Semi-structured expert interview

Date and time:

Channel:

Part I – Introduction

This interview aims at assessing the implications of autonomous cargo vehicle demonstrations on airport staff. It is part of the second stage of our three-stage approach, in which we want to complement the findings from the first stage with hands-on experience from experts in the field.

The following questions suggest a guideline for the semi-structured interview. They can, but do not have to be followed in this particular order. Certain questions might be skipped or replaced by other questions, for example in case the discussion drifts towards another specific relevant topic.

Part I includes general questions about the interviewee and the organization with regard to the interview topic.

1. Could you please specify your job title and responsibilities?
2. How innovation-friendly would you say your organization and its staff is in general?
3. At a high level, which experience have you gained so far regarding demonstrations of autonomous cargo vehicles at airports?
4. Please specify the scope and the outcomes of these demonstrations.

Part II – Challenges for demonstrations

Part II includes specific questions regarding challenges the interviewee and the organization was faced with before or during the demonstration of autonomous cargo vehicles.

5. Which were the main challenges you were faced with after the decision for the demonstration was made (before it started)?
6. Which departments, units, or responsible managers where particularly skeptical or critical, and why?
7. If applicable, what did it take to convince them to support the project?
8. If applicable, which documents needed to be created and by whom, in order to get the demonstrations running?

9. If applicable, which exemptions had to be made and why?
10. Which were the main challenges you were faced with after the start of the demonstration; how did you deal with them?

Part III – Human factors

Part III includes specific questions regarding the application of the SHELL model and the examination of human-related factors.

11. GENERAL: How were human-related factors taken into consideration during the development and testing of the autonomous driving system?
12. GENERAL: What were the main features and limitations of the test vehicle(s) used in the autonomous driving testbed?
13. SOFTWARE: Could you elaborate on the links and data exchange between the test system and the existing airport IT systems during the demonstration?
14. SOFTWARE: Which manuals or training materials had to be adjusted to enable the demonstration?
15. HARDWARE: In what ways were other hardware, such as aircraft or other Ground Support Equipment (GSE), integrated into the testbed for autonomous driving at the airport?
16. ENVIRONMENT: Can you describe the modifications that were made to the existing infrastructure in order to accommodate the autonomous driving demonstration?
17. LIFEWARE: How did the autonomous vehicle(s) interact with the human workforce along the process chain during the demonstration?
18. GENERAL: What considerations were taken into account to ensure a safe and efficient interaction between autonomous vehicles and human workers at the airport?

Part IV – Other relevant aspects

Part IV aims at gathering more information about other aspects, which have not been covered in parts I – III. By asking questions from different perspectives, additional details are expected to be mentioned by the interviewee.

19. Where there any surprises (so far) in the way the staff dealt with the project and/or the technology? If so, please specify the surprises.
20. Where there any particular scenarios (so far) which humans would have handled much better or worse than the test vehicle? If so, please specify these scenarios.
21. Is there anything else you find worth noting on human-related factors when it comes to the demonstration of autonomous cargo vehicles?

AUTHORS' BIO

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