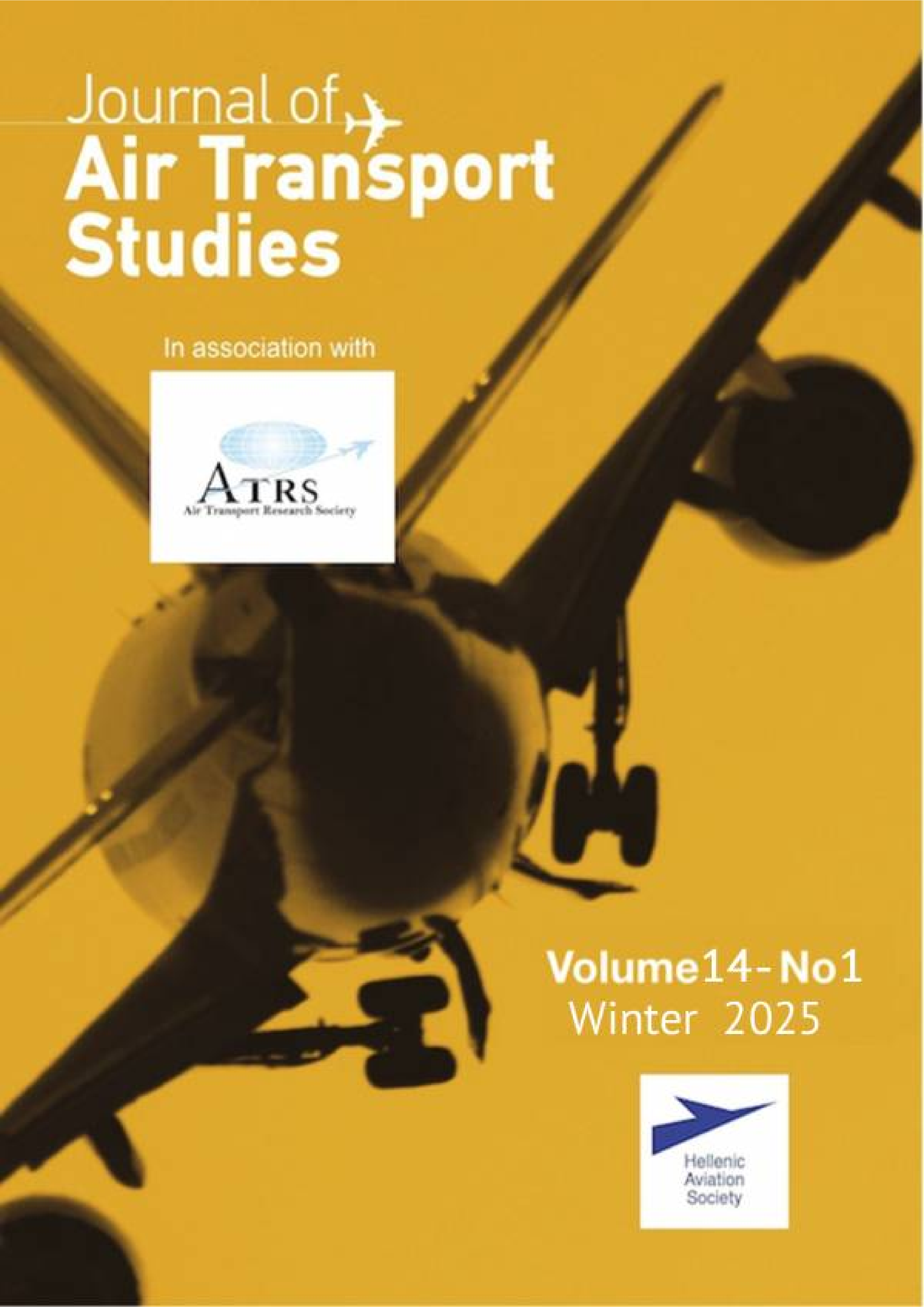

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# TESTING AUTONOMOUS CARGO VEHICLES AT AIRPORTS – AN ANALYSIS OF THE BASIC REQUIREMENTS FOCUSING ON STAFF-RELATED HUMAN FACTORS

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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).

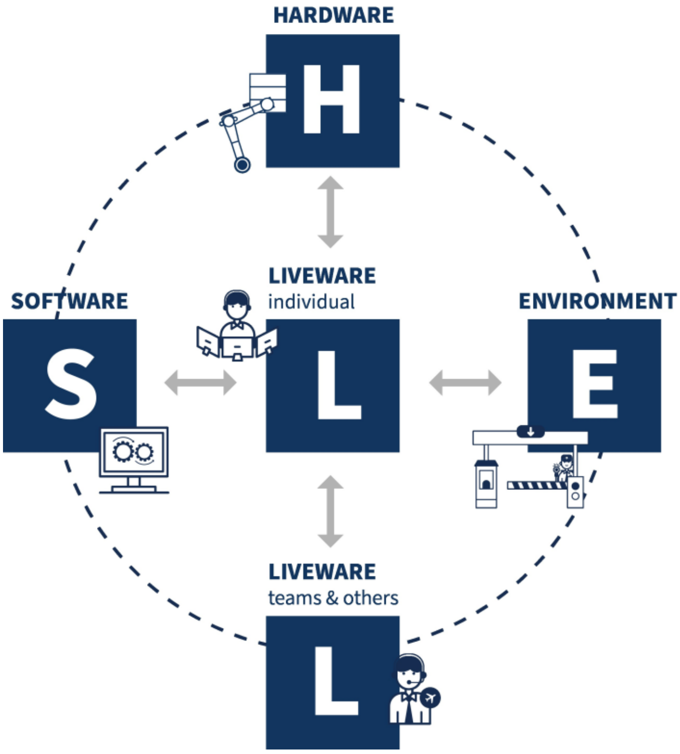



Figure 2. The SHELL model based on ICAO (2018)

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.

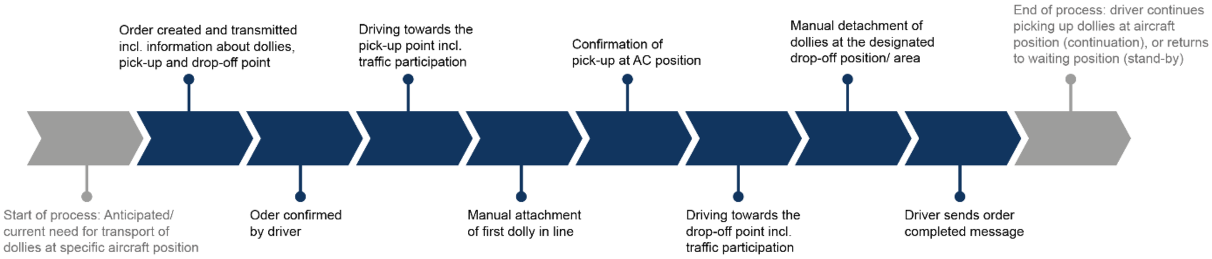



Figure 4. Simplified representation of the current manual process

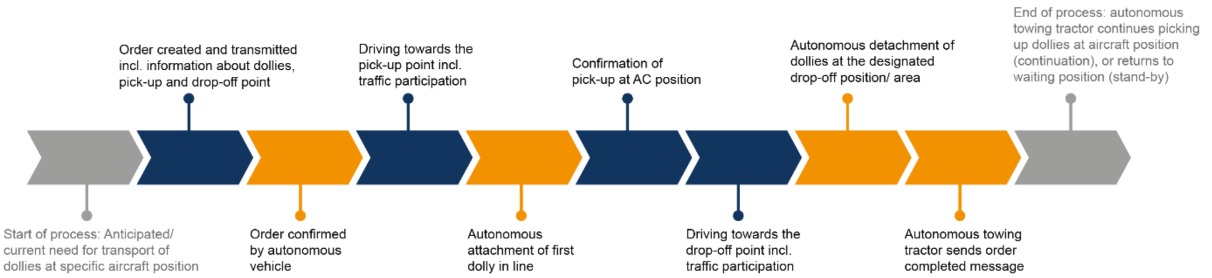



Figure 5. Simplified version of the process utilizing an autonomous towing tractor instead of manual handling

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.

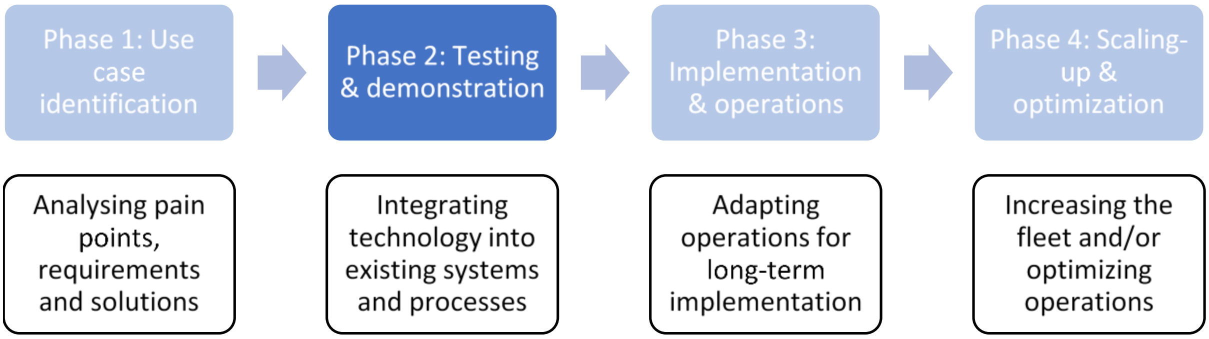



Figure 6. Testing and demonstration phase in the context of a 4-phase approach towards the implementation of autonomous air cargo vehicles at airports

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.

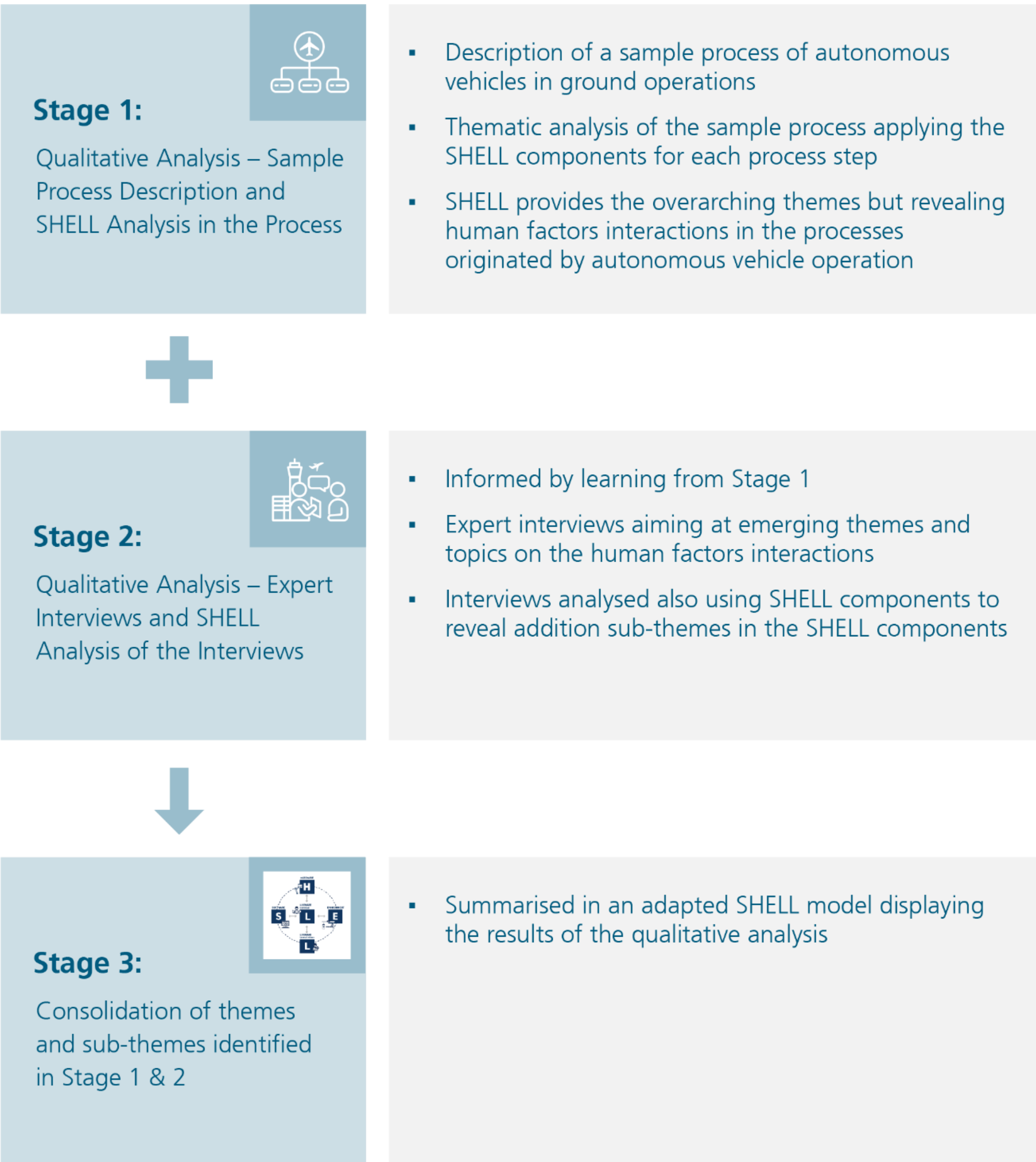


Figure 7. Three staged qualitative methodological approach

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.

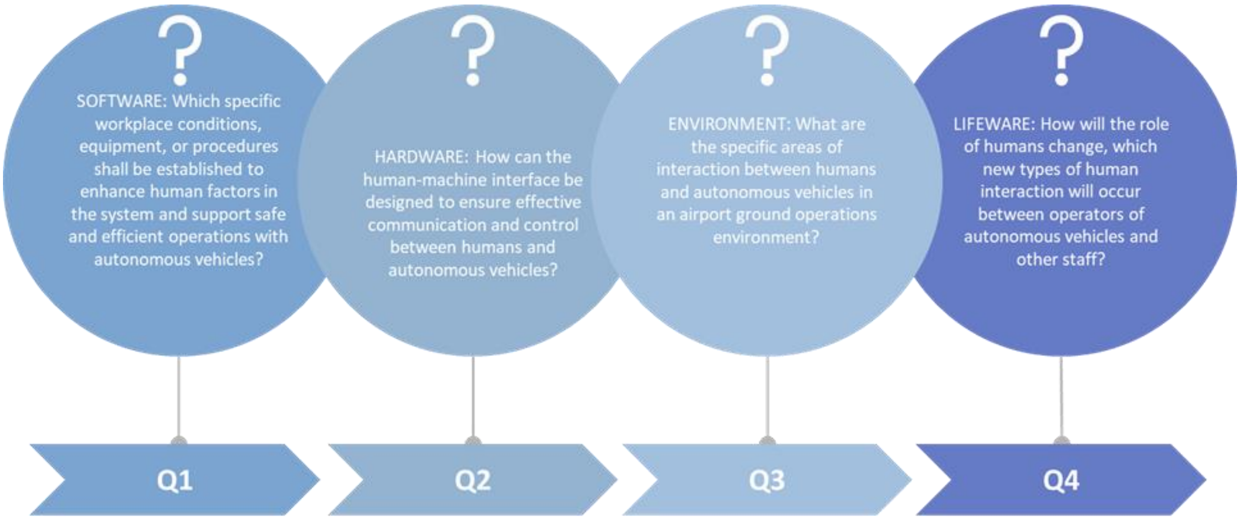


Figure 8. SHELL model assessment in the research approach

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

Table 2. Exemplary process analysis – Process Step 2

**Process Analysis**
**Process Step #2:**


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

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

Table 3. Exemplary process analysis – Process Step 3

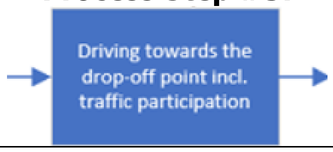
| **Process Analysis**<br>**Process Step #3:**<br> | | |
|---|---|---|
| **SHELL** | **Physical / Digital / Link** | **Categories** |
| Lifeware-Lifeware | X | X |
| Lifeware-Software | X | X |
| Lifeware-Hardware | - Dealing with human driving behaviour<br>- Dealing with speeding and/or dangerous situations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

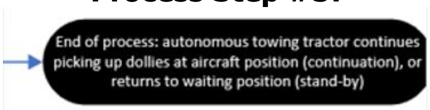
Table 4. Exemplary process analysis – Process Step 4

**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<br>- AGV sensors recognize designated position<br>- Unlinking vehicle and first dolly<br>- If applicable, secure dolly (human assistance might be necessary)<br>- Autonomous identification of designated drop-off point | - AGV operations<br>- AGV sensors and recognition<br>- Dolly handling |
| Lifeware-Environment | - Manoeuvring near the drop-off point / at the warehouse (pedestrians, also other vehicles, obstacles, restricted areas)<br>- 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 |

**Note:** 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.<br>- 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.<br>- 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.

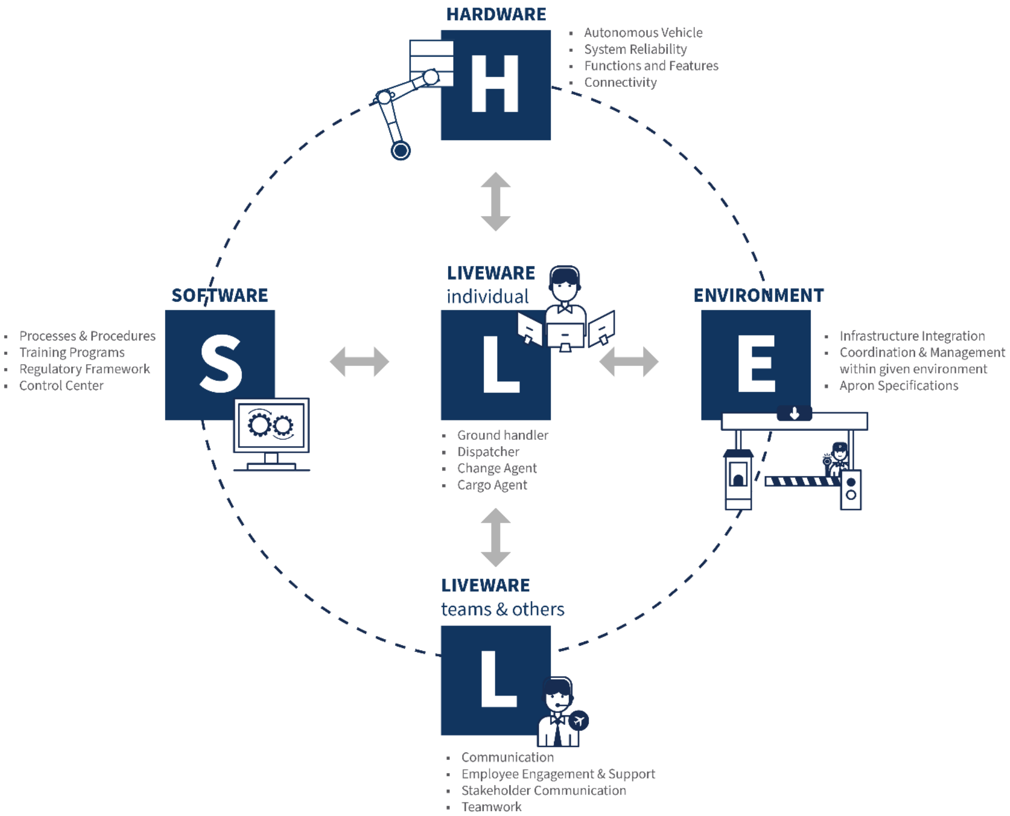



Figure 9. Applied SHELL Model

## 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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**Manuel Wehner** is project Manager at Fraunhofer IML and specialises in the automation of air cargo ground operations. He co-founded the Institute for Aviation & Tourism (IAT) at Frankfurt University of Applied Sciences and coordinated autonomous vehicle tests for Fraport AG. Wehner studied Management & Technology (M.Sc.) in Munich/Querétaro and Aviation Management (B.A.) in Frankfurt/Riyadh.

# EXAMINING THE EFFECTS OF MARKET CONCENTRATION ON DEPARTURE AND ARRIVAL ON-TIME PERFORMANCE AT LARGE AIRPORTS

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**ABSTRACT**

This study explores the relationship between market concentration and on-time performance at major airports. It investigates whether higher market concentration levels are associated with improved or worsened flight punctuality. The research is based on extensive data from various airlines operating at these airports and provides valuable insights for airport operators, airlines, and policymakers. The findings indicate that variation in market concentration significantly impacts on-time performance. On-time performance decreases to approximately 0.6 to 0.7 in markets with heightened concentration and reduced competition. However, moderately concentrated markets demonstrate higher competition and relatively high on-time performance. These results provide policymakers with opportunities to enhance overall system performance through strategic interventions.

**KEYWORDS**

departure on-time performance; arrival on-time performance; market concentration; large airports; Herfindahl Hirschman index; market dominance

## 1. INTRODUCTION

The airline industry allows global connectivity and the movement of people and goods over long distances and is an essential component of modern transportation. Despite advancements in technology and infrastructure, the industry concerns about the industry's efficiency and reliability remain, particularly in terms of departure and arrival punctuality. Delays and disruptions inconvenience passengers, have significant economic implications for airlines, and have broader implications for the aviation ecosystem (Suzuki, 2000).

Timely departures and arrivals are critical for airlines to maintain operational efficiency, ensure passenger happiness, and reduce costs (Suzuki, 2000). A delay in the intended departure time can cause a chain reaction of delays and disturbances across the network (N. Kafle, 2016), resulting in missed connections, greater fuel consumption, and decreased aircraft utilization. On the other hand, delays in arrival might have a domino effect, influencing subsequent flights and passenger schedules.

Furthermore, delays and cancellations can result in financial penalties, compensation claims, and reputational harm to the airline. As the world's largest domestic market, the US costs 30 billion USD annually due to delays, which is a considerable burden for stakeholders (Ball Michael, 2010).

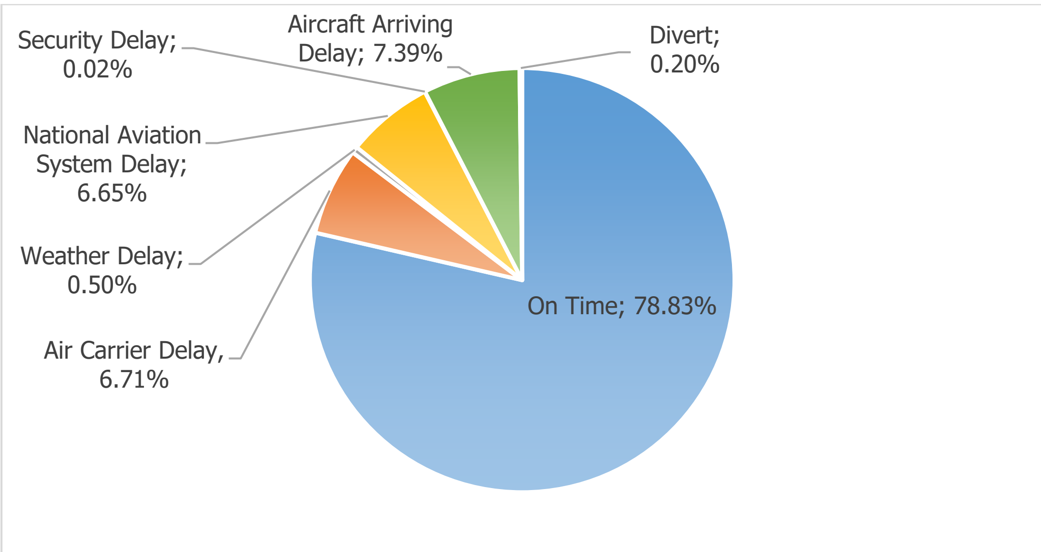


Figure 1: On-time performance during April 2017

Data from the FAA (Federal Aviation Association) provide six main reasons for flights' on-time performance. The delay can occur due to air carriers, weather, the national aviation system, security delays, aircraft arrival delays, and diverts. As per FAA data, air carrier delays, national aviation system delays, and aircraft arrival delays were significant among these reasons (Figure 1). From the mentioned causes, the study focuses on areas that air carriers can control.

The air carrier delay can be grouped into several subcategories. Examples of occurrences that may determine carrier delay are aircraft cleaning, aircraft damage, awaiting the arrival of connecting passengers or crew, baggage, bird strike, cargo loading, catering, computer, outage-carrier equipment, crew legality (pilot or attendant rest), damage by hazardous goods, engineering inspection, fueling, handling disabled passengers, late crew, lavatory servicing, maintenance, over sales, potable water servicing, removal of unruly passengers, slow boarding or seating, stowing carry-on baggage, and weight and balance delays (FAA, 2020).

Many reasons can explain carrier delays. The present study attempts to determine how market concentration affects departure and arrival delays because the impact of airline market concentration on on-time performance has received less attention. The degree of dominance exercised by a few airlines or carriers within a specific market or geographical area is referred to as market concentration. In a highly concentrated market, a small number of firms dominate a sizable percentage (Mark Hansen, 2015), potentially resulting in less competition and weakened incentives for operational efficiency.

Recognizing the connection between market concentration and departure and arrival on-time performance is critical for various reasons. For starters, it illuminates the dynamics of the airline business, providing insights into the competitive landscape and the possible impact on operational efficiency. Second, it assists airlines and industry stakeholders in identifying and addressing any adverse effects of market concentration, such as poorer service quality or higher prices. Third, it provides essential information to policymakers to establish and implement appropriate regulations and policies that foster competition and improve operational efficiency.

This research paper intends to contribute to the current literature and fill gaps in our understanding of this relationship by thoroughly examining the impact of market concentration on departure and arrival on-time performance at large airports. The study findings can help airlines, passengers, and policymakers establish strategies and policies to increase timeliness, improve the passenger experience, and foster healthy competition in the airline business. The market concentration is a hidden force capable of reshaping the market itself. Researchers in this study aim to see how the market concentration affects the overall on-time performance of flight operations.

In summary, the background and significance of this research can be found in recognizing the importance of departure and arrival punctuality in the airline industry, the potential impact of market concentration on operational efficiency, and the need for scientific evidence to inform decision-making and policy development. This study seeks to provide significant insights into the consequences of market structure on the functioning of large airports and the broader aviation ecosystem by investigating the relationship between market concentration and on-time performance. This study intends to cover four objectives:

1. To calculate the market share for each operation day, operating between large airports.
2. To calculate market concentration by using the first objective's results.
3. To identify separate market segments inside short-haul OD pairs.
4. To identify how market concentration affects OTP (On-Time Performance) from perfect competition to imperfect competition.

Collectively, these objectives aim to contribute to understanding how this hidden force shapes airline operation performance at large airports while suggesting practical implications for industry stakeholders to mitigate the inefficiencies of overall operations.

This study aims to contribute to the existing literature on airline operations, competition, and market structure by addressing the research problem. It aims to provide empirical evidence and a thorough understanding of the impact of market concentration on departure and arrival on-time performance at large airports. Finally, these study findings can provide valuable insights and inform decision-making processes for airlines, passengers, and policymakers seeking to improve punctuality and overall airline industry performance.

## 2. LITERATURE REVIEW

### 2.1. ON-TIME PERFORMANCE

Customer happiness is essential to the success of a service industry company, such as commercial aviation. However, this industry is sensitive to the external environment; for example, the civil aviation industry faced a massive challenge among other modes of transportation with the immediate impact of COVID-19 (M.Mavin De Silva, 2023). Airlines must maintain a high level of service across all their vehicles to keep their customers happy. The most notable characteristic of the industry is punctuality in performance. The world's largest domestic aviation market incurred approximately $30 billion annually in delay costs (Ball Michael, 2010). This proves that OTP is a critical output of aviation as well as any transport-related industry. In aviation, on-time performance can be a competitive edge of the airline against competitors because travelers choose flights based on their preferred arrival time due to the purpose of the travel (Lu Hao, 2014). Airlines heavily rely on the number of passengers they can carry on their flights regarding revenue, draw in new business, and keep existing clients. They must ensure on-time departure of their flights since delays can lead to lost sales, bad feedback, and a tarnished reputation (Jakub Haijko, 2020).

Airlines must prioritize safety measures in addition to on-time performance to guarantee the trust and loyalty of their customers—regular maintenance inspections, thorough security checks, and knowledgeable staff are all part of this. Airlines can position themselves as dependable and trustworthy options for travelers by prioritizing both on-time performance and safety measures. By putting money into technology like real-time flight tracking systems, airlines can spot potential delays and take proactive measures to fix them before they become major problems (N. Kafle, 2016).

Overall, the aviation sector's success depends on keeping a laser-like focus on both operational effectiveness and customer satisfaction (Chow, 2015). Achieving high OTP results from the success of a highly disruptive process. The risk of losing OTP is significantly high. Therefore, knowing how the particular route will perform under a specific condition is worthwhile, just like a real-time risk assessment system (Vihan Weerapura, 2023).

### 2.1.1. CALCULATING ON-TIME PERFORMANCE

On-time performance calculations are different from a general point of view. The International Civil Aviation Organization (ICAO) has implemented a 15-minute rule as a safety-first operation (ICAO, 2017). This rule explains that a flight will be considered an on-time performance if the flight's actual departure or arrival time is within (±15) minutes of the scheduled time (Cheng-LungWu, 2010).

## 2.2. MARKET CONCENTRATION IN THE AIRLINE INDUSTRY

In any deregulated market, market concentration determines the distribution of negotiation power between consumer and supplier (Doganis, 2010). The supplier and consumer may change based on the situation, but behavior will not change because the power of negotiation decides the behavior. Based on the concentration level, we can label the market structure as a 'perfect competition market' or 'imperfect competition market'. In other terms, oligopoly markets and monopoly markets (Tamotsu Onozaki, 2003). With the deregulation of civil aviation in 1978, the market has behaved the same way as explained above.

### 2.2.1. CALCULATION OF MARKET CONCENTRATION

The Herfindahl-Hirschman Index (HHI) and concentration ratios are the most frequently used metrics by researchers to measure market concentration. The HHI determines market concentration by multiplying the squared market shares of various companies engaged in a market. A higher HHI value indicates greater concentration, implying that a few dominant companies control a sizable portion of the market. The market share held by a predetermined number of top companies is calculated by concentration ratios, which provide a simpler measurement. These quantitative measures of market concentration enable researchers to compare market concentration levels across different markets and historical periods (Ismail, 2017). Based on HHI value, the market can be categorized into three market structures as follows: (Bromberg, 2023)

- Unconcentrated markets: HHI <0.15 (high competition)
- Moderately concentrated markets: HHI between 0.15 ⩽ HHI<0.25 (medium competition)
- Highly concentrated markets: HHI ⩾0.25 (low competition)

$$HHI = \sum_{i=1}^{n} MS(i)^2$$

Equation 1. Herfindahl-Hirschman Index (HHI)

Equation (1) illustrates how to calculate the concentration index, where MS(i) is the market share of the 'i' airline for the OD market. As mentioned above, market concentration levels give us an idea of the market competition level.

## 2.3. THE RELATIONSHIP BETWEEN MARKET CONCENTRATION AND OPERATIONAL PERFORMANCE

Numerous studies revealed that airline schedules were more likely to be padded to account for airborne and surface delays in competitive markets to improve the operation performance or, in other terms, to increase the OTP (Skaltsas, 2011) (Thomas Morisset, 2011). Parallel to this study, another investigation in 2012 identified that an increase in market share in a particular OD market negatively impacts the OTP. They specifically realized that a higher market share leads to the rise of overage and underage cost ratio, thus reducing the likelihood of OTP (Deshpande & Arikan, 2012). These findings perfectly align with (Mazzeo, 2003) that additional competition positively correlates with OTP, which aids the airline in gaining market share, and the authors concluded that a monopolistic market illustrates OTP.

Conversely, some studies argue that competition worsens OTP, and a market with less competition illustrates high OTP (Rupp, Owens, & Plumly, 2006) (rince & Simon, 2014). Based on this literature, a correlation between market share and on-time performance is evident, as discussed in (Cheng-LungWu, 2010). Even though controversial, it is clear that on-time performance impacts airline market share. These controversial results make us doubt the methodologies authors have followed to analyze market concentration data. According to our observations in Equation 1, HHI will not produce linear results, as explained in (Yadav, Acharya, & Acharya, 2021). However, all authors we mentioned in the aviation research field have utilized OLS regression to analyze data. This could be the underlying reason for such controversial results. These results signify that starting with comparison is better. Hence, this study compares the HHI and OTP results to get a clear idea.

We identified another research gap regarding the categories of airports. In previous studies, we could not determine how a researcher can overcome this issue. Therefore, the analyses were performed without physical factors because we think different airport categories will perform differently with the concentration level. Researchers in this study aim to determine how concentration affects when departure and arrival occur only at large airports. We assume that the airport categories at the same level will respond similarly. Since airlines facing competition tend to allocate more resources to ensure timely departures and arrivals to attract and retain customers, as mentioned in this study, we assume that the airports of the same category could provide the same level of service for each airline. Thus, the main objective of this study is to understand the on-time distribution against concentration.

## 3. METHODOLOGY

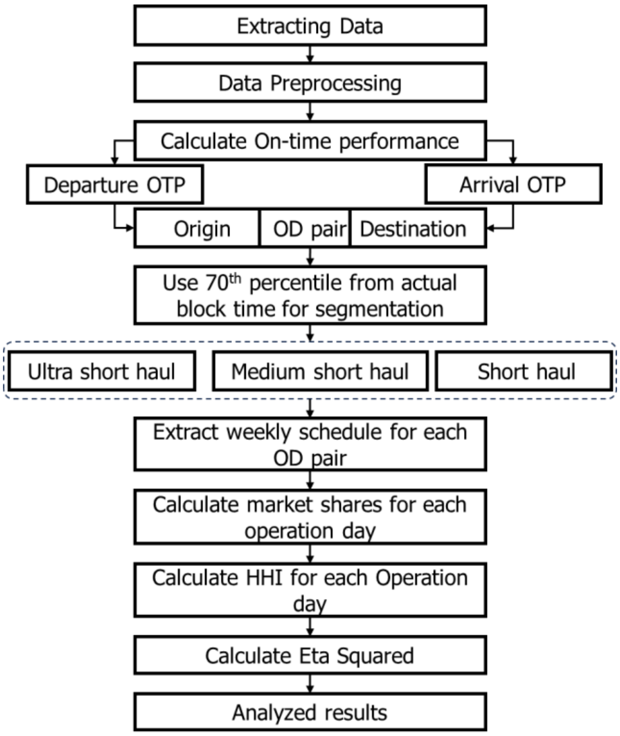


Figure 2. Research Flow

The methodology utilized in this study rigorously investigated the relationship between market concentration and on-time performance in the airline industry, explicitly focusing on departures and arrivals at large airports in the United States. The study sample includes all domestic flights aggregated by all sixty-three large airports in the US during the summer season (from April to September) in 2017. Still, we selected data only from April for the analysis. The study utilized two data sets published by the US Department of Transportation. In this analysis, we analyzed only 460,932 scheduled flight data to conclude. We excluded the non-schedule flights in the raw dataset.

As Figure 2 illustrates, this section outlines the sampling process, Airport category selection, Identification of different markets in the short-haul, Calculation of OTP, Calculation of Market Concentration, and Market Share Calculation. Finally, the study calculates the Eta-squares value between market concentration and on-time performance to observe the influence of market concentration on the on-time performance when the market moves from an oligopoly market to a duopoly market or vice versa.

### 3.1. DATA SOURCES & DESCRIPTION

The study utilized two data sources as primary data sources, published by the US Department of Transportation (DOT). The first data source is the Airline On-Time performance dataset, which contains scheduled and unscheduled domestic flight operational data. The second database provides details about airports.

### 3.2. SAMPLING PROCESS

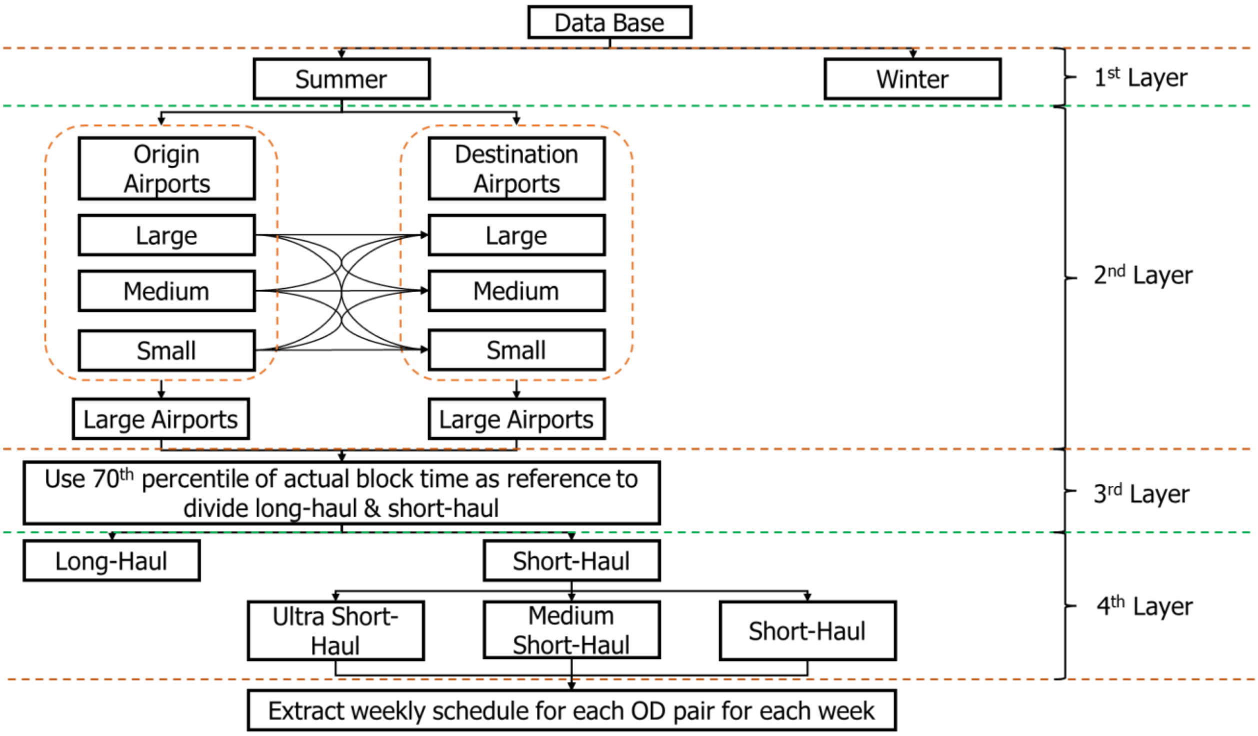


Figure 3. Sampling Process

Many factors impact the on-time performance. The main objective of this study is to identify how market concentration influences an airline's on-time performance. Therefore, we use a detailed sampling method, as presented in Figure 3, to eliminate other factors as much as possible.

The sample selection method is a crucial aspect of studying on-time performance (OTP) and market dynamics in the airline industry due to its high sensitivity to external factors. Studies have adopted various approaches to select airports for analysis, each tailored to their specific research objectives. In our paper, we focused on selecting a sample to ensure consistency and comprehensively analyze the impact of market concentration on OTP. This approach contrasts with and complements the methodologies utilized in other significant studies.

For instance, Mazzo-2003 analyzed data from US domestic flights by major carriers from 1988 to 2000, covering 250 airports and over 66 million flights (Mazzeo, 2003). This extensive data set aimed to capture a broad spectrum of market conditions and their impact on service quality and OTP. Here, the authors did not consider airport size or trip type (long haul, short haul), and the study analyzed data without separating summer and winter while introducing season as a parameter. The Zhang and Zhang-2006 approach selected the 25 most delayed airports in 1999 to identify "airport capacity and congestion when carriers have market power" (Zhang & Zhang, 2006). The approach in this case is somewhat narrowed down, but still, it does not consider the airport size. The traffic management strategy changes with the airport size. Therefore, in this case, the impact of airport traffic management may not be fully captured. Similarly, Vinayak Deshpande (Deshpande & Arikan, 2012) utilized OTP data between 2005 and 2007 without considering seasonal effects and the level of airport size, as previous studies mentioned. Lastly, (Bubalo & Gaggero, 2015) analyzed 3.5 million flights scheduled among 100 European airports with the same issue, without considering the season or the airport level.

Based on the literature mentioned above, (Mazzeo, 2003) found that additional competition positively correlates with OTP, which aids airlines in gaining market share. The authors concluded that a monopolistic market illustrates OTP. The findings of (Deshpande & Arikan, 2012) align with Mazzeo's findings.

On the other hand, some studies argue that competition worsens OTP, and markets with less competition illustrate high OTP (Rupp, Owens, & Plumly, 2006) (rince & Simon, 2014). These literature findings confirm a correlation between market share and on-time performance, as discussed in (Cheng-LungWu, 2010).

An airline has two seasons to publish its schedules (Ionescu, Gwiggner, & Kliewer, 2015). The summer season starts on the last Sunday of March and ends on the last Sunday of October. Winter begins on the last Sunday of October and finishes on the last Sunday of March (IATA). In (Mazzeo, 2003) study, January, April, and July were used for analysis, leading to some controversial results. The study produces unreliable coefficients for weather variables due to this selection. Typically, weather causes a maximum of 2% delay annually. Hence, we decided to control the weather factor while attempting to understand the effect of market concentration on OTP.

The study first selects summer to reduce uncertainties occurring due to weather conditions. Figure 4 shows that April in summer has comparatively average weather effects on on-time performance. Based on this observation, we selected April as the subject month for the analysis. We used a weekly schedule to analyze each operation date scheduled for flights and identified Monday (D1) as the first operation date of the week, and the rest followed the flow.

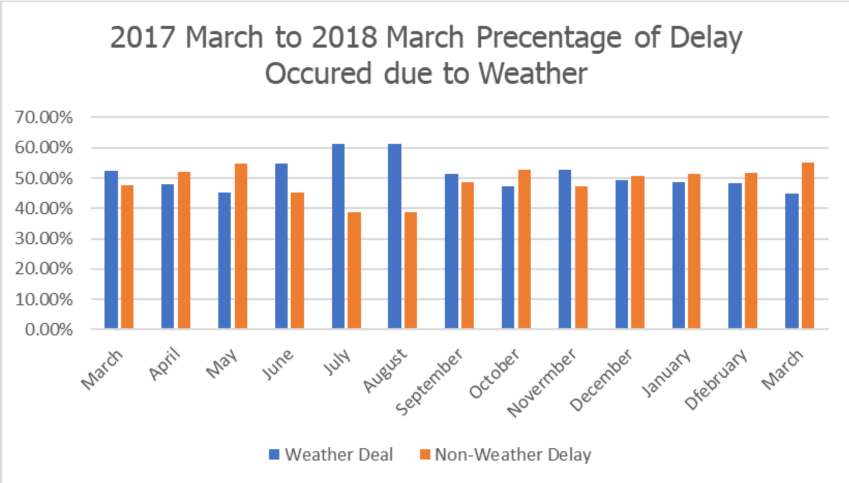


Figure 4. Delay percentage of 2017 March to 2018 March due to weather conditions and non-weather conditions

### 3.3. AIRPORT SELECTION

Table I. FAA Airport Category

| Statutory Definition | Criteria |
|---|---|
| **Large Hub** | Handle one percent or more than one percent of commercial passengers per year |
| **Medium Hub** | Handle 0.25 to 1 percent of commercial passengers per year |
| **Small Hub** | Handle 0.05 to 0.25 percent of commercial passengers per year |
| **Non-Hub** | Handle less than 0.05 percent but more than 10,000 annual commercial passengers |

Selecting airports for this research was challenging. Hence, the study employed the categorizing method developed by the FAA (Federal Aviation Authority) based on annual passenger movement, as shown in Table I (FAA, 2020). The first study ignores the non-hub category among the four airport categories due to the fewer enplanements. When considering the other three categories, the study identified nine Permutations (P(3,1)*P(3,1)) as shown in Figure 3 in the second layer (Hao & Hansen, 2013). The study assumed that the operation strategies of same-size airports are the same.

Based on that assumption, only three combinations were valid for the study, i.e., Large to Large, Medium to Medium, and Small to Small. Considering this study's number of movements and operational complexity, we consider OD pairs, which are Large to Large permutations. Before proceeding with our analysis, we checked whether our assumption matches the Large to Large combination, which has analyzed the 2017 departure OTP distribution. We noted here that the mean of the Dep. OTP is 81.35% with a 3.7% standard deviation, and all large airports maintain over 70% efficiency. With the descriptive value, we could assume that consistency prevails between the operational strategies of all large airports.

### 3.4. IDENTIFICATION OF DIFFERENT MARKETS IN REGULAR SHORT-HAUL

Air transportation has two main trip patterns, as explained in Table II, which explains the characteristics of these two markets (Sebastian Birolini, 2020). Among these two, the study chose the short-haul market for the analysis due to the market diversity. In a further study, a high percentage of airlines utilized narrow-body aircraft such as the Boeing 737 series or Airbus 320 series for short-haul markets due to low operation costs and faster turnaround times. Still, narrow-body aircraft have some weaknesses. The first weakness is the low range and capacity restriction.

Table II. Characteristics of short and long-haul flights

| Criteria | Regular Short-Haul | Long-Haul |
|---|---|---|
| **Aircrafts** | Narrow & Wide Body | Wide Body |
| **Schedule Block Time (SBT)** | 0 Hr < SBT < 6 Hrs | SBT > 6 Hrs |
| **Distance** | Less than 3000 Km | More than 3000 Km |

The study identified that airlines use frequency strategies to overcome narrow body capacity constraints and lower the cost of passenger uplift. Therefore, the study determined that regular short-haul market frequency is a key factor in becoming a dominant competitor in a particular market.

Since this short-haul market shows significant complexity, we divided it into three subcategories in Table III. The objective of this segmentation is to obtain sharp results. The segmentation of the database study occupied the percentile method, commonly used within carriers to set SBT (schedule block time) (Hao & Hansen, 2013). In the subcategorizing method study, we used actual block time (ABT) instead of scheduled block time because of airport slot-related complications. It constantly fluctuates in ABT, so we use the 70th percentile (Hao & Hansen, 2013) of each OD pair for the clustering process (Table III).

Table III. Regular short-haul subcategories

| Short-haul Subcategory | ABT duration | Value of 'a' |
|---|---|---|
| **Ultra Short-haul** | 0<ABT⩽120 | 1.7 |
| **Medium Short-haul** | 120<ABT⩽ 240 | 1.5 |
| **Short-haul** | 240<ABT⩽ 360 | 1.3 |

### 3.5. CALCULATION OF ON-TIME PERFORMANCE (OTP)

$$\text{On\_Time Performance} = \frac{\text{Number of Flights Operate On\_Time}}{\text{Total Number of flights operate}} \text{x}100\%$$

Equation 2. On-time performance calculation

As described, if a flight operates under the fifteen-minute rule (ICAO, 2017), it is considered an on-time flight. Flights operating outside the fifteen boundaries are considered as flights without on-time performance. As shown in Table IV, flight DL23 departure from PNS at 0920 falls into the departure time bulk of 0900–0959 and arrives at ATL at 1130, falling into the arrival time bulk of 1100–1159.

Then, by using Equation 2, we calculate the OTP for flight DL23; for the study, we used that value for all DL23 that depart in the 0900–0959 departure time bulk. As explained, the study utilizes the mentioned method to calculate departure and arrival on-time performance for all OD pairs.

Table IV. Example flight details

| Flight number | Origin | Departure time bulk | Departu re time | Destinati on | Arrival time bulk | Arrival time |
|---|---|---|---|---|---|---|
| **DL23** | PNS | 0900-0959 | 0920 | ATL | 1100-1159 | 1130 |
| **DL43** | SLC | 2200-2259 | 2216 | PSC | 2200-2259 | 2255 |

### 3.6. CALCULATION OF MARKET CONCENTRATION

Market concentration is the "degree to which a limited number of companies control a significant portion of a market" (Press, 2023). This means the function of market share that each company holds in the same market, as illustrated in Equation 1. Calculation may not be possible without knowing the market share of each airline, as illustrated in Figure 2. After extracting the weekly schedule for each week and each OD-pair, we first calculate the market share for each carrier for the selected OD-pair as flowchart concentration can be explained: "the degree to which a limited number of companies control a significant portion of a market" (Press, 2023) which means its function of market share that each company holds in the same market as illustrated in Equation 1. Calculation may not be able to be undertaken without knowing the market share of each airline, as illustrated in Figure 2. After extracting the weekly schedule for each week and each OD-pair, we first calculate the market share for each carrier for the selected OD-pair as follows.

### 3.7. MARKET SHARE

Market shares depend on how much an airline influences its market and makes people willing to pay for its service. The degree of success rate of influence will be reflected in the percentage of market share that airlines gather. Airlines can influence customers based on three factors (Peter Belobaba, 2016), as mentioned below:

- Operating frequency
- Ticket fares relative to competitors
- Quality of the service

Two main models calculate market share based on the factors mentioned above: the first is the frequency share model (S-curve model), and the second is the quality of service index model. Since we consider only short-haul flights in this study, the study employed a frequency share model as shown in, where "MS(i)" is the market share of "ith" airline and "FS" frequencies of the subjected market. "n" is the number of airlines that operate in the subject OD market. "a" is an exponent, which always has more than one. As mentioned in Table III, the study used predetermined values for the exponent based on scheduled block time.

$$MS(i) = \frac{FS(i)^a}{\sum_{i=1}^{n} FS(i)^a}$$

Equation 3. Frequency Share Model/S-Curve Model

The s-curve (frequency share) model can be employed where 'frequency' is the key parameter of changing market share. This means airlines with higher frequencies tend to capture a more significant market portion. Therefore, this relationship is generally stronger in short-haul markets, i.e., trips less than 6 hours of block time. Since this study focuses on short-haul markets, the frequency share model can be used for market share calculations. The exponent value typically varies between 1.3 and 1.7. As we divided the short-haul market into three sub-markets, we allocated the exponent value as 1.7 to Ultra short-haul, 1.5 to Medium short-haul, and 1.3 to regular short-haul.

(SBT) or distance between OD, as explained in Table III: Characteristics of Short and Long-Haul Flights (Sebastian Birolini, 2020). Among these two, the study selects the short-haul flight operation for analysis because it is highly sensitive to time. From the passenger viewpoint, passengers prefer shorter schedule block time (Lei Kang, 2017) because it offers less travel time. Most airlines use narrow-body aircraft (e.g., Boeing 737 family or Airbus 320 family) for operation due to their lower operation costs. Still, capacity restrictions may occur due to the narrow-body aircraft's seat configuration. Hence, we believe that a future study must develop a robust method to calculate more accurate exponent values for each market because each market is different.

The airlines use frequency strategies to overcome narrow body capacity constraints and lower the cost of passenger uplift. We identified that with an increase in schedule block time as strategy to gain market share. Because of that in this study, we divide short-haul flights into three subcategories, as shown in Table III: Short-Haul Subcategories, to illustrate accurate results. In the subcategorizing method study, we used actual block time (ABT) instead of scheduled block time because of airport slot-related complications SBT can be deviate from ABT. Even ABT also constantly fluctuates; hence, we use the 70th percentile of each OD pair for the clustering process, as shown in Table III: Short-Haul Subcategories.

### 3.8. CALCULATING ETA-SQUARED ($\eta^2$)

Eta squared is a method to measure the association between independent and predictor variables. Eta squares measure the proportion of variance associated with predictor variables maintained with independent variables (Adams M.A, 2014). Market concentration Equation 1 is not a linear function. In a non-linear relationship, Pearson's r correlation will not provide accurate results to understand how market concentration affects on-time performance. The study utilized Eta squared for the calculation to mitigate this issue. Eta squared can be calculated using Equation 4, where the $SS_{effect}$ is the sum of squares of effects for one variable and $SS_{total}$ is the total sum of squares.

$$\eta^2 = \frac{SS_{effect}}{SS_{total}}$$

Equation 4. Eta Squared calculation

The value of Eta squares varies between 1 and 0; if the values closer to 1 reflect a higher proportion of variance of the predictor variable, it can be explained by an independent variable or variables. The Eta squared does not have a specific guideline for interpreting results. Therefore, the study follows Table V (National University Academic Success center, 2023).

Table V. Guideline for interpretation

| Eta Squared | Effect Size |
|---|---|
| **$0 \le \eta^2 \le 0.06$** | Small effect size |
| **$0.06 < \eta^2 \le 0.14$** | Medium effect size |
| **$0.14 < \eta^2 \le 1$** | Large effect size |

### 3.9. HYPOTHESIS

As explained in the introduction, the main objective of this study is to understand the behavior of OTP concerning changes in corresponding market concentration. However, we must first check whether or not the impact of market concentration on OTP is significant. We analyzed this behavior by using the following hypothesis:

- $H_0$ = The punctuality of scheduled flight services is internally independent of the level of airline market concentration in markets where flight frequency is a pivotal factor in acquiring market dominance.
- $H_1$ = The punctuality of scheduled flight services is not internally independent of the level of airline market concentration in markets where flight frequency is a pivotal factor in acquiring market dominance.

## 4. RESULTS & DISCUSSION

We intend to discuss the results of the study in this section. As Table II illustrates, the study discovered interesting facts on how competition for short-range trips shapes the carrier's on-time performance. The section contains four main areas, which are subcategories. Table III of the short-haul market, as Figure 1 illustrates, shows that airlines lost 6.72% of their on-time performance due to issues they could control. Nevertheless, from an airline's perspective, they could not control most things because every carrier does their best to increase their market share. In this case, the competition will not be at equilibrium for a long period because the carrier with the competitive edge will gain the market share. The increase in market share means the market is becoming more concentrated on the carrier. The study tries to apply its hypothesis here because on-time performance is one of the most critical KPIs in the aviation industry. Hence, understanding how market concentration affects is vital. In the discussion, first, we debated the result of Eta squared and then used the kernel density function to analyze the behavior of OTP when market concentration changed.

### 4.1. ETA SQUARED RESULTS

Table VI. Eta Squared Results

| Operation Day | Eta Squared value | | | | | |
|---|---|---|---|---|---|---|
| | Ultra Short-haul Market | | Medium Short-haul | | Short-haul | |
| | DEP | ARR | DEP | ARR | DEP | ARR |
| **1** | 0.477002 | 0.49425 | 0.33471 | 0.3257 | 0.53337 | 0.49436 |
| **2** | 0.453839 | 0.47088 | 0.32073 | 0.29593 | 0.54344 | 0.52925 |
| **3** | 0.442793 | 0.459 | 0.33643 | 0.32266 | 0.4919 | 0.46874 |
| **4** | 0.434547 | 0.45125 | 0.28895 | 0.29303 | 0.49067 | 0.49855 |
| **5** | 0.457466 | 0.46953 | 0.30027 | 0.30276 | 0.44521 | 0.45152 |
| **6** | 0.46462 | 0.4986 | 0.28564 | 0.29362 | 0.46279 | 0.43979 |
| **7** | 0.480299 | 0.48961 | 0.28574 | 0.28249 | 0.4715 | 0.45211 |

Before further analysis, we checked for any effects and the intensity of the effects based on Table V. The study utilized Eta squared to measure the impact of arrival on-time performance (ARR_OTP_OD) and departure on-time performance (DEP_OTP_OD) for the subjected OD pair by market concentration. The analysis has been run for each short-haul sector for each operation day. The results illustrated in Table VI confirm that concentration can generate a significant effect on OTP in all short-haul markets. The outcomes of Eta square revealed that market concentration can considerably impact each market segment in short-range air travel. Based on the Table VI values, the effect of market concentration on OTP is significant except in medium- and short-haul markets. This scenario can result from our assumption about the value of the exponent of the S-curve function.

As shown in Table III, the study assumes the value of the exponent based on scheduled block time. However, the Eta squared results indicate that the effects of market concentration over 0.4 in ultra-short and short-haul segments mean that in these segments, concentration can explain over 40% of OTP variation, though it is less than 34% in medium-short-haul (For all related tables and figures, please refer to Appendices A, B, and C for statistical evidence).

### 4.2. ULTRA SHORT-HAUL

According to Figure 6, departure on-time performance and arrival on-time performance have similar distributions. Hence, we can conclude the presence of minimum external influences on flight operation. As illustrated in Figure 5, each operation day has a nearly similar market distribution. Due to this similarity, we extracted the generalized density function, Figure 6, for all three parameters. Figure 6 illustrates the market concentration of this ultra short-haul market, with a minimum value of 0.216, clearly explaining that this market has only moderately and highly concentrated markets.

Among these two markets, the percentage of the moderately concentrated market is less than 25%. The majority of ultra short-haul markets are highly concentrated, meaning most of these markets are duopoly or monopoly. Less than five carriers will dominate the market if they are an oligopoly. In this case, the market is starting to reach its peak "monopoly" at the 75th percentile, and the remaining 25% are monopoly markets.

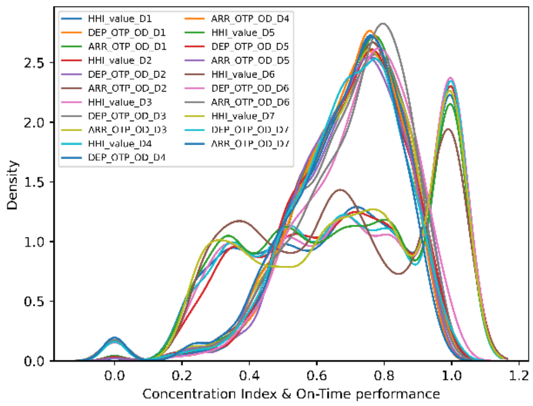


Figure 5. HHI & OTP comparison of all operation day ultra-short

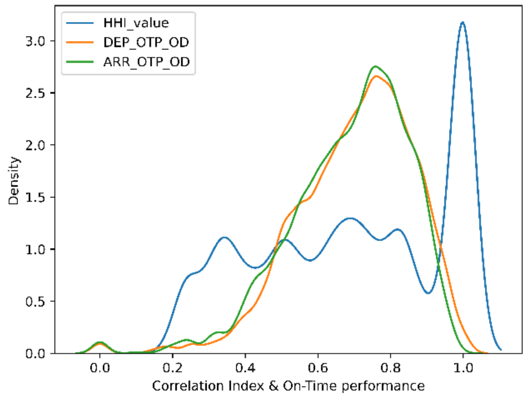


Figure 6. Generalized Density Functions of HHI & OTP for all operation days ultra-short

#### 4.2.1. MODERATELY CONCENTRATED ULTRA SHORT-HAUL MARKETS

Next, the study used HHI conditions (Bromberg, 2023) to re-cluster the ultra short-haul market. We used the $0.15 \leqslant HHI < 0.25$ condition to filter out moderately concentrated markets from ultra short-haul. Figure 7 illustrates the same scenario as Figure 5, and Figure 8 illustrates the same scenario as Figure 6, but within the mentioned HHI limit. We noted a significant difference in OTP distribution between D6 (Saturday) and the rest in Figure 8. The mean value of D6 is 0.82 (ARR) and 0.81 (DEP), which illustrates good OTP, but the average mean values of the rest of the operation days are 0.523 (ARR) and 0.58 (DEP).

The next question is why the OTP of D6 improved the way it occurred. We did some frequency analysis to answer that question, as shown in Figure 10. With Figure 10, we recognized that the low frequency of D6 may cause a significant improvement in OTP. However, this D6 improvement could not significantly impact generalized distribution. Figure 9 shows the low frequency of D6, allowing us to ignore the difference.

Figure 7 shows the unique behavior of OTP in this market. The characteristic of this market is that several carriers hold significant market share, but only a few. Each carrier has some degree of market power in this situation, and there can be more product diversification. This indicates product innovations and a somewhat easy market for newcomers to enter. Due to this continued competition to gain more market share, new carriers may cause operational inefficiencies, as illustrated in Figure 7.

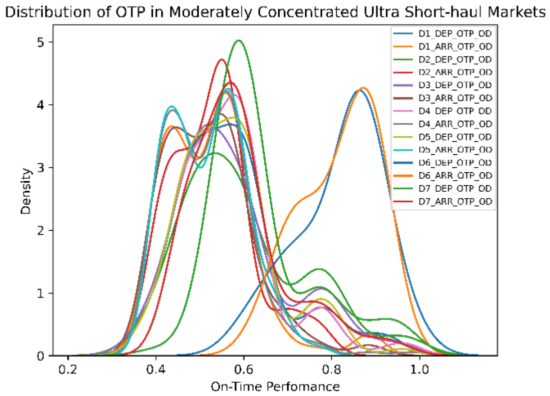


Figure 7. OTP Distribution for each Operation Day in Moderately Concentrated Ultra Short-Haul Markets

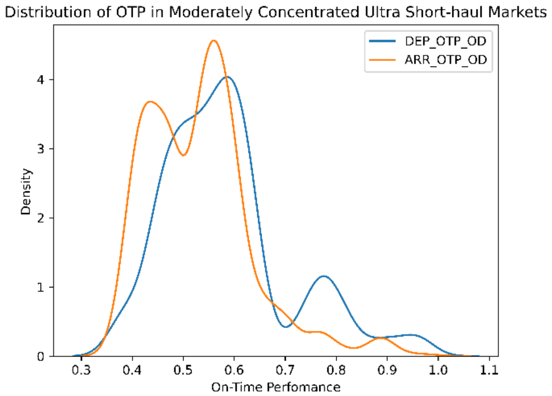


Figure 8. Generalized OTP Distribution for Moderately Concentrated Ultra Short-Haul Markets

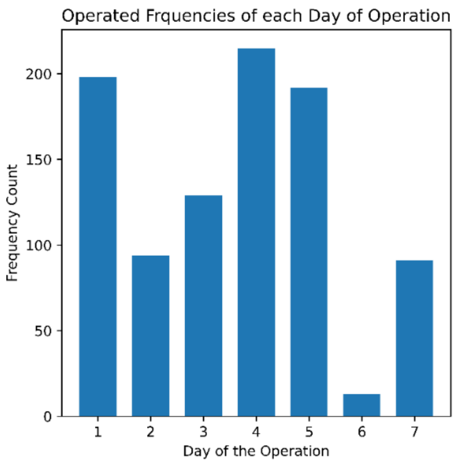


Figure 9. Frequency Analysis of Each Operation Day of Moderately Concentrated Ultra Short-Haul Market

#### 4.2.2. HIGHLY CONCENTRATED ULTRA SHORT-HAUL MARKETS

Figures 11 and 12 follow the same scenarios as Figures 7 and 8. When the market becomes highly concentrated, it becomes dominant by very few carriers. The common structure of a highly concentrated market is a duopoly or monopoly, so the most noticeable thing is imperfect competition. Comparing Figures 7 and 10 signifies the competition reductions because, in Figure 11, uniformity increases within OTP density functions for each operation day. Since carriers of highly concentrated markets hold high market power, they can maintain OTP at certain levels without losing market share. In this study, the subject market has a mean departure OTP of 0.71 and a mean arrival OTP of 0.7. The OTP of this market is neither highly efficient nor highly inefficient.

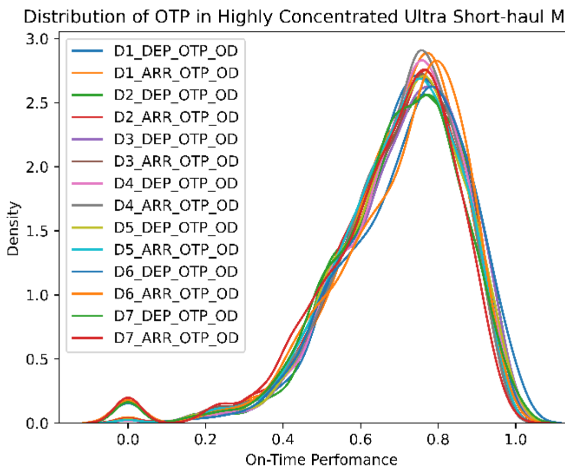


Figure 10. OTP Distribution for each Operation Day in Highly Concentrated Ultra Short-Haul Markets

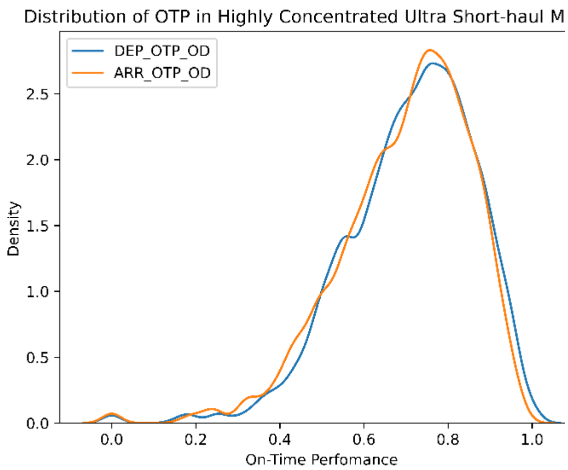


Figure 11. Generalized OTP Distribution for Highly Concentrated Ultra Short-Haul Markets

### 4.3. MEDIUM SHORT-HAUL

#### 4.3.1. MODERATELY CONCENTRATED MEDIUM SHORT-HAUL MARKETS

Moderately concentrated medium short-haul market OTP behavior significantly differs from moderately concentrated ultra short-haul market. As illustrated in Figure 12, D7 operations do not exist in this market because all D7 operations are in highly concentrated markets. According to the generalized density function illustrated in Figure 13, with 0.81 of the mean arrival OTP and 0.79 of the mean departure OTP, those values indicate that the market is keeping good OTP. However, only on some operation days, for example, for D5 departure OTP, the shape of the density function shows that the OTP of Day 5 is not so good, with a flatter distribution. Still, generally, arrival-on-time performance is better than departure OTP.

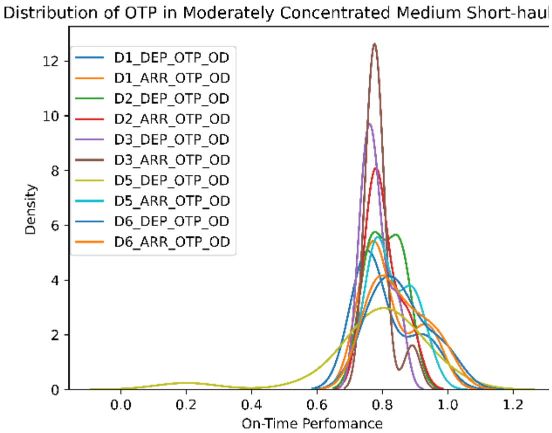


Figure 12. OTP Distribution for each Operation Day in Moderately Concentrated Medium Short-Haul Markets

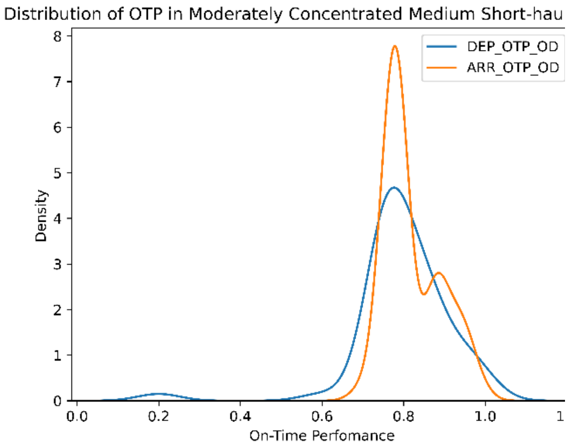


Figure 13.Generalized OTP Distribution for Moderately Concentrated Medium Short-Haul Markets

### 4.3.2. HIGHLY CONCENTRATED MEDIUM SHORT-HAUL MARKETS

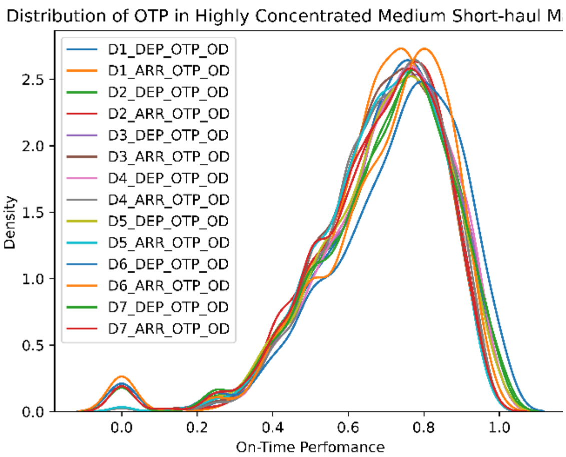


Figure 14. OTP Distribution for each Operation Day in Highly Concentrated Medium Short-Haul Markets

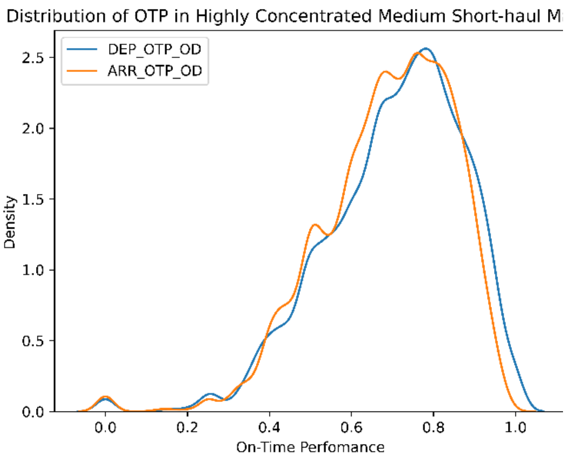


Figure 15. Generalized OTP Distribution for Highly Concentrated Moderately Short-Haul Markets

As illustrated in Figure 14 and Figure 15, the highly concentrated medium short-haul market also demonstrates similar characteristics to the highly concentrated ultra short-haul market. Unlike the ultra short-haul market, when concentration shifts from moderate to high in this medium short-haul market, mean OTP decreases from arrival and departure sectors. On arrival, OTP decreased from 0.81 to 0.68, and departure from 0.79 to 0.70. This phenomenon explains the reduction of competition when the market becomes highly concentrated.

## 4.4. REGULAR SHORT-HAUL

### 4.4.1. MODERATELY CONCENTRATED SHORT-HAUL MARKETS

Figures 16 and 17 illustrate OTP behavior in a moderately concentrated short-haul market. In the common behavior of medium and short, the density around the mean is higher in the arrival density function than in departure. This is obvious when comparing the standard deviations of functions. It means airlines are more concerned about arrival time than departure time because customers select departure time based on their preferred arrival time (Lu Hao, 2014). The mentioned consumer behavior leads airlines to introduce a longer schedule block time with buffer time than is actually required to ensure the OTP, which increases the operation costs. The carrier that achieves the highest arrival OTP with the minimum cost can gain market share. High competitiveness is the nature of moderately concentrated markets, represented in Figure 16.

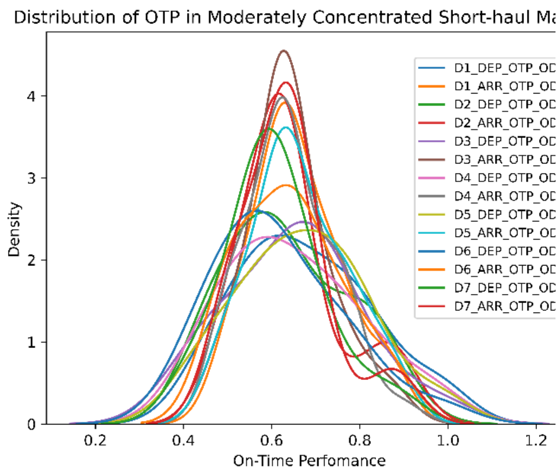


Figure 16. OTP Distribution for each Operation Day in Moderately Concentrated Short-Haul Markets

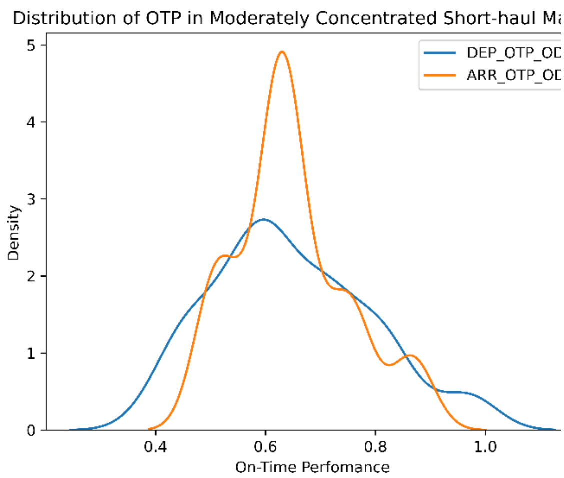


Figure 17. Generalized OTP Distribution for Moderately Concentrated Short-Haul Markets

### 4.4.2. HIGHLY CONCENTRATED SHORT-HAUL MARKETS

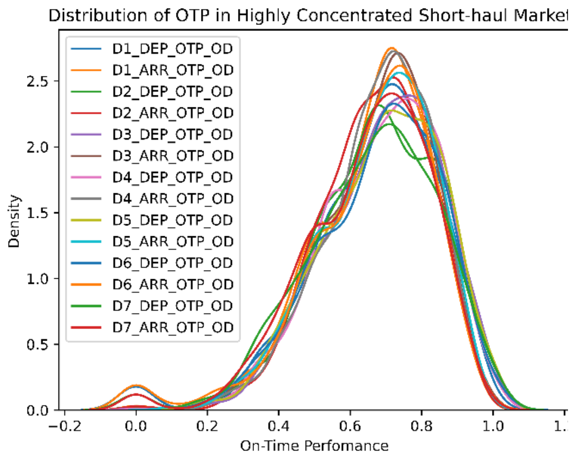


Figure 18. OTP Distribution for each Operation Day in Highly Concentrated Short-Haul Markets

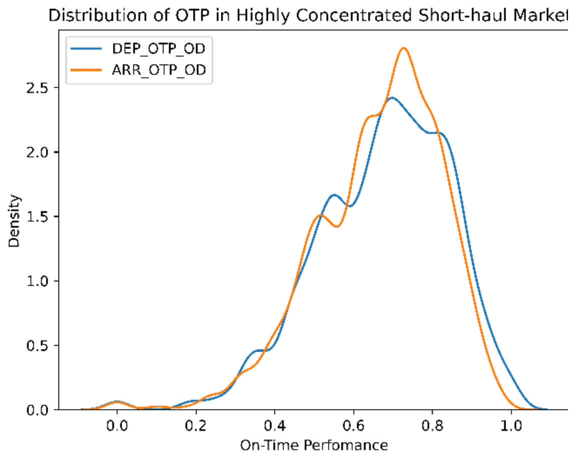


Figure 19. Generalized OTP Distribution for Highly Concentrated Short-Haul Markets

Highly concentrated markets throughout all segments illustrate the same level of service. Figure 18 shows that the density function of OTP for all operation days is more or less the same as in Figures 10 and 14. Figure 19 illustrates that arrival OTP 0.66 and departure OTP 0.67 are nearly identical to other segments. It explains that if any short-haul market gets more and more concentrated, there is a risk of losing OTP in the market.

## 5. CONCLUSION

The study's findings highlight the importance of sampling in understanding market competition in the aviation market. The research used a sampling method based on industry standards and added two extra layers to improve generalizability. The findings suggest that focusing on a diverse range of airports or locations is essential for a comprehensive understanding of market dynamics and making informed decisions based on reliable data. This approach ensures a more accurate representation of market dynamics and enhances the generalizability of the findings.

By dividing short-haul flights into three groups, we can understand how competition varies in different markets, even with the same level of market concentration. However, in every market condition, reject the null hypothesis.

The study suggests that to gain market share, each market must approach it with slightly different strategies. For example, the most competitive market for all three short-haul segments is moderately concentrated. Every carrier attempts to become a market leader by gaining market share, so the level of competition in each segment is different. In highly concentrated markets, all three market segments show the same level of OTP because of low competition.

In the ultra short-haul market, it helps to understand unexpected cases because D6 OTP shows a higher mean value than the rest. It helps to understand that a decrease in frequency leads to an increase in OTP. This issue requires further investigation.

The study helps both the main stakeholders' airlines and airport operators. Airlines can use the study results as follows:

Airline can deliberately utilize these insights to modify flight frequency to gain more market share and become a market leader, especially in markets with moderate concentration. However, if the market fails to demonstrate satisfactory operational performance, airport operators can use this type of study to determine the level of competition in that particular market. If the market becomes monopoly-level, the carriers will not care about the OTP based on results due to a lack of competition and high negotiation power. Similarly, it is crucial for airport operators to comprehend the reasons behind the carriers' underperformance. Studies suggest that if the underperformance of airlines is due to a lack of competition, airport operators can modify their policies to compel carriers to increase their OTP, thereby enhancing passenger satisfaction. But before implementing new policies, operators need to understand why and how competition changes to a certain level because there can be several factors that cause a market to reach a certain level.

In conclusion, market concentration needs more detailed analysis to understand its impact at the microlevel. Market concentration influences other uncertain factors to reach a certain operational efficiency level.

We can recommend several improvements to this study. First, since market concentration significantly affects every short-haul market, it is a critical factor in modeling OTP. However, since the mathematical function of market concentration does not provide linear values, we may not be able to utilize the linear technique to model OTP. The second recommendation is that further studies are necessary to determine the exponent value of the s-curve function, which will help to increase this study's accuracy. We think future studies need to look to improve the s-curve function to capture more complex parameters such as pricing strategies, connectivity, consumer preference, et cetera. The final recommendation is that it would be better to expand this study to all origin-destination combinations in order to build a more sophisticated decision support system.

Market concentration is a widely used measure to assess the level of competition within an industry. By examining the market share of a few dominant firms, it provides insights into the competitive dynamics and potential barriers to entry. However, as mentioned, it is important to consider other factors, such as pricing strategies, product differentiation, and consumer preferences, to comprehensively understand how competition influences and shapes the market.

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## APPENDIX

### APPENDIX A. ETA SQUARED RESULTS FOR ULTRA SHORT-HAUL SEGMENT

| Operation Day | Source | SS | DF | MS | F | p-unc | Eta Square |
|---|---|---|---|---|---|---|---|
| 1 | ARR_OTP_OD | 108.704992 | 450 | 0.241567 | 6.347734 | 1.33E-216 | 0.494245 |
| | HHI Value | 111.236444 | 2923 | 0.038056 | - | - | - |
| | DEP_OTP_OD | 104.912467 | 439 | 0.238981 | 6.095586 | 4.60E-203 | 0.477002 |
| | HHI Value | 115.028969 | 2934 | 0.039206 | - | - | - |
| 2 | ARR_OTP_OD | 71.790466 | 430 | 0.166955 | 4.217898 | 1.04E-106 | 0.470882 |
| | HHI Value | 80.668962 | 2038 | 0.039582 | - | - | - |
| | DEP_OTP_OD | 69.192027 | 409 | 0.169174 | 4.183253 | 1.66E-102 | 0.453839 |
| | HHI Value | 83.2674 | 2059 | 0.040441 | - | - | - |
| 3 | ARR_OTP_OD | 87.674534 | 453 | 0.193542 | 4.667354 | 3.75E-137 | 0.459003 |
| | HHI Value | 103.33621 | 2492 | 0.041467 | - | - | - |
| | DEP_OTP_OD | 84.578199 | 436 | 0.193987 | 4.572968 | 3.11E-130 | 0.442793 |
| | HHI Value | 106.432545 | 2509 | 0.04242 | - | - | - |
| 4 | ARR_OTP_OD | 120.902114 | 464 | 0.260565 | 6.475735 | 2.56E-244 | 0.451248 |
| | HHI Value | 147.026415 | 3654 | 0.040237 | - | - | - |
| | DEP_OTP_OD | 116.427537 | 452 | 0.257583 | 6.232959 | 4.78E-229 | 0.434547 |

| Operation Day | Source | SS | DF | MS | F | p-unc | Eta Square |
|---|---|---|---|---|---|---|---|
| | HHI Value | 151.500992 | 3666 | 0.041326 | - | - | - |
| 5 | ARR_OTP_OD | 104.660377 | 467 | 0.224112 | 5.551516 | 2.42E-187 | 0.469534 |
| | HHI Value | 118.242377 | 2929 | 0.04037 | - | - | - |
| | DEP_OTP_OD | 101.970349 | 450 | 0.226601 | 5.520157 | 6.70E-182 | 0.457466 |
| | HHI Value | 120.932406 | 2946 | 0.04105 | - | - | - |
| 6 | ARR_OTP_OD | 67.292009 | 397 | 0.169501 | 4.263124 | 1.26E-96 | 0.498595 |
| | HHI Value | 67.671303 | 1702 | 0.03976 | - | - | - |
| | DEP_OTP_OD | 62.706648 | 387 | 0.162033 | 3.839092 | 2.51E-81 | 0.46462 |
| | HHI Value | 72.256664 | 1712 | 0.042206 | - | - | - |
| 7 | ARR_OTP_OD | 109.351258 | 426 | 0.256693 | 6.642935 | 8.57E-222 | 0.48961 |
| | HHI Value | 113.99247 | 2950 | 0.038642 | - | - | - |
| | DEP_OTP_OD | 107.271868 | 410 | 0.261639 | 6.685689 | 1.62E-218 | 0.480299 |
| | HHI Value | 116.07186 | 2966 | 0.039134 | - | - | - |

## APPENDIX B. ETA SQUARED RESULTS FOR THE MEDIUM SHORT-HAUL SEGMENT

| Operation Day | Source | SS | DF | MS | F | p-unc | Eta Square |
|---|---|---|---|---|---|---|---|
| 1 | ARR_OTP_OD | 63.4302 | 459 | 0.13819 | 3.53583 | 2.63E-97 | 0.3257 |
| | HHI Value | 131.32 | 3360 | 0.03908 | - | - | - |
| | DEP_OTP_OD | 65.1848 | 478 | 0.13637 | 3.51646 | 4.05E-99 | 0.33471 |
| | HHI Value | 129.565 | 3341 | 0.03878 | - | - | - |
| 2 | ARR_OTP_OD | 49.2455 | 453 | 0.10871 | 2.74084 | 2.81E-57 | 0.295929 |
| | HHI Value | 117.164 | 2954 | 0.03966 | - | - | - |
| | DEP_OTP_OD | 53.3719 | 476 | 0.11213 | 2.90735 | 6.33E-67 | 0.320726 |
| | HHI Value | 113.038 | 2931 | 0.03857 | - | - | - |
| 3 | ARR_OTP_OD | 60.2853 | 459 | 0.13134 | 3.21526 | 2.62E-80 | 0.322664 |
| | HHI Value | 126.551 | 3098 | 0.04085 | - | - | - |
| | DEP_OTP_OD | 62.8579 | 475 | 0.13233 | 3.28969 | 9.08E-86 | 0.336434 |
| | HHI Value | 123.978 | 3082 | 0.04023 | - | - | - |
| 4 | ARR_OTP_OD | 67.7444 | 479 | 0.14143 | 3.55905 | 1.76E-106 | 0.29303 |
| | HHI Value | 163.442 | 4113 | 0.03974 | - | - | - |
| | DEP_OTP_OD | 66.802 | 478 | 0.13975 | 3.49757 | 4.58E-103 | 0.288953 |
| | HHI Value | 164.384 | 4114 | 0.03996 | - | - | - |
| 5 | ARR_OTP_OD | 53.9454 | 459 | 0.11753 | 2.98562 | 5.97E-70 | 0.302757 |
| | HHI Value | 124.235 | 3156 | 0.03937 | - | - | - |
| | DEP_OTP_OD | 53.5022 | 473 | 0.11311 | 2.85053 | 4.49E-65 | 0.30027 |
| | HHI Value | 124.678 | 3142 | 0.03968 | - | - | - |
| 6 | ARR_OTP_OD | 49.5516 | 415 | 0.1194 | 2.62723 | 9.52E-48 | 0.29362 |
| | HHI Value | 119.209 | 2623 | 0.04545 | - | - | - |
| | DEP_OTP_OD | 48.205 | 422 | 0.11423 | 2.47873 | 2.09E-42 | 0.285641 |
| | HHI Value | 120.556 | 2616 | 0.04608 | - | - | - |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 7 | ARR_OTP_OD | 62.0498 | 442 | 0.14038 | 3.50688 | 1.22E-96 | 0.282491 |
| | HHI Value | 157.602 | 3937 | 0.04003 | - | - | - |
| | DEP_OTP_OD | 62.7642 | 461 | 0.13615 | 3.40006 | 2.86E-94 | 0.285744 |
| | HHI Value | 156.888 | 3918 | 0.04004 | - | - | - |

## APPENDIX C. ETA SQUARED RESULTS FOR THE SHORT-HAUL SEGMENT

| Operation Day | Source | SS | DF | MS | F | p-unc | Eta Square |
|---|---|---|---|---|---|---|---|
| 1 | ARR_OTP_OD | 25.9705 | 219 | 0.11859 | 3.98229 | 2.34E-45 | 0.533368 |
| | HHI Value | 22.721 | 763 | 0.02978 | - | - | - |
| | DEP_OTP_OD | 24.0712 | 225 | 0.10698 | 3.28941 | 5.05E-34 | 0.494362 |
| | HHI Value | 24.6203 | 757 | 0.03252 | - | - | - |
| 2 | ARR_OTP_OD | 20.4853 | 202 | 0.10141 | 2.99344 | 2.46E-23 | 0.543443 |
| | HHI Value | 17.2101 | 508 | 0.03388 | - | - | - |
| | DEP_OTP_OD | 19.9503 | 197 | 0.10127 | 2.92769 | 2.94E-22 | 0.529252 |
| | HHI Value | 17.745 | 513 | 0.03459 | - | - | - |
| 3 | ARR_OTP_OD | 19.498 | 213 | 0.09154 | 2.6316 | 6.03E-20 | 0.491896 |
| | HHI Value | 20.1405 | 579 | 0.03479 | - | - | - |
| | DEP_OTP_OD | 18.5802 | 202 | 0.09198 | 2.57708 | 9.74E-19 | 0.468741 |
| | HHI Value | 21.0583 | 590 | 0.03569 | - | - | - |
| 4 | ARR_OTP_OD | 30.3681 | 234 | 0.12978 | 3.78348 | 7.15E-47 | 0.490671 |
| | HHI Value | 31.5229 | 919 | 0.0343 | - | - | - |
| | DEP_OTP_OD | 30.8558 | 235 | 0.1313 | 3.8838 | 6.89E-49 | 0.498551 |
| | HHI Value | 31.0352 | 918 | 0.03381 | - | - | - |
| 5 | ARR_OTP_OD | 22.4148 | 224 | 0.10007 | 2.79441 | 1.24E-25 | 0.445214 |
| | HHI Value | 27.9314 | 780 | 0.03581 | - | - | - |
| | DEP_OTP_OD | 22.7324 | 219 | 0.1038 | 2.95083 | 4.54E-28 | 0.451522 |
| | HHI Value | 27.6138 | 785 | 0.03518 | - | - | - |
| 6 | ARR_OTP_OD | 19.3028 | 185 | 0.10434 | 2.92894 | 2.85E-23 | 0.462786 |
| | HHI Value | 22.4072 | 629 | 0.03562 | - | - | - |
| | DEP_OTP_OD | 18.3435 | 181 | 0.10135 | 2.74545 | 1.99E-20 | 0.439787 |
| | HHI Value | 23.3665 | 633 | 0.03691 | - | - | - |
| 7 | ARR_OTP_OD | 28.261 | 219 | 0.12905 | 3.64191 | 4.80E-42 | 0.471499 |
| | HHI Value | 31.6775 | 894 | 0.03543 | - | - | - |
| | DEP_OTP_OD | 27.0989 | 217 | 0.12488 | 3.40724 | 1.50E-37 | 0.452112 |
| | HHI Value | 32.8396 | 896 | 0.03665 | - | - | - |

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# A DEMONSTRATOR FOR INTERCONNECTING INDEPENDENT MATERIAL FLOW SIMULATION MODELS IN THE AIR CARGO SUPPLY CHAIN USING THE IATA ONE RECORD STANDARD

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**ABSTRACT**

In this paper we demonstrate the concept of a digital twin for the air cargo transport chain which is based on data provided via the new IATA ONE Record standard (1R). Using ONE Record data which is based on the linked data concept enables overarching optimization without the necessity to build interfaces to many legacy systems or share sensitive data between supply chain partners. Real shipment data was transformed into the 1R format and stored in GraphDB from where it was retrieved with SparQL to feed a simulation model built with Siemens Plant Simulation. The concept shows how certain activities can be used the predict the near-term workload of the downstream supply chain partners. For the outbound ground handling process an information advantage of 15 minutes for 85% of all ULDs or even 30 minutes for 40% of all ULDs can be achieved.

## KEYWORDS

value of information; air cargo; logistics; digital twin; discrete event based simulation

# 1. INTRODUCTION

Air Cargo shipments represent about a third of global trade when measured in value (IATA 2016). Despite the relevance there is not a lot of research in air cargo compared to aviation in general or passenger transport. In this paper we focus on the forwarder-airline-driven air cargo supply chains and do not consider the Integrator business model or airmail or other air transport concepts for goods. The air cargo supply chain is characterized by volatile demand with changing and flexible supply chain partners. Compared to passenger services and other industries air cargo is lagging in digitization (Feng, Li & Shen 2015b). Message forwarding which is the current standard in data exchange between the supply chain partners has some deficits, esp. in cases where changes to the shipment or the transport plan occur. IATAs ONE Record (1R) standard aims at resolving these deficits. While past research mostly focused on the optimization of one partner, we conceptualize a digital twin that helps to optimize the supply chain. Due to the volatility in demand, but also short-term operational changes a digital twin improves the short-term allocation of resources and thereby improves quality of service and lead times.

The objective of this paper is to demonstrate how 1R data can be used to build a digital twin of the air cargo supply chain and how this digital twin can be used for short-term workload predictions. From the complete end-to-end-air transport chain which is covered by the concept and 1R in this paper we focus with our demonstration on the on-airport activities and partners (Figure 1).

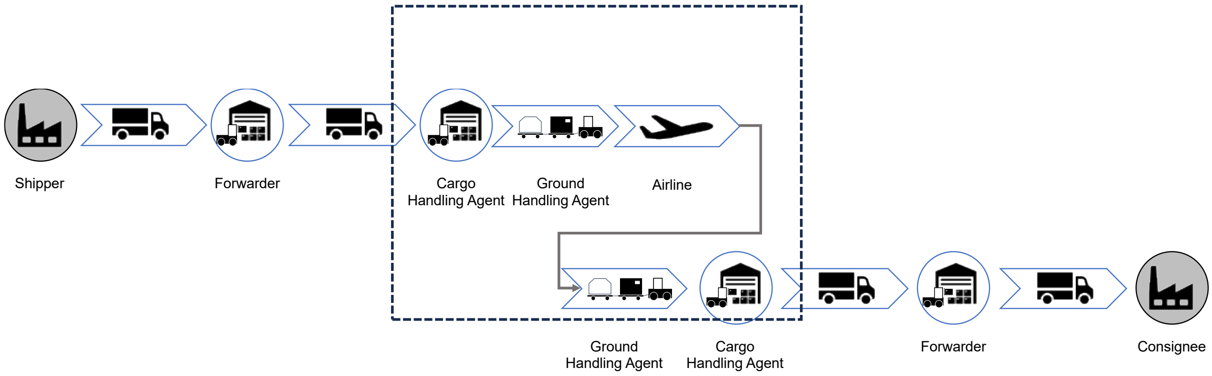



Figure 1: Simplified Air Cargo Transport Chain (dotted line indicates the focus area - (Source: authors representation)

The paper is structured as follows. Section 2 contains the literature review on air cargo and digital twins in logistics. This is followed by an in-depth description of the air cargo supply chain, its partners and processes as well as in introduction to the ONE Record standard, the underlying architecture and a description of the digital twin itself (section 3). Section 4 presents the results which is followed by the discussion in section 5 and the limitations in section 6. The last section summarizes the findings and provides an outlook on future research (section 7).

## 2. LITERATURE REVIEW

A comprehensive overview of air cargo operations research is given by Feng, Li & Shen (2015b) while Morrel & Klein (2019) or Schäfer (2020) present a detailed overview of all aspects of air cargo. Merkert (2022) presents a keyword map of relevant literature of the last 60 years.

Research addresses primarily the airline or cargo handling agent perspective with the objective to optimize airline strategy (Dewulf, Meersman & Van de Voorde 2019), airline revenues (Chao & Li 2017, Eren et al. 2023, Vancroonenburg et al. 2014, Popescu et al. 2006, Feng, Li & Shen 2015a), networks (Lee, Zhang & Ng 2019, Heinitz, Hirschberger & Werstat 2013, Huang, Xiao & Liang 2022, Janić 2022), airlines choices from a forwarder perspective (Chu 2014, Taner 2022) or load planning (Brandt & Nickel 2019, Lee et al. 2021). Bombelli & Fazi (2022) as well as Romero-Silva & Mota (2022) analyze the potentials of a cooperation between the ground handlers and forwarders to optimizing truck scheduling with the help of a central coordinator.

Material Flow Simulation, a sub-type of discrete event-based simulation, is used for analyzing real systems that have many influencing business-related and stochastic factors. Setting up a simulation model is done by abstracting a real system and building a model from it. Then, various input parameters are tweaked in experiments and the results are compared. In the domain of air cargo, simulation studies look at systems of warehouse, landside, or airside operations. Relevant works include Cao et al. (2011), DeLorme et al. (1992), He, Morris & Qin (2010), Nsakanda, Turcotte & Diaby (2004), Lee et al. (2006), Ou, Zhou & Li (2007), Romera-Silva & Mujica Mota (2021), Suryani, Chou & Chen (2012), Sencer & Karaismailoglu (2022). These known models focus solely on the air cargo handling terminals to either identify bottlenecks or evaluate benefits of technical improvements. Wong, Mo & So (2020) develop a digital twin for air cargo loading operations. Pérez Bernal et al. (2012) use a simulation software to model a forwarder-to-consignee air cargo supply chain for the airport of Zaragoza, Spain. They conclude that double-digit savings are possible if an overarching simulation model would be used.

Digital twins have been used in other industries for a long time, e.g. the aerospace industry, in general with a focus on installations or equipment (Haße et al. 2019, Tuegel et al. 2011). A digital twin uses constantly updated data and is also adapted according to the changes in reality (e.g. exchange of a certain machinery or any kind of extension) (Rosen et al. 2015). To enable the digital twin functionality provision of data from various systems, formats and owners is a challenge (Bazaz, Lohtander & Varis 2019). Haße et al. (2019) and Korth, Schwede

& Zajac (2018) describe a digital twin in the field of logistics while Franke, Hribernik & Thoben (2021) research the topic of interoperability in logistics.

To the best of our knowledge a digital twin of an air cargo transport chain that comprises of multiple stakeholders does not exist.

With the invention of 1R as a new form of data exchange the relevant and constantly updated data to build a digital twin becomes available. RDF and graph data models can be used to create interoperability between the distributed 1R data and a local simulation model.

As 1R itself is under development real-life 1R data is not available yet. Therefore, the authors had to transform real-life air cargo handling data into the 1R format to then use it as a data feed for the digital twin experiments.

## 2.1. CONCEPT OF AN 1R-DRIVEN DIGITAL TWIN OF THE AIR CARGO TRANSPORT CHAIN

### 2.1.1. AIR CARGO PLAYERS AND PROCESSES

Today's air cargo transport chain is centered around the contractual relationship which is defined by the airway bill (AWB). Typically, a shipper does not directly contract an airline, but hires a forwarder to organize the transport, so the AWB is set between the forwarder and the airline. As most tradelanes (origin-destination-combinations) are served by multiple airlines and air cargo does not represent a constant transport volume, the air transport chain is part of a volatile and flexible network, meaning a shipper might use multiple forwarders while the forwarders use multiple airlines (even for the same, recurring shipments).

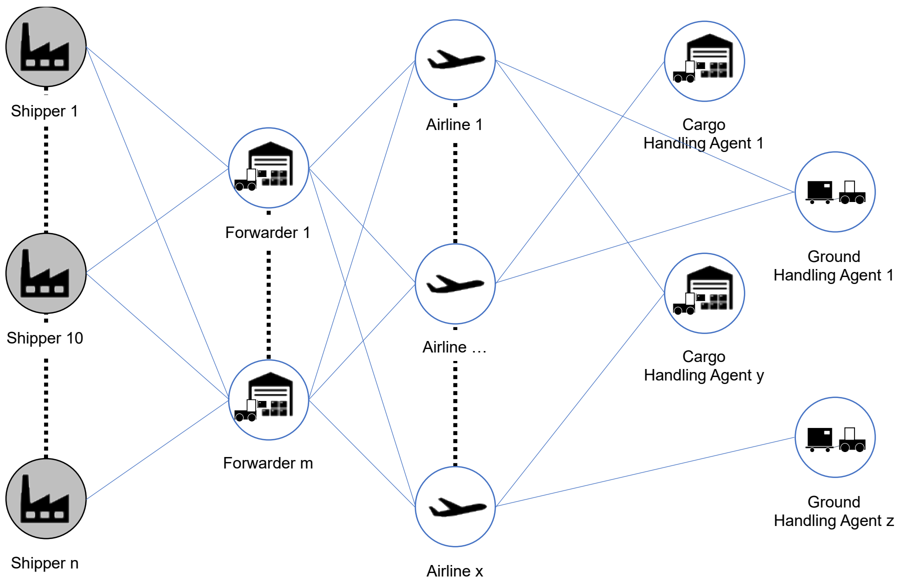



Figure 2: Complex network structures in the air cargo transport chain (Source: authors representation)

Forwarders and airlines most of the times outsource parts of their offer to several logistics service provider. While the air transport is the core value proposition of an airline all other surrounding services like ground handling, warehouse handling, road transport (Road feeder services RFS) are typically outsourced to other companies. The forwarders also heavily rely on outsourcing. This leads to more complex contractual situations than the 2-party-contract of the AWB indicates (figure 2).

IATA's master operating plan (MOP) describes the necessary material handling and documentary processes on a high-level-basis (IATA, 2019). The air transport from shipper to consignee is split into 19 main processes (with multiple sub-processes) which are either carrier- (airline) or forwarder-driven processes. Morrell & Klein (2019) describe the processes in more detail, specifically regarding ULDs and warehouse handling processes. Although company-specific differences in handling exist, the authors use the generic process described in the MOP as a baseline for the simulation model.

Different than in manufacturing supply chains with recurring transports under the same contractual terms AWBs cover individual transports only (as identical transports are rare).

For all companies involved in the air transport chain basic (physical) information about the shipment is essential for the correct identification and handling of the shipment (e.g. shipper, consignee, number of pieces and the weight). Because of security and customs regulation further data (e.g. a customs code or a basic cargo description) is needed to process the shipment.

Data exchange in air cargo is relying on CargoIMP and CargoXML, formats derived from EDIFACT, and a plentitude of individual solutions (cf. figure 3). Both formats revolve around messages portraying the contents of the air waybill document (FWB and xFZB) with limited capacities around that. These were originally designed for communication between the forwarder and the airline and form the backbone of this bilateral data exchange. Since the air waybill does not cover all needs that air cargo has today – consider track and trace needs, evolving dangerous goods regulation, or subcontracting – various individual solutions exist to enhance these. This includes IATA standards, such as eDGD, but also a lot of company- or provider-solutions such as web APIs, community systems, but also emails, phone calls, and telefax.

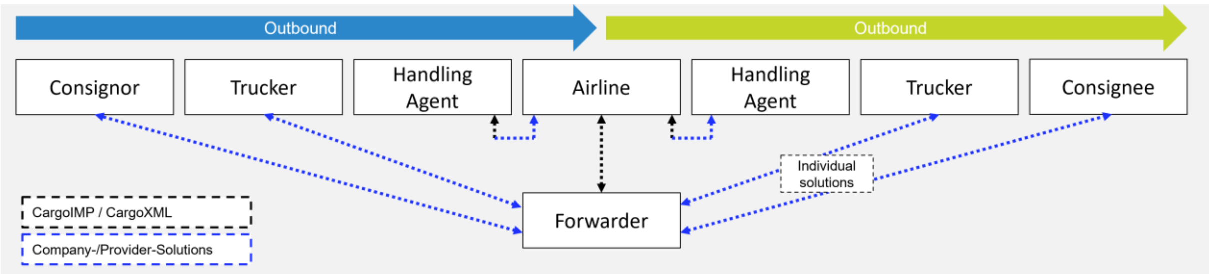



Figure 3: Current data exchange in air cargo (Source: authors representation)

All of this causes a fractured landscape of data pools along the air cargo supply chain that – while loosely basing on air waybill data – are too diverse to accurately and standardized retrieve process data from them.

### 2.1.2. THE ONE RECORD DATA MODEL AND ITS APPLICABILITY ON PHYSICAL AIR CARGO PROCESSES

ONE Record (1R) is an upcoming data transmission standard to share air cargo shipment data on piece level. Replacing the prevalent, restrictive EDI messaging, 1R is designed as a layer on top of the various IT systems used by supply chain partners, connecting the data pools and serving as authoritative source of truth.

The ONE Record standard aims connect the various data pools along the supply chain which exist independently, creating an internet of logistics, as stated by Blaj et al. (2020). It is built upon the W3C standard RDF (Resource Description Framework), which is a data model portraying relationships between webhosted resources as directed graphs. Data is described as subject-predicate-object, forming a triple. Every participant hosts and manages their own data, while consuming all data they need to access. Data is hosted on a per-resource basis. Each resource, being a node in the graph, has a weblink and can be accessed by standardized API-calls, to create, change or retrieve it. In total, the 1R defines 154 types of nodes, and 528 types of edges to describe properties of and relationships between the nodes.

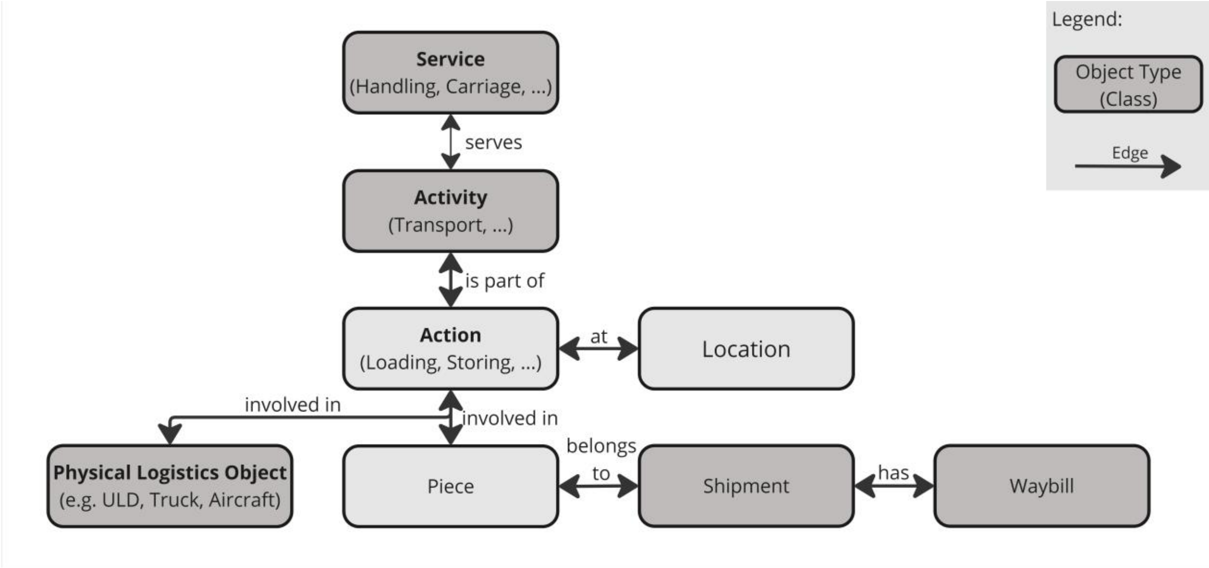



Figure 4: Logical data model of ONE Record 3.0.0[1] (Source: authors representation)

In the center of 1R is its cargo ontology, which defines the vocabulary and data model for the air cargo industry based on pieces, the physical world and processes. The core design principle is piece-centricity and physics-orientation (figure 4), meaning that each physical object and especially the pieces have digital equivalents in data traffic. These hold identifiers, dimensions, weight, handling requirements and all other physical parameters that their twin in the real world possesses in practice. This is in stark contrast to the document driven approach of CargoIMP and CargoXML, where this information is only available consolidated within a digital air waybill. Spanning from the piece, the data model includes objects to describe the relevant contractual data of the air waybill and airline booking parameters but are now limited to just non-physical parameters. In addition, processes are described as actions, where pieces and other physical objects interact with each other, that are part of a larger activity. This includes the Transport Movement activity covering Loading actions for flights and truck transportation, the Unit Composition activity including Composing actions for build-up and break-down processes and the Storage activity with Storing actions to describe storage times. These activities, in turn, are consolidated as services to be executed on a specific waybill – for example as part of a ground handling service. Further features include customs and security information, insurance information, and internet-of-things data, which are irrelevant for this project at the current state.

### 2.1.3. ONE RECORD CONNECTOR FOR MATERIAL FLOW SIMULATIONS IN AIR CARGO

[1] Full model visualization available on GitHub: https://github.com/IATA-Cargo/ONE-Record/blob/master/2023-12-standard/Data-Model/

Air cargo process simulation depends on pieces, physical objects, and process parameters. As such, the ONE Record connector is built on pieces, physical logistics objects, actions, activities, and services available as RDF-data. From the relationship nodes between the objects, the material flow inside, to and from the warehouse can be derived. Required descriptive nodes are the weight and destination per piece, the security status, and the times of actions performed on the pieces.

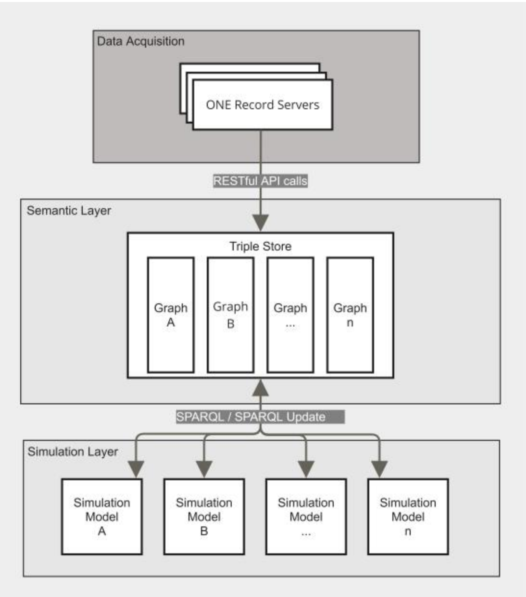



Figure 5: Architecture (Source: authors representation)

The proposed architecture is composed of three layers, namely the data acquisition layer in form of the network of ONE Record servers, the semantic layer holding the triple store, and the simulation layer running the simulation models (figure 5). For layer intercommunication, the approach relies on SPARQL and SPARQL Update. Both are W3C-standardized languages for querying and updating RDF data, respectively. The database server, as central layer, serves as provider of inter-model semantic interoperability as well as feeding the models with live data.

At simulation start, the database server fetches operational data using subsequent GET-Requests for every required resource. It is assumed that security permissions for access are present, but even partial data suffices in case access is denied. The returned JSON-LD files are parsed as triples and stored in a graph database, tailored towards handling RDF-data. In the proposed approach, the database includes separate, dedicated subgraphs for each connected simulation model. Upon completion, the separate instances of the simulation software running on the model server fetch the required input data by sending predesigned SPARQL-queries to the RDF4J-endpoint of the graph database. The database returns the query results as comma-separate-values, which are parsed and stored into the control tables of the simulation models. During the simulation run, the simulation models may routinely query the graph database for updates, while updating the graphs of connected simulation models by posting SPARQL Update queries against their respective endpoint in the graph database.

### 2.1.4. DIGITAL TWIN OF A FORWARDER HUB

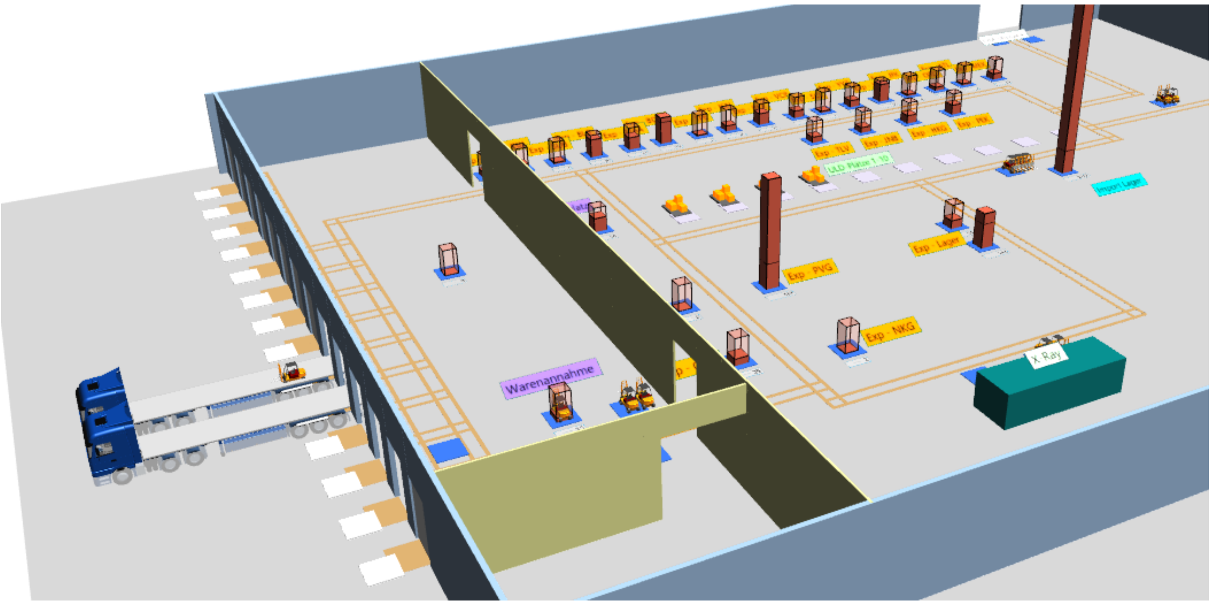



Figure 6: 3D model screenshot (Source: authors simulation model)

The presented demonstrator considers a single forwarder handling facility that is located at Frankfurt Airport built with Siemens Plant Simulation 2201 (figure 6). The model simulates the flow of import and export shipments on piece level, which are handled in the same area. It is operated by four control units, namely truck control, import control, export control and ULD control. Where truck control creates and sinks movable units in the form of pieces, import and export control handle the overall flow of these pieces through the warehouse. On trucks dropping off shipments at the warehouse, the model operates in a push fashion; on trucks picking up shipments at the warehouse, the model operates in a pull fashion. All trucks are created by the simulation based on pre-defined events holding the historical or planned timeslot of the trucks. The ULD control is a special case since it only applies for shipments arriving in ULDs in import or shipments to be packed on ULDs in export. In Import, it is triggered by the push of an ULD arriving at the warehouse; in export, it is triggered by the pull of an approaching latest acceptance time limit when the finished ULDs leave warehouse.

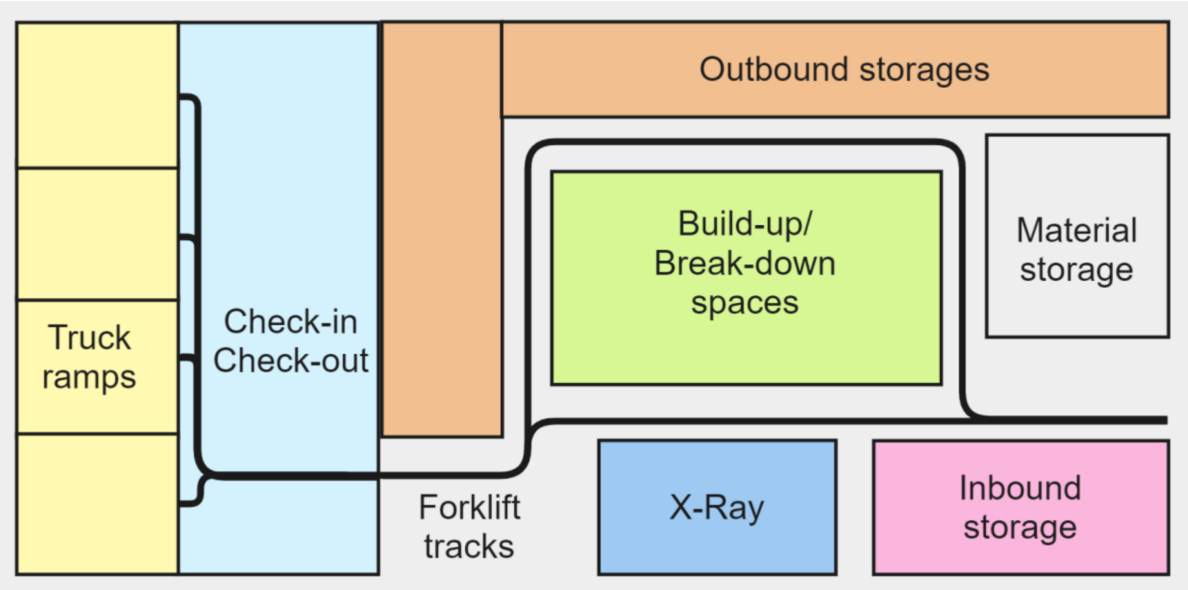



Figure 7: Schematic depiction of the model layout (Source: authors representation)

The warehouse covers consolidation and deconsolidation, loading and unloading, security screening, storage processes and the movement in-between stations. The processes are triggered through the abovementioned control units. Processes take time and require resources that are restricted, such as space at any station or labor for all processes except storage. Figure 7 depicts the model layout. As a core feature, the model portrays the build-up and break-down processes in high detail, including retrieving/collecting, composing/decomposing, and netting. Furthermore, it comprises four truck ramps that are used for incoming, outcoming and airport-internal trucks interchangeably. Pieces are stored in 28 sub-storage spaces based on forwarder company and flight destination or origin. Security screening including dark alarms through X-Ray, sniffing and explosive detection dogs is included. Each process happens in dedicated areas of the warehouse, which are connected through forklift tracks. The operation of movement by forklift as well as labor is controlled by shift plans.

The model is capable of realistically depicting warehouse KPIs. This includes the throughput in terms of AWBs, total weight and total pieces; Truck dock occupation and truck waiting times; Workforce and forklift utilization. These model-produced KPIs were used for data-based validation based on reporting data from February and March 2023. Additionally, the model and its parametrization were visually validated by the warehouse operator.

The current model operates on historical data of 32,694 pieces of export and import freight handled in February 2023 by the depicted company. It originates from six partially independent data pools (cf. table 1) and includes, next to the shipment information, also trucking data. Due to redundancies, the total dataset has some duplicate and contradictory information. On the contractual side, the pieces are consolidated as 8,879 house air waybills and 3,923 master/direct air waybills. The dataset includes relevant meta data in form of weight per piece, the time and type of performed security checks and an indicator for build-up/break-down as well as forwarder, airline company and flight destination. On the physical side, information of 1,611 trucks from forwarders and 1,175 airport-internal trucks is part of the dataset with their onload described on a per-house air waybill level.

| Data set | Relevant content | 1R 3.0.0 classes used |
|---|---|---|
| AWB data | AWB number, flight destination, ULD indicator, forwarder, carrier | Waybill, Location, LogisticsService, ActivitySequence, UnitComposition, Party, Company |
| Warehouse receipts export | Pieces, HAWB number, AWB number, gross weight, store-in date, store-out date, external truck number, internal truck number | Piece, Shipment, Waybill, Value, Storing, Storage, Loading, OtherIdentifier |
| Warehouse receipts import | Pieces, HAWB number, AWB number, gross weight, store-in date time, store-out date time, external truck number, internal truck number | Piece, Shipment, Waybill, Value, Storing, Storage, Loading, OtherIdentifier |
| Security checks | Pieces, security check type, security check date time | Piece, Check |
| External trucks | External truck number, registration date time, loading/unloading date time | Loading, TransportMovement, Location |
| Airport internal trucks | Internal truck number, loading/unloading date time | Loading, TransportMovement, Location |

Table 1: Dataset and mapping to ONE Record classes (Source: authors representation)

The semantic layer operates on the ONE Record Datamodel 3.0.0 RC4 and comprises 1,431,595 RDF triples. With the data only present in csv files, custom pipelines were developed to convert and clean the input data. GraphDB was chosen as database software. During conversion of the six datasets into a combined ONE Record graph, 52 different properties and 18 different classes were used. The mapping to the logical data model of figure 4 is listed in table 1. Communication between GraphDB and external ONE Record servers has been successfully trialed, but not implemented yet. At the current stage it is of little value due to the as per time of writing still changing API specifications and the lack of real available ONE Record data.

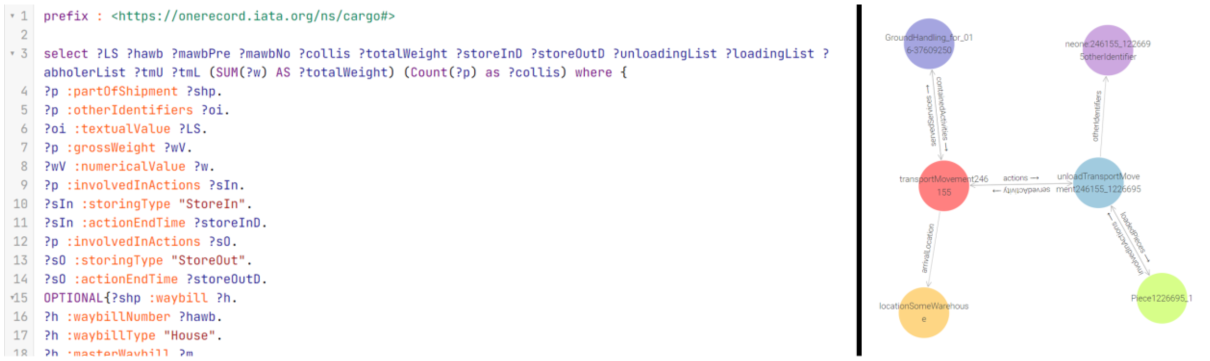



Figure 8: Sample SPARQL query and excerpt of the total graph (Source: authors representation)

A set of dedicated queries retrieve simulation-relevant data using the RDF4J-SPARQL endpoint of the database software is used on a per-element level. A sample query and an excerpt of the data structure is provided in Figure 8. The queries run on simulation start, retrieving and converting data into simulation-understandable tables within seconds. Truck dock elements are fed with load lists and information about the consolidation state of pieces (on ULD or loose). The storage area and security checks are operating on piece-level information about the destination and to-be-performed checks. Build-up/break-down processes are triggered by build-up and break-down plans. In contrast to directly feeding the elements with data from the six sub-tables, using ONE Record ensures the elimination of contradictory information as a single source of truth. Furthermore, implementation of the standard for operating a simulation model proved to be very simple in comparison to complex analyses of proprietary data formats from handling systems.

## 3. RESULTS

Based on the 1R-transformed input data the utilization of resources, process and waiting times and storage levels can be retrieved from the simulation to optimize the forwarder operation (e.g. reduce the number of staff or to achieve more constant storage levels).

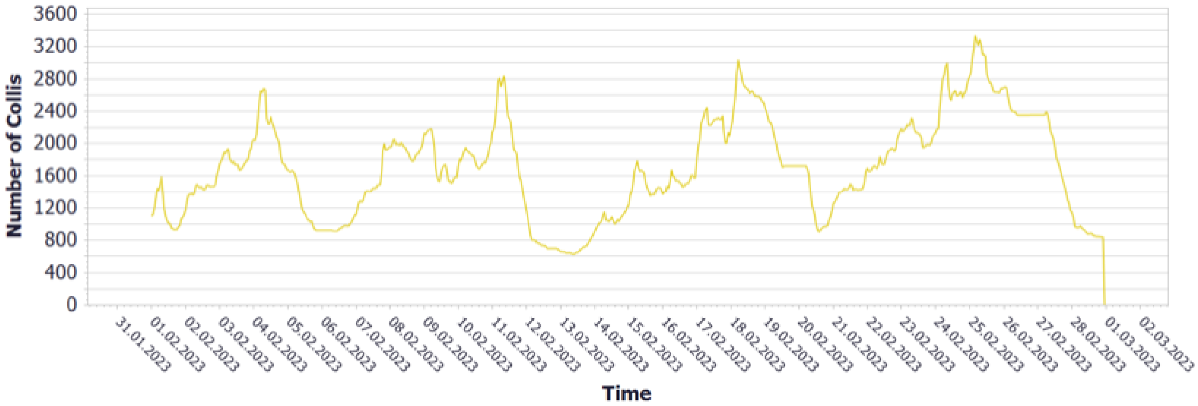



Figure 9: Number of pieces in storage (Simulation results - Source: authors calculations)

For the scope of this paper, we focus on processes and events that are visible in 1R while representing valuable information for downstream supply chain partners.

In the outbound process the start of the build-up process (B/U) can be identified in 1R when an AWB is linked with an ULD. BUPs (Built-Up Pallets) thereby represent ULDs that are build-up at the forwarder. Today, the ground handling agent as the downstream supply chain partner gets a transport order once the B/U is complete and the finished ULD is ready to be picked up at a designated handover area. Based on our simulation results the ground handling agent would be informed about upcoming ULDs (which will be transport orders once finished) at least 15 minutes earlier then today for more than 85% of the ULDs. For 40% of the ULDs the advantage is 30 or more minutes (Figure 10).

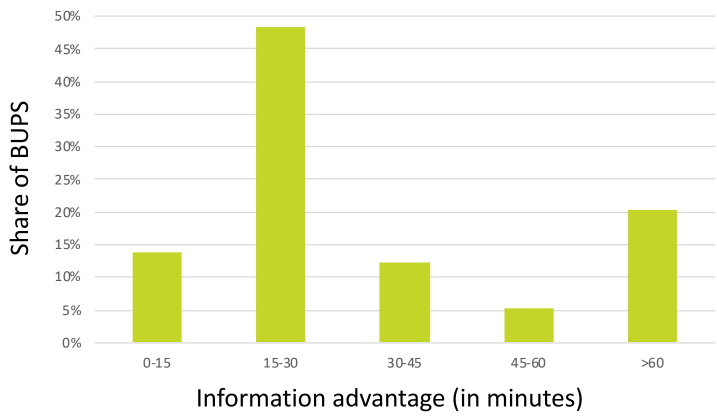
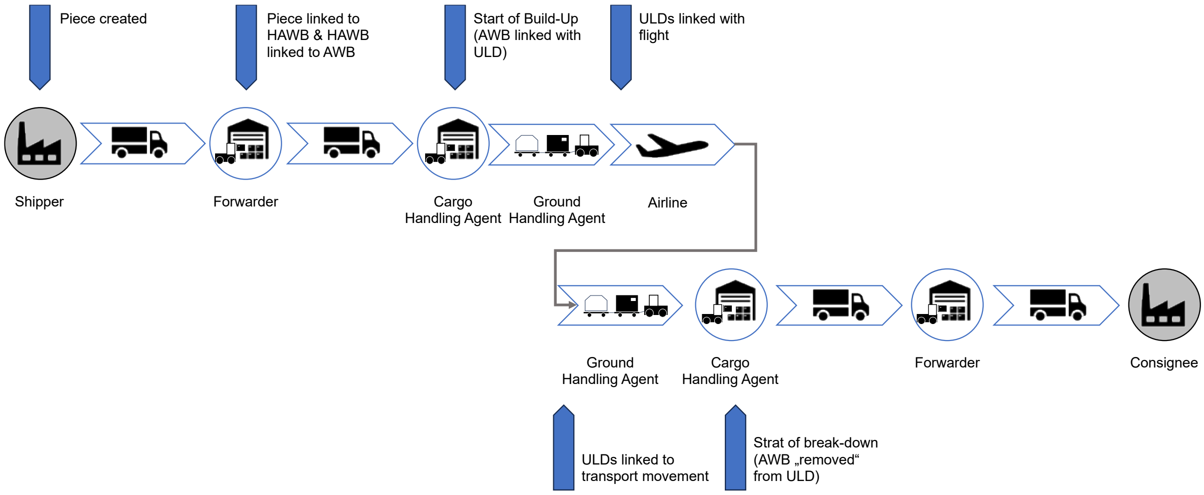



Figure 10: Information advantage based on the identification of a started B/U (Simulation results - Source: authors calculations)

## 4. DISCUSSION

The forwarder hub simulation model shows potential benefits for the downstream supply chain partner, in this case the ground handling agent. As consolidation and deconsolidation activities are transparent in 1R, these events indicate the future workload for the downstream partner and allows for a better resource planning and allocation. A sample of relevant (de-)consolidation events is shown in Figure 11.




The methodology and architecture used for the forwarder hub can be easily extended to the

Figure 11: Sample of relevant de-/consolidation events in the air cargo transport chain (Source: authors representation)

full air transport chain. The other processes can be derived from IATA's MOP if more detailed information is not available.

Related to the most important partners next to the forwarder model a model for the air cargo handling agent (e.g. the warehouse where the airline handling takes place) and a model for the ground handling agent need to be developed. While an overarching model which covers the whole air transport chain is relevant for scientific research and to analyse effects and impacts at the various partners, from an industry perspective separated models are preferable as only the respective partners know their available resources and can decide about their operational strategies to cope with bottlenecks or peaks.

Beside the benefits from a short-term workload prediction (for all partners, based on different processes) the digital twin serves all use cases of classic simulation approaches: Users can assess the impact of process automation, autonomous vehicles, and different operational strategies.

## 4.1. LIMITATIONS

As One Record data and structures are not available today, the twin reflects potential benefits which cannot be validated as a direct comparison is not possible. To feed the twin with 1R-style data, existing shipment data had to be transformed according to the 1R data model. It is thereby assumed that all the data used will be available in 1R.

The concept assumes full adaption of the new standard by all major forwarders and airliners. Being an international business, it is understood that adaption speed will differ and it has to be seen which share of non-adopters is acceptable to still be able to calculate benefits.

The research focuses on the classic, forwarder-driven air cargo transport chain and is not applicable to integrator or airmail operations. The model reflects the processes at an European air cargo hub and is based on IATA's MOP. Different processes and structures could apply at other airports. Additionally, effects from bottlenecks or otherwise limited resources which impact the process and lead times have so far not been regarded.

# 5. CONCLUSION

Due to the structures in air cargo transport chains information exchange is important. 1R has the potential to serve as an industry-wide standard that contains all relevant data elements. This data can be used to feed digital twins of the complete or partial processes in the air transport chain (e.g. of one partner) without the need to connect multiple legacy systems or IT-systems of other partners.

As 1R servers, data exchange and respective data are not available, because the new standard is still in development, shipment data from a forwarder hub had to be transformed into 1R-style data first. The data was transformed into RDF triples and stored in a GraphDB. The data was retrieved with SparQL and inserted into a standard simulation software.

It could be demonstrated with the digital twin of the forwarder hub that valuable information – here workload prediction – could be derived from 1R data which helps the downstream partner – the ground handling agent – to create an event-based short term workload prediction (which allows for a more efficient resource allocation). Based on the results the ground handling can achieve an information advantage of 15 minutes for 85% of all ULDs or even 30 minutes for 40% of all ULDs.

With the help of the planned integrated digital twin further use cases can be analysed and the results for other supply chain partners and processes evaluated.

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