Air cargo logistics automation and digital airport process management: comprehensive empirical insights from Germany

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Abstract

Purpose – This paper investigates an integration of automation and digital technologies within air cargo logistics, focusing on empirical testing of the O^{3}dyn pallet transport robot prototype at Munich Airport. The presented research identifies challenges and opportunities regarding dynamic airport environments, enhancing understanding of technology implementation and its implications for operational efficiency.

Design/methodology/approach – The conducted research employs an empirical methodology involving 10 days of real-world testing. This includes defining test parameters, documenting operational metrics and monitoring interactions toward other robotic systems. Various scenarios were tested to assess the system's effectiveness in navigating complex airport environments, collecting data on travel times, load weights, manual interventions and operational challenges relevant to air cargo handling.

Findings – The findings indicate that while the robot effectively performed transport tasks in a dynamic airport environment, its autonomy was limited, necessitating significant human intervention. Challenges included obstacle detection and navigation, indicating a need for further development in real-time decision-making and integration with logistics processes.

Research limitations/implications – The focus on a single airport may not fully capture broader challenges, and the short testing duration may overlook various operational scenarios. Future research should involve multiple and diverse environments and longer periods of data capturing for more comprehensive insights into air cargo handling systems.

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Practical implications – This study provides guidance for air cargo logistics stakeholders, highlighting critical investment areas and the need for collaboration among industry partners to overcome automation barriers and challenges.

Originality/value – This paper presents unique empirical findings on air cargo robotics, demonstrating their practical implications and advancing the understanding of automation in dynamic airport environments.

Keywords Automation, Robotics, Air cargo, Airport, Navigation, Prototyping

Paper type Research article

1. Introduction

Development trends for logistics management include concurrent technology-oriented innovations in Industry 4.0 and Logistics 4.0 due to the digital transformation and automation efforts, as well as emerging human-centric organisational concepts connected to Industry 5.0 and Logistics 5.0 paradigms (Moghaddam and Klumpp, 2025; Menti *et al.*, 2023; Maghazei *et al.*, 2022; Breque *et al.*, 2021; Culot *et al.*, 2020).

These concepts ideally involve an integrated innovation approach during the development of technology and processes, keeping the "human in the loop". In several transport sectors and processes, automation and digital transformation are important developments (Akkermans *et al.*, 2024; Sternberg *et al.*, 2022), while connected and autonomous vehicles have entered markets beyond public road transportation (Uhlemann, 2021). In sectors other than air transportation and air cargo ground handling, the optimisation of robot fleets is already taking place at a system level (Ho *et al.*, 2025; Zhi, 2025; Pan *et al.*, 2024), with seaports being more cost-effective than airports due to a higher level of automation and relevant economies of scale, among other factors (Juliet, 2025).

Owing to specific requirements within air transportation, automation developments face relevant challenges, especially regarding safety, handling, efficiency, data security or transparency (Jodejko-Pietruczuk *et al.*, 2025b; Bierwirth and Scheiber, 2023; Thums *et al.*, 2023). A common challenge in this regard is the anticipation of automation and digital developments to meet such requirements, enabling comprehensive, successful and economically viable project implementations in the dynamic air cargo transport R&D ecosystem (Jodejko-Pietruczuk *et al.*, 2025a; Chakraborty and Vimala Rani, 2025; Gosling and Barton, 2022; Carosio *et al.*, 2019). Besides autonomous aircraft pushing and taxiing to and from the runway (Garcia *et al.*, 2025; von der Burg and Sharpanskykh, 2023), Autonomous mobile robots (AMRs) represent a promising technology for improving air cargo ground operations (Tadić *et al.*, 2024; Adenigbo *et al.*, 2023).

Air cargo handling is characterised by intricate processes that require individual planning for each flight, often referred to as the air cargo load planning problem. This complexity arises from the diverse requirements associated with different goods, loading units and aircraft models, leading to inefficiencies and low data transparency across the supply chain (Bierwirth and Scheiber, 2023; Brandt and Nickel, 2018). The complex regulatory environment (Orzechowski, 2025; Orzechowski *et al.*, 2024), as well as the absence of standardised procedures, further complicates the automation of these processes, making it difficult to implement uniform robotic solutions (Muecklich and Wehner, 2025; Adenigbo *et al.*, 2025) and enhance air cargo network resilience (Xu *et al.*, 2025; Hong *et al.*, 2025).

Despite advancements in technology and increasing interest in automation, air cargo ground handling remains largely manual at airports. Several factors contribute to this lag in automation, including the complexity of operations, a lack of standardisation and dynamic operational environments. The air cargo supply chain is plagued by dynamic requirements that necessitate real-time decision-making, which current robotic systems are not fully equipped to handle (Wandelt and Wang, 2024). Ground staff must constantly adapt to changing conditions, such as fluctuating cargo volumes and variable traffic patterns, which pose significant challenges for autonomous systems (Chung *et al.*, 2025; Bunahri *et al.*, 2023).

The aftermath of the COVID-19 pandemic has exacerbated these issues, leading to a shortage of skilled labour in the aviation sector, thus increasing the urgency for automation. However, the lack of experienced personnel has simultaneously accelerated the transition toward automated

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solutions, given ground handling operations' firm reliance on human expertise (Gomez-Belderrain *et al.*, 2025; Wandelt *et al.*, 2024). Therefore, the highly dynamic, mixed-traffic environment at airports remains a challenge for the safe localisation and navigation of robotic vehicles (Edlinger *et al.*, 2022; Steininger *et al.*, 2022). Furthermore, implementation costs and infrastructure compatibility remain critical factors (Källbäcker *et al.*, 2025).

This paper presents valuable contributions to technology development through observations and analyses by reporting the results of laboratory testing, preparation and prototyping for the automated cargo transport system "O^{3}dyn" in a real-life air cargo environment at Munich Airport, Germany, throughout 2024. O^{3}dyn, along with other robotic systems, is evaluated using a constructivist approach for its capabilities in real-world operational environments, particularly focusing on the handling of standardised Euro pallets (EPAL). O^{3}dyn was subjected to extensive testing as part of the Digital Testbed Air Cargo (DTAC) project in Germany (Wehner and Lacoste, 2024; Mehrtens *et al.*, 2023).[1].

By examining the challenges and opportunities associated with autonomous operations in a dynamic airport environment, including distinctive error analysis, this research highlights the critical factors influencing the successful implementation of robotic systems in air cargo handling. The findings aim to inform future advancements in technology and process management, ultimately contributing to more efficient and effective air cargo logistics.

The paper is structured as follows: Section 2 provides an overview of the technological development of the O^{3}dyn system, highlighting its essential features and the modifications made for field deployment. Section 3 details the empirical testing phase conducted at Munich Airport, including the methodology and test parameters. Section 4 illustrates the results obtained during operations. Section 5 discusses the implications of the findings for future developments in air cargo logistics automation, addressing the challenges and opportunities identified throughout the testing process. Furthermore, an investment evaluation is given. Finally, Section 6 outlines an outlook on further research challenges and industry implications.

2. Technology development

This section outlines the innovation development of the O^{3}dyn robotic prototype and its preparation for the initial test deployment in real-world operations beyond laboratory conditions. It commences with a summary of O^{3}dyn's key features, followed by a discussion of the necessary hardware and software adjustments for field deployment.

2.1 Overview O^{3}dyn

O^{3}dyn is a highly dynamic, omnidirectional pallet transport robot that operates indoors and outdoors (see Figure 1). The name O^{3}dyn is derived from its four main features: outdoor-rated, omnidirectional, open-source and dynamic. Currently, O^{3}dyn can handle and transport EPALs. In the current prototype version, it can handle pallets weighing up to 350 kg. This weight limit was established at the beginning of the design process and could be significantly increased in future versions. O^{3}dyn can reach a top speed of up to 10 meters per second.

The robot is equipped with two computers. The first is an embedded PC (CX5130) that operates as a Programmable Logic Controller (PLC) and is responsible for real-time critical tasks, including operating the motor controllers, handling the pneumatic valves of the air suspension system and controlling the load handling device. The second is a high-performance laptop running higher-level, navigation-related logic. Bidirectional communication between both computers is established through a suitable interface. The higher-level control logic, which includes localisation, mapping, global and local path planning, as well as transport order processing, was implemented using the robot operating system (ROS).

Most of the hardware components, as well as the navigation and localisation software, are available as open-source solutions. Furthermore, the robot-independent Differential Global Positioning System (DGPS) is available as an open-source implementation under the Open

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Figure 1. Robot "O^{3}dyn" at Munich Airport. Source: Authors' own work

Logistics Foundation License (OLFL) [2]. Previous O^{3}dyn-related publications focus on GPS localisation (Blesing *et al.*, 2023), damping behaviour of the suspension (Ullrich and Gössner, 2022), semantic mapping systems (Schweigert *et al.*, 2022) and simulation modelling (Wiedemann *et al.*, 2024).

For the DTAC application, several software and hardware modifications and O^{3}dyn updates were required beforehand to ensure precise and reliable operation in the highly dynamic environment of the cargo area at Munich airport.

2.2 Vehicle development

The execution of automated transport orders in the test area requires a stable and reliable load transfer process. A critical subprocess in this operation is positioning the vehicle in front of the pallet during the loading process. Inaccurate alignment of O^{3}dyn, including lateral misalignment or rotation, can result in the pallet being misaligned or displaced upon engagement with the load handling device. To mitigate this issue, constructive adjustments to the load handling device are required, addressing both potential interference contours and the clearance between the vehicle and pallet.

The current load handling device design was analysed, and three design improvements were identified – the geometry of the rear pickup hooks, the end stops of the rear pickup hooks and the lateral guide plates. In the case of the rear pickup hooks, the rectangular shape's sharp edge caused an interference contour. This edge collided with the pallet during vehicle positioning, causing displacement and rotation and consequently preventing a reliable pallet pickup. This edge was eliminated through mechanical processing in the form of a bevel (see Figure 2 left). Considering sustainability, modifying the existing hooks was preferred over complete remanufacturing. Additionally, further processing of less stressed areas was undertaken to reduce weight.

The end stops of the rear pickup hooks (see Figure 2, centre) were optimised to allow for variable positioning. This change involved a new design using a minimal number of components to ensure integration with the existing components of the load handling device,

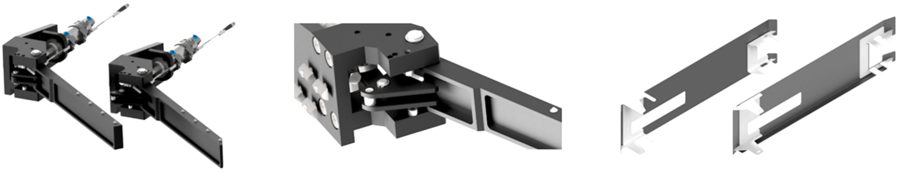

Figure 2. 3D model of optimised load handling device hook design (left), mechanical end stops (centre) and lateral guide plates (right). Source: Authors' own work

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thereby minimising the need for reprocessing of existing parts. The physical end stop was realised using a hexagon screw, which is mounted onto the fixture, allowing for continuous adjustment of the stop. The counterpart located on the pickup hooks consisted of an inserted bushing, which was integrated into the newly designed connecting plates welded onto the pickup hooks. With this adjustment, the hooks' end position of the hooks was fine-tuned to guarantee their flush fit against the lateral guide plates.

The shape and position of the lateral guide plates (see Figure 2, right) determined the clearance between the pallet and the vehicle and represented a potential interference contour. By modifying the shape of the guide plates, the clearance on both sides was increased from 10 to 14 mm. This resulted in a free space of 828 mm in the vehicle that could not be further increased due to other vehicle components. In this case, the modification of the guide plates could not be achieved through mechanical processing, resulting in the manufacturing of new components. The guide plates were made from cut and bent sheet metal plates that were welded together. These modifications led to significant improvements in subsequent tests, resulting in a robust, reliable and more failsafe load transfer process.

To improve automatic load handling, O^{3}dyn was equipped with an IFM 3D camera using Time-of-Flight technology to detect and locate pallets. The camera was tested against a 2D laser system based on accuracy, reliability and speed. Settings were optimised using IFM software, with filters like Depth Hint and Stray-Light-Filter influencing performance. While loaded pallets were reliably recognised in auto mode, unloaded ones required manual adjustments, reducing practicality. Tests showed limited effectiveness, especially in differentiating load states. IFM is working on improvements, and combining the camera with a laser scanner may enhance reliability.

The test area at Munich Airport spans several interconnected halls. O^{3}dyn's task is to link multiple sources and sinks. There is no uniform network (Wi-Fi) coverage across all test halls and connecting pathways. Therefore, it is essential for the vehicle to be equipped with a mobile router, and the Teltonika RUTX50 was selected accordingly. This high-performance industrial router offers very low latency and 5G mobile communication via a SIM card, allowing for remote vehicle access through the integrated Remote Management System. The router is equipped with two PUCK-2-V2 antennas from POYNTING Antennas (see Figure 3), providing a 2.4 GHz and 5 GHz Wi-Fi network. The advantage in the test area is that the operator does not require a physical cable connection to the vehicle and can move freely or remain in a secure area independent of the vehicle. With the router's 5G mobile

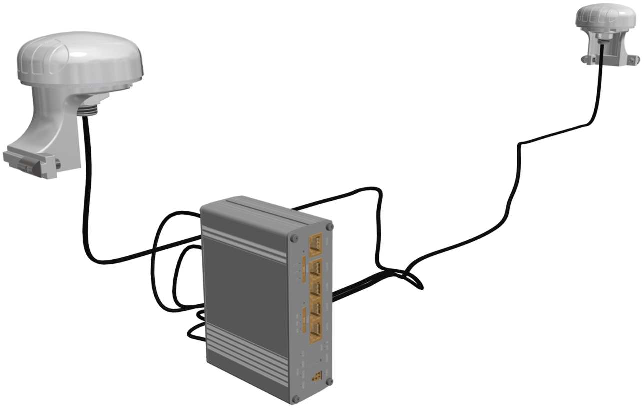

Figure 3. 3D model of the Teltonika RUTX50 5G router and connected POYNTING PUCK-2-V2 antennas – courtesy of POYNTING Antennas. https://teltonika-networks.com/de/products/routers/rutx50. Source: Authors' own work

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communication, O^{3}dyn is not dependent on existing Wi-Fi structures, thereby enhancing operational stability.

The router also enables remote maintenance, granting access and troubleshooting from the research lab in Dortmund in case of faults during operation in Munich. The router was installed in the vehicle's control cabinet and connected to 5G antennas, mounted at the front of the vehicle, via antenna cables. The antennas were connected to the vehicle frame using 3D-printed adapters. Additionally, the router features a four-port switch that manages internal vehicle communications and is connected to the embedded PC and the laptop running the navigation software components. Furthermore, the two rear laser scanners, used for load handling among other functions, are connected to other components through the router-integrated switch.

2.3 Software development

After analysing the Simultaneous Localisation and Mapping (SLAM) approaches available in the open-source community, two solutions proved suitable for our use case in the highly dynamic airport environment. The first one, named SLAM Toolbox (Macenski and Jambrecic, 2021), was introduced to the ROS community in 2019. The second one, called Cartographer (Hess *et al.*, 2016), was developed by Google and initially published in 2016. Both Cartographer and SLAM Toolbox use an internal pose graph in the SLAM process.

A pose graph consists of nodes and edges, where each node represents a robot pose and a laser measurement. Nodes are added to the graph either after the robot has travelled a certain distance or after a specified amount of time. Subsequently, nearby poses are connected by consecutive edges that model spatial constraints between the nodes. If the robot revisits a previously encountered part of the environment, non-consecutive edges can be added to the graph, a process known as loop closing.

The main concept behind the pose graph is to find a node configuration for all nodes in the graph that minimises the total squared error introduced by the spatial edge constraints. To achieve this, various graph optimisation techniques can be applied to the pose graph. Another major advantage of the graph-based SLAM approach is that the occupancy grid map is not necessarily required to keep up an accurate robot pose over time. This can significantly minimise the required computing power, especially for very large maps.

Cartographer proved to be the most suitable graph-based SLAM algorithm for our use case because it can consider nearly all sensor data available on the robot in the "out of the box" version. The sensor data include wheel odometry, 3D point clouds from the Velodyne VLP-16 and 2D scans from the same sensor (see Figure 4, left). Furthermore, acceleration and velocity data from an Xsense-MTI-100 inertial measurement unit (IMU) are used (see Figure 4, centre).

Owing to the existing wheel kinematics (Mecanum wheels and height-adjustable chassis), the wheel odometry is subject to significant error, which increases proportionally to the robot's

Figure 4. Velodyne VLP-16 LIDAR sensor (left), XSense MTI-100 IMU (centre), Sparkfun GPS-RTK2 Board – ZED F9P (right). https://www.aeroexpo.online/de/prod/velodyne/product-176220-32079.html, https://www.mouser.de/ProductDetail/Movella-Xsens/MTI-100-2A8G4?qs=B6kkDfuK7%2FD4DcRKGaHttg%3D%3D, https://www.sparkfun.com/sparkfun-gps-rtk2-board-zed-f9p-qwiic-gps-15136.html. Source: Authors' own work

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travelled distance. Meanwhile, an Extended Kalman Filter (EKF) keeps the error within a range acceptable for navigation tasks. The EKF is a generalised form of the Kalman Filter (KF) and is suitable for the state estimation of nonlinear systems. Inside the filter, the odometry pose is fused with the nine-axis acceleration and velocity values from the IMU.

When generating the occupancy grid map, all 16 layers of the VLP-16 as well as the 2D scan are used, meaning all layers are projected onto a 2D plane. Consequently, the map also contains range data of the upper measuring rings and significantly more features alongside a spatial representation of the environment.

It is important to note that the 3D sensor data of the VLP-16 must be pre-filtered due to the measurement principle's nature, as some of the 16 layers hit the ground. These radial lines are removed by the implemented pre-filtering. The underlying filter algorithm is based on a progressive morphological filter primarily developed for removing nonground measurements from airborne LIDAR data (Zhang *et al*., 2003). If the radial lines are not removed by filtering, problems occur during the mapping process. In such a case, the SLAM algorithm adds an obstacle to the map in the form of circular measurement data. Figure 5 shows the sensor data of the VLP-16 before and after filtering. Applying the filter to the raw sensor data does not affect the 20 Hz scan frequency.

To test the SLAM algorithm, the environment most similar to the air cargo testbed was selected at the laboratory in Dortmund, Germany. The mapping process covers an area of 137 × 116 meters, corresponding to a total area of 15,892 m^2. The test area provides sufficient space to test the SLAM algorithm's performance under realistic conditions and ensure that the generated map is spatially accurate and consistent over time. The test area was specifically chosen because it offers the maximum possible environmental range and includes indoor and outdoor driving (see Figure 6).

As a result, it efficiently encompasses the widest possible range of structures in the test field. The trajectory, indicated by the dashed line, was defined using an implemented tool to ensure that both indoor and outdoor areas were traversed. The total route covers approximately 143 m, with two further locations, L1 and L2, having been defined. A location can serve as a destination point, but it can also be associated with an action, such as picking up or offloading.

In addition to the previously mentioned sensors, O^3dyn employs GPS data for navigation through two antennas that serve as GPS signal receptors. Placed diagonally at the front right and rear left of the robot, each one is connected to a SparkFun GPS-RTK2 board, which features a U-Blox ZED-F9P module (see Figure 4, right). The German state of North Rhine-Westphalia provides the RTK data via the SAPOS satellite positioning service. To receive said data, O^3dyn must maintain a stable Internet connection. A corresponding ROS node establishes a connection to the O^3dyn-assigned SAPOS server and receives the RTK data, which is then sent to the ZED-F9P module via a serial interface. This module calculates a robot pose based on the GPS and RTK data, achieving accuracy in the single-digit centimetre range.

In indoor or transition areas between indoor and outdoor environments, there is no sufficient GPS signal coverage, meaning no reliable DGPS pose can be calculated. Another

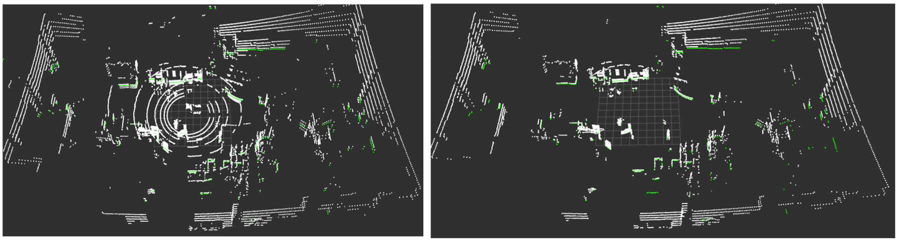

Figure 5. Velodyne VLP-16 LIDAR raw data (left). Filtered point cloud (right). Source: Authors' own work

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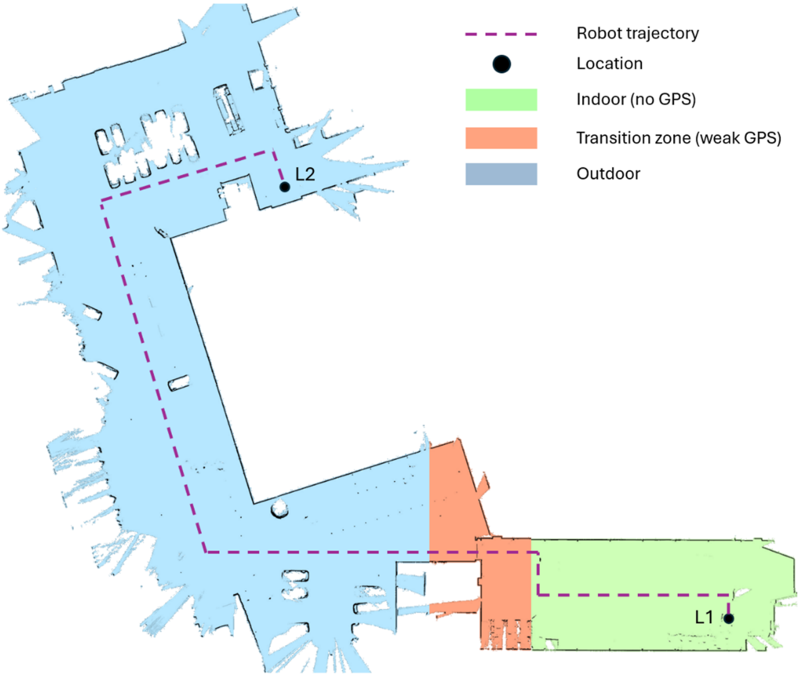

Figure 6. Map of the test area. Source: Authors' own work

issue, in addition to transition areas, is outdoor spaces where tall buildings create shading that obstructs much of the sky's visibility.

3. Empirical testing

This section outlines the on-site test preparations at Munich Airport, followed by the development of the test parameters.

3.1 Testbed overview and preparations

Overall, O^3dyn was deployed for ten days from April to May 2024 at the Munich airport testbed to carry out transport tasks between three warehouses with a total of three storage locations. The warehouses are connected by a busy road used by regular forklifts, tugger trains, other vehicles and pedestrians.

To minimise the risk of accidents, the robot moves along fixed trajectories and stops if its path is blocked by a static or dynamic obstacle. Since this was the first deployment of O^3dyn in a real industrial environment, the transport tasks were manually created using purpose-built software in a safe and controlled process before being sent to the robot. To ensure the highest level of safety, the execution of the transport tasks was visually monitored by two scientists, allowing the robot to be manually stopped in an emergency, such as an imminent collision. O^3dyn functions as a transport robot designed to operate autonomously within the intricacies of air cargo logistics.

The system was tested in conjunction with other robotic systems (see discussion in Section 5), including the Spot® robot for large storage pallet (LSP) identification and Emma, an automated forklift for on- and offloading. The integration of these systems was critical, as they needed to work collaboratively to streamline the cargo handling procedures at the airport.

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During the test period, O^{3}dyn was tasked with transporting EPALs from storage areas to designated processing locations, such as other warehouses, demonstrating its ability to dynamically navigate in changing environments filled with obstacles, such as personnel and other machinery. Within the cargo handling procedure, O^{3}dyn operates at the nexus of LSP unloading and providing the cargo stored on EPALs for the subsequent handling process (see Figure 7).

A major challenge in this operation is the 0.18 m height difference between the hall floor and the LSP, which cannot be effectively handled by O^{3}dyn alone. Moreover, the existing infrastructure does not provide for vehicles to access or drive onto the LSP. To address these challenges, a specialised ramp has been developed to facilitate O^{3}dyn's LSP access (see Figure 8).

This ramp serves as a crucial transition point in the transport process, allowing for O^{3}dyn's seamless movement (see Figure 9). During the transport process, the LSP is positioned in front

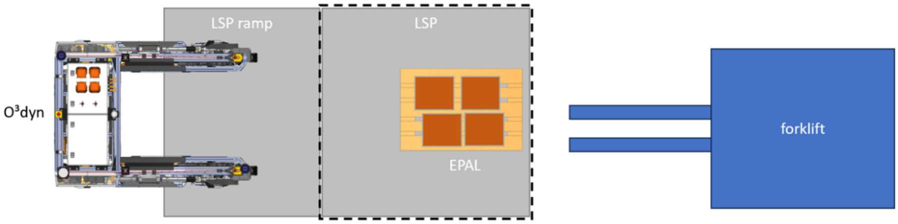

Figure 7. Top-down view of O^{3}dyn in the test layout, showing the handover position of the EPAL stored on the LSP. Source: Authors' own work

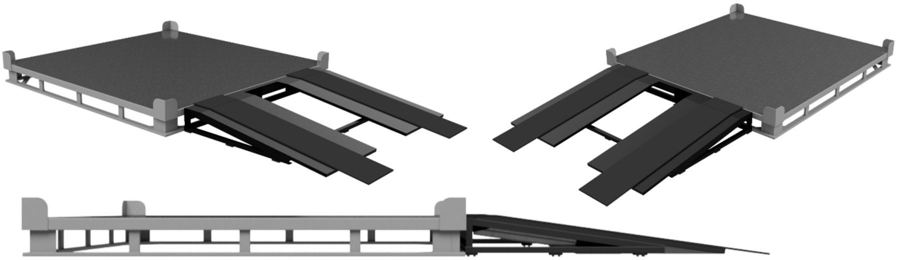

Figure 8. 3D model of the LSP and the developed ramp in front of it. Source: Authors' own work

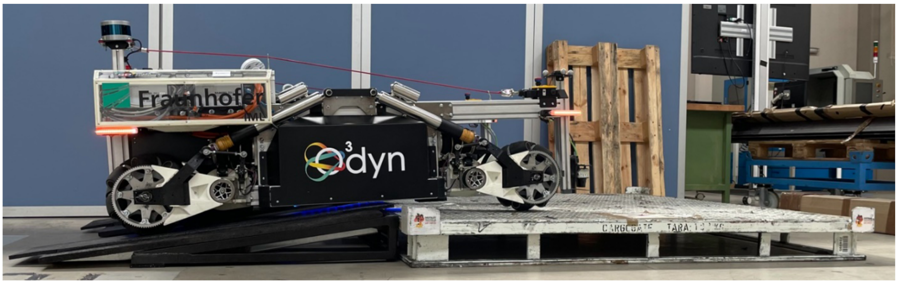

Figure 9. O^{3}dyn transitioning onto an LSP via the ramp in the laboratory. Source: Authors' own work

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of the ramp, creating a smooth transition. The ramp has been carefully designed to ensure it is adequately sized for O^{3}dyn and capable of supporting the weight of a fully loaded vehicle.

This enhances the efficiency of the transport process and ensures operational safety and reliability while transporting heavy cargo (Drljača *et al.*, 2020). The ramp's deployment represents a significant advancement in the system's logistical capabilities.

O^{3}dyn's field tests at Munich Airport required thorough preparation to ensure compliance with regulatory standards and operational efficiency. Key activities included obtaining necessary approvals, securing insurance, establishing signage, conducting employee briefings, marking the ground, setting up project offices and creating designated parking and loading areas.

To initiate the testing phase, all necessary approvals were obtained from airport authorities and regulatory bodies by the involved DTAC project partners. Comprehensive insurance coverage was obtained from KRAVAG-Logistic Versicherungs-AG, which included coverage for the robot fleet valued at approximately € 450,000, as well as € 100 million in liability insurance, including aviation-specific risks, thereby ensuring financial protection during operations. Visible markings and signage were implemented throughout the testing area to delineate safe zones and operational pathways for both robotic systems and personnel. These markings were designed to facilitate navigation and minimise the risks of accidents. Employee briefings were essential to educate personnel about the O^{3}dyn system's functionalities as well as safety protocols to follow during testing.

A project office was established at the airport to coordinate all activities related to the O^{3}dyn testing. This office served as a hub for data collection, test operation monitoring and communication among team members. Furthermore, designated parking and loading positions were defined to streamline cargo transfer between O^{3}dyn and other operational units.

3.2 Test parameters

The testing phase was carefully planned, emphasising the need for structured testing protocols (Edlinger *et al.*, 2022). A comprehensive methodology was developed to evaluate each robotic system's functionalities and address both normal and disrupted operational conditions. This structured approach ensured that all tests were aligned with the overall project objectives.

Various test parameters were defined for O^{3}dyn's transport tasks between storage locations. These included directions, floor types, velocity, loads, static and dynamic hindrances, as well as weather conditions. Extreme cases, such as very tall or heavy loads, were deliberately analysed. A total of 305 functionality tests were defined for evaluating O^{3}dyn, to assess as many as possible while the robot executed transport tasks during airport operations.

Throughout the test period, a total of 36 transport tasks were completed, and critical metrics, including travel time, distance, speed, load weight, battery status, number of manual interventions and any errors encountered, were documented for each executed transport order. This comprehensive data collection allowed for an in-depth analysis of the system's performance under varying conditions, contributing significantly to the understanding of its operational capabilities.

The testing methodology was designed to encompass a variety of scenarios to simulate real-world conditions. Different environmental factors were considered to ensure that the robotic systems could adapt to the challenges presented by the airport setting. This involved testing the systems under different lighting conditions, a range of flooring types and various obstacles that could affect the robots' navigation.

4. Results

It could be shown that the SLAM algorithm was able to generate a consistent and spatially accurate map of the operational environment. The DTAC test field area mapped using the SLAM algorithm covers an area of 402 × 398 m, corresponding to a total area of 159,996 m^2 and exceeding that of the laboratory tests by roughly one order of magnitude.

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The mapping process was carried out during early morning hours to ensure minimal dynamic interference, meaning vehicular traffic was low and the test area was vacant of air cargo, which might otherwise obscure static environmental features. Figure 10 shows the generated occupancy grid map, including the robot trajectories between the three storage locations. Also depicted is the parking location L0 and the three partner warehouses of Cargogate (L1), DB Schenker (L2) and CHI Cargo (L3). Furthermore, the indoor and outdoor areas are colour-coded. It should also be noted that there was insufficient GPS signal coverage in the roofed outdoor area.

During the tests, it became apparent that the SLAM algorithm had difficulties maintaining the map's internal consistency under certain conditions. This issue occurred when a large amount of air cargo was unloaded from trucks and placed kerbside. In this case, the environment changed so drastically in an extremely short period of time that the local SLAM component of the Cartographer could no longer integrate the newly created sub-maps into the existing map accurately, leading to Cartographer's inability to maintain accurate localisation over time.

To ensure more consistent localisation, a particle filter (Dellaert *et al*., 1999) was used in Cartographer's place. The input data for the particle filter consist of the occupancy grid map and the 2D scan data from the Velodyne VLP-16. Owing to the map's size, small static obstacles (<10 cm) were manually removed from it to minimise the particle filter's computation time of the particle filter. This approach ensured accurate localisation over time, even in extreme situations where the environment had significantly changed. Additionally, videos of the 36 transport tasks with a total length of 3 h and 20 min were systematically analysed to explore noticeable hardware or software issues.

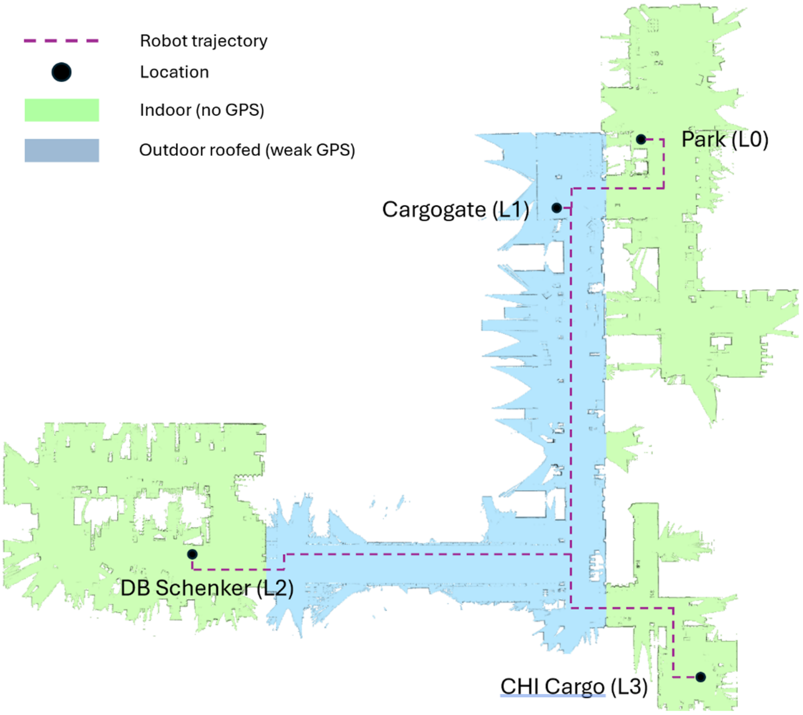

Figure 10. Map of operational area, including robot trajectories, Munich Airport. Source: Authors' own work

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Table 1 provides a detailed overview of the recorded data during transport order execution. The transport orders presented in this table were executed alternately between Cargogate (L1) and DB Schenker (L2). Between these two storage locations, a total of 18 orders were carried out, covering a total distance of 3,327 m. In 98.68 min of driving time, O^3dyn successfully transported 4.080 kg between the two locations, demonstrating its capacity for continuous and reliable operation in the airport environment. In total, the supervising operators had to intervene manually six times during the operation, with each manual intervention being triggered by traffic scenarios that O^3dyn could not resolve independently, primarily due to its constraint to a predefined trajectory that limited its reactive capabilities.

From a general perspective, traffic scenarios can be categorised as either simple or complex. Simple scenarios include stopping in a timely manner when the route is blocked, resuming driving when the route is clear again, as well as simple intersection situations with a maximum of two participants, including O^3dyn itself. Complex scenarios involve intersection situations with more than two participants and cannot be resolved by the robot itself. Manual interventions were only necessary in complex situations. This is due to O^3dyn's lack of traffic perception and prediction.

Besides the manual interventions, three distinct error cases were observed during the execution of the transport tasks. In task ID 1, a trajectory-related issue was identified in which a waypoint was assigned an incorrect robot orientation, causing it to approach the target position with a 180° offset. To be precise, this is not a direct error caused by the robot, but rather a human-made mistake during the software-assisted creation of the route. This type of error typically occurs when the routes are traversed for the first time and can be resolved by manually adjusting the robot's orientation at the specific target position.

In task ID 6, a dynamic obstacle that briefly crossed the vehicle's planned path mistakenly persisted in the local costmap. A costmap is typically *n* x m meters in size, depending on the robot's dimensions and represents the difficulty of traversing different areas. It is a fundamental concept in ROS navigation, divided into global and local costmaps. The global

Table 1. Executed transport orders between the Cargogate (1) warehouse and DB Schenker (2)

Transport id	Source/ Destination	Time [min]	Distance [m]	Velocity [m/s]	Load weight [kg]	Battery state [%]	Manual interventions	Errors
1	1/2	05:39	185	0.8	160	42	0	1
2	2/1	05:42	185	0.8	160	41	0	0
3	1/2	05:42	186	0.8	160	41	2	0
4	2/1	05:41	185	0.8	160	40	0	0
5	1/2	05:41	184	0.8	190	83	0	0
6	2/1	10:21	186	0.8	190	72	1	1
7	1/2	04:28	185	1.2	190	71	0	0
8	2/1	04:40	185	1.4	190	71	0	0
9	1/2	06:00	185	0.8	190	70	0	0
10	2/1	04:25	184	1.2	190	69	0	0
11	1/2	04:48	184	1.2	190	68	0	1
12	2/1	05:22	185	1.2	190	66	1	0
13	1/2	04:18	185	1.0	320	66	1	0
14	2/1	04:52	184	1.0	320	65	0	0
15	1/2	05:38	185	1.0	320	60	0	0
16	2/1	04:48	185	1.0	320	59	0	0
17	1/2	05:16	184	1.0	320	59	1	0
18	2/1	05:20	185	1.0	320	57	0	0
Sum		*98.68*	*3,327*	*∅ 0.98*	*4,080*		*6*	*3*

Source(s): Authors' own work

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costmap includes static obstacles represented as cost values from the occupancy grid map generated by the SLAM algorithm, while the local costmap contains only dynamic or transient objects that appear in the LiDAR data. Normally, objects are removed when they exit the LiDAR sensor's field of view. However, during task 6, artefacts from a non-existent object remained, blocking the already planned path. Since the dynamic obstacle avoidance was disabled to give the robot a driving behaviour that is predictable for other participants in traffic, the only possible action was to remain stationary. The solution was to restart the software component responsible for updating the local map.

Finally, in task ID 11, the pallet loading procedure failed, resulting in the unsuccessful completion of the transport task. In detail, the fine positioning in the angular component was not precise enough. In this case, the reason was insufficient floor traction, which resulted in wheel slip. To fix this error, the robot was positioned by the remote control in the correct alignment, and the load pickup process was triggered again. These incidents highlight limitations in trajectory planning, environment representation and interaction with peripheral systems, which should be addressed in future iterations of the system.

Table 2 presents detailed data recorded by O^3dyn during the execution of transport tasks between Cargogate (L1) and CHI Cargo (L3). A total of 18 transport tasks were executed between these two locations. In total, the pure driving sums up to 74.24 min, the distance covered was 2,600 m and the total weight transported during the tasks was 4,460 kg. Furthermore, it is worth noting that seven manual interventions were required. As in the previous scenario between L1 and L2, all interventions were related to traffic situations that O^3dyn was unable to resolve autonomously, primarily due to the deactivated dynamic obstacle avoidance. No errors occurred during the execution of these 18 transport tasks. Moreover, the tables indicate that O^3dyn's maximum velocity varied between 0.8 and 1.6 meters per second.

These adjustments were made prior to each transport task and based on the traffic conditions. The payload weight also varied between 190 and 320 kg, representing a medium load within the available capacity and approaching the upper limit of the system's payload

Table 2. Executed transport orders between the Cargogate (1) warehouse and CHI Cargo (3)

Transport ID	Source/ destination	Time [MIN]	Distance [M]	Velocity [M/S]	Load weight [kg]	Battery state [%]	Manual interventions	Errors
1	1/3	03:44	144	1.2	190	68	0	0
2	3/1	03:49	144	1.2	190	68	0	0
3	1/3	04:02	144	1.0	190	67	0	0
4	3/1	03:52	144	1.0	190	66	0	0
5	1/3	04:01	145	1.0	190	65	0	0
6	3/1	04:02	145	1.0	190	64	0	0
7	1/3	04:08	144	1.0	190	64	0	0
8	3/1	04:37	145	0.8	190	63	0	0
9	1/3	04:52	144	0.9	190	62	1	0
10	3/1	04:11	144	0.9	190	61	0	0
11	1/3	04:43	145	1.0	320	100	0	0
12	3/1	04:41	144	1.0	320	98	0	0
13	1/3	04:47	145	1.2	320	96	4	0
14	3/1	03:58	145	1.2	320	95	0	0
15	1/3	03:39	144	1.4	320	92	0	0
16	3/1	03:38	145	1.4	320	90	0	0
17	1/3	03:48	144	1.6	320	88	2	0
18	3/1	03:45	145	1.6	320	87	0	0
SUM		*74,26*	*2,600*	*∅ 1.13*	*4,460*		*7*	*0*

Source(s): Authors' own work

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capacity, respectively. Considering the battery status, it can be observed that battery consumption ranged from 0% to 3% depending on the payload and maximum speed for each task. To test the localisation system's limitations, a load that significantly restricted the 360° field of view of the VLP-16 was deliberately created (see Figure 11, left). It was observed that the restricted field of view had minimal impact on the reliability of the localisation component. It was also found that the load, up to the maximum weight of 320 kg, had no significant impact on the driving performance.

Using an evaluation matrix provided by the Association of German Engineers (VDI), O^3dyn's evaluated autonomy index was determined to be 20% (Albrecht *et al.*, 2021). The matrix establishes specific criteria to distinguish autonomous systems from driverless automation solutions, acknowledging the shift in logistics process structures toward real-time, decentralised control and decision-making (Kopfer and Schönberger, 2011; Windt *et al.*, 2010). O^3dyn dynamically updates the environment model and operates in areas instead of fixed routes. Other autonomous functions, such as obstacle avoidance and object recognition have yet to be fully developed for field operations.

This indicates that while the system can perform specific tasks autonomously, it still requires significant development to operate independently in a fully dynamic environment (Fottner *et al.*, 2021). As previously mentioned, some autonomous functions that were successfully tested in a laboratory environment, such as dynamic obstacle avoidance, could not be tested at Munich Airport.

Besides obstacle avoidance, improvements in route planning and task sequencing are essential to enhance the robot's operational efficiency. Of the 305 defined functionality tests, 146 were operationally feasible and approved, of which 142 were considered successful. Tests were not conducted on driving behaviour on spilled oil and dangerous substances (due to lack of approval), as well as operations in heavy rain and other extreme weather conditions (not applicable). No accidents or injuries occurred during testing.

5. Discussion

This section provides a comprehensive analysis of the findings from the tests conducted with the O^3dyn automated cargo transport system at Munich Airport. It begins with a summary of the results, followed by an overview of the multi-robot testbed processes, an economic evaluation of the O^3dyn system and an outline of both theoretical and managerial learnings, as well as the limitations encountered.

5.1 Summary of results

The tests revealed several challenges inherent in deploying an autonomous system within a busy airport environment. One significant issue was the need for robust obstacle detection and

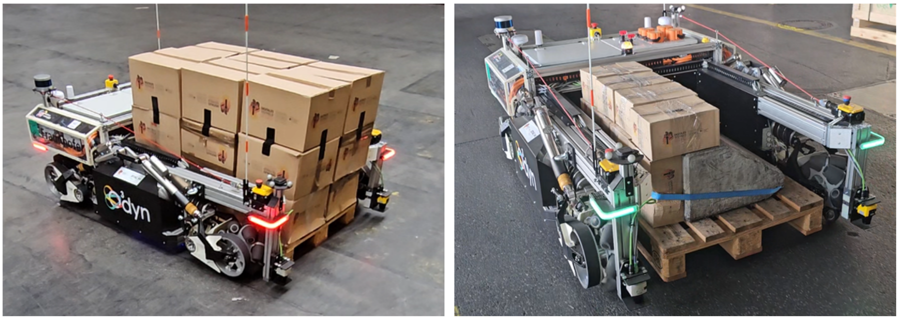

Figure 11. O^3dyn with a high load consisting of cartons (left) and with the heaviest load (320 kg) in the tests (right). Source: Authors' own work

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navigation capabilities. O^{3}dyn encountered difficulties when faced with unexpected obstacles or when operating in narrow spaces, necessitating the presence of a human operator to intervene during critical situations. This reliance on human oversight highlights the need for further advancements in the robot's autonomy, particularly in its ability to make real-time decisions in complex environments. Furthermore, the manual interventions described in Section 4 suggest improvements in the area of traffic perception and prediction. For example, it would be useful to predict the trajectories of human-operated vehicles for a certain time to respond accordingly.

Moreover, the varying conditions, such as changes in lighting and the presence of diverse cargo types, posed additional challenges for O^{3}dyn's sensors and navigation algorithms. The need for a stable and reliable communication infrastructure was also emphasised, as uninterrupted connectivity is essential for the effective operation of autonomous systems in such dynamic settings. The integration of advanced communication technologies, such as 5G systems, was crucial in addressing these connectivity issues, allowing for real-time data exchange and remote monitoring capabilities.

5.2 Multi-robot process flow

The testing phase revealed critical insights into the interaction between O^{3}dyn and other robotic systems deployed at Munich Airport, as illustrated in Figure 12. This schematic representation outlines the complete process flow of air cargo handling, highlighting the roles of various robotic deployments along the import process chain. A depicted airport import process starts with the unloading of larger aviation-specific cargo units, known as unit load devices (ULDs), from the aircraft and ends with the handover of consolidated or single goods to public road trucking. Furthermore, the open-source solution openTCS was used as a manufacturer-independent and centralised control system software to strengthen the multi-robot fleet approach (Franke *et al.*, 2023). Similar to multi-agent systems for autonomous aircraft movements and air traffic control (von der Burg and Sharpanskykh, 2025), such solutions could potentially control growing robotic fleets for airport ground operations in the cargo sector and beyond.

Overall, O^{3}dyn cannot be regarded as a standalone solution, as air cargo processes are characterised by various tasks that require distinct specifications for human–machine interaction, loading units, haptics, weights, paths and other factors. The robot was specifically designed to operate in environments where traditional forklifts currently manage the transportation of EPALs. In its current configuration, O^{3}dyn is not yet equipped to handle ULDs or individual packages not stored on EPALs.

However, its first successful integration into the existing airport workflow demonstrates the potential benefits for air cargo logistics automation. The successful coordination between O^{3}dyn and other robotic systems is vital for streamlining operations and enhancing overall efficiency in air cargo handling (Lange, 2019). For instance, while O^{3}dyn manages the transport of EPALs between storage locations, Emma focuses on loading and unloading tasks and Spot® assists in identifying LSPs. This collaborative operation not only minimises manual labour but also optimises the workflow by ensuring that each robotic unit operates within its designated capacity.

Additionally, the openTCS control system has been employed experimentally to manage these robotic systems. This software offers the potential for centralised and integrated control of future heterogeneous robot fleets at airports, allowing for more coordinated and efficient operations across various robotic platforms (Gebser *et al.*, 2018).

5.3 Economic evaluation

In terms of economic considerations, the net present value method is applied to assess the economic feasibility of deploying O^{3}dyn at a medium-sized airport [3]. For simplification purposes, a greenfield approach with initial investments for two options, including a fully

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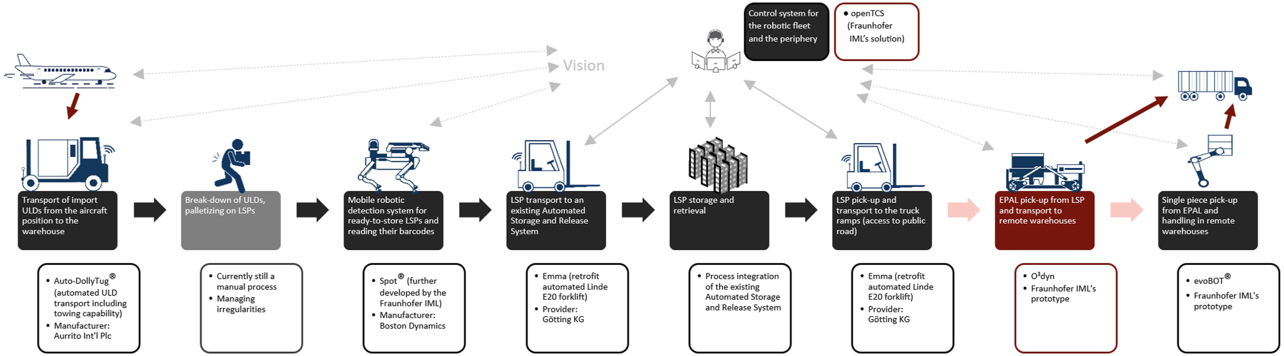

Figure 12. Schematic representation of robotic deployments along the import process chain of air cargo handling at airports. Source: Authors' own work

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manual process and a 50% replacement of manual forklifts with O^3dyn robots, is considered. In the brownfield context, as described in Section 1, there are many factors influencing the successful implementation of a robot fleet. These factors include, among others, a lack of space, the flexible nature of the processes and limited standardisation regarding goods and loading units along airport material flow.

Conversely, greenfield approaches provide the opportunity to define new standards for certain facilities around robotic solutions, as examples from Paris [4] and Amsterdam [5] airports illustrate. This evaluation of O^3dyn in the context of the DTAC project at Munich Airport builds on the empirical insights gathered during testing, as outlined in Sections 3 and 4 and is anchored in a series of critical assumptions.

(1) *Operational Framework*: As highlighted in Section 2, the current operational setup involves six forklifts facilitating transport between three warehouses, with two forklifts assigned to each partner (CHI, DB Schenker and Cargogate) across two shifts.

(2) *Labour Considerations*: The analysis assumes that each forklift requires approximately 1.25 drivers per shift, accommodating factors such as vacation and sick leave, with an annual gross salary approximating €48,000.

(3) *Capital Expenditure*: In the hypothetical greenfield project scenario discussed in Section 2, the estimated investment is €40,000 per forklift, totalling €240,000 for six units, with annual maintenance costs projected at €10,000.

(4) *Alternative Automated Solution*: Opting for a semi-automated approach utilising three O^3dyns to cover 50% of the baseline workload 24 h per day, an investment of €250,000 per O^3dyn is anticipated alongside a corresponding reduction in staffing requirements.

(5) *Additional Expenditures*: The implementation of a robotic control system incurs an estimated cost of €100,000, with 10% allocated for implementation and a further €50,000 earmarked for necessary infrastructure adjustments.

(6) *Mixed-Model Cost Implications*: In a 50:50 operational model, maintenance costs are expected to rise by 50% to €15,000 annually, along with additional annual fixed costs of €35,000 for qualified personnel to monitor the automated operations.

(7) *Risk Mitigation*: Insurance and damage costs are projected to decrease from €25,000 to €10,000 annually in a more automated environment.

(8) *Economic Assumptions*: Ongoing costs are subject to a 3.75% annual inflation rate and a discount factor of 9.75% is applied to reflect the innovative nature of this project, both representing conservative estimations.

(9) *Future Considerations*: It is crucial to note that the current analysis does not account for potential increases in training demands, the need for teleoperators in complex traffic scenarios and possible synergy effects among the three industry partners in the event of joint investments.

Given these foundational assumptions, the calculated payback period for the O^3dyn system stands at approximately 2.99 years (i.e. 3 years and 0 months). Over a seven-year horizon, the present value of anticipated cost savings is estimated at around €951,500 (calculation model shown in Appendix 1).

5.4 Theory learnings

This paper contributes to the theory presented in Section 1 by providing empirical insights into the integration of automation and digital technologies within air cargo logistics. It illustrates the practical challenges and opportunities of implementing autonomous systems, such as the

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O^3dyn robot, in dynamic airport environments. By establishing a connection to theoretical frameworks related to Industry 4.0 and 5.0 (Moghaddam and Klumpp, 2025), as well as system-level optimisation (Zhi, 2025), the paper enhances the understanding of technological adaptation in logistics settings, offering a robust case study that informs future theoretical developments.

The findings of this project demonstrate that while robotic systems can be effectively integrated into existing air cargo logistics processes for testing purposes, their current levels of autonomy remain limited. Most functionalities assessed during the tests can be classified as automated driving, with robotic systems still requiring human intervention for critical tasks.

The identified research opportunities span several areas for future exploration. Firstly, the (re)development of robotic systems should focus on air cargo-specific load carriers that can accommodate the unique requirements of this environment (Bolanakis *et al.*, 2019). Secondly, there is a need to consider the overall process chain, including both operational areas and aircraft positions, to ensure that robotic solutions are effectively integrated into the entire logistics workflow (Brandt and Nickel, 2018). Finally, the integration of robotic fleets and control systems into the complex IT architecture of airports is essential for achieving optimal efficiency (Bierwirth and Scheiber, 2023).

5.5 Management learnings

The findings of this paper offer valuable insights for management in the air cargo industry, particularly regarding experimental design, execution and economic feasibility. The study emphasises the importance of meticulous planning and coordination between autonomous robots and human operators to ensure smooth operations. It highlights how the integration of robotic solutions can improve operational efficiency and reduce labour costs, while also identifying critical areas for investment and collaboration among industry stakeholders. The following aspects should be considered by air cargo management:

(1) *Technological Infrastructure:* Invest in robust communication networks (e.g. 5G) for autonomous operations and ensure scalability of technological infrastructure for future advancements.

(2) *Coordination:* Establish communication protocols for real-time decision-making.

(3) *Performance Monitoring:* Establish key performance indicators for robotic systems and conduct regular evaluations for continuous improvement (Faveto *et al.*, 2021).

(4) *Training:* Develop comprehensive training programs for staff on robotic systems.

(5) *Incremental Implementation:* Start with pilot projects to test robotic systems in specific environments and gradually increase task complexity to build capabilities.

(6) *Collaboration:* Foster collaboration among industry stakeholders for shared insights and risks.

(7) *Regulatory Challenges:* Engage with regulatory bodies early to understand compliance requirements.

5.6 Limitations

This paper presents several limitations that must be acknowledged to provide a balanced perspective on the findings.

Single Airport Focus: The research is conducted exclusively at Munich Airport, which may not represent the complexities and challenges faced at other airport environments. Each airport has unique operational characteristics, regulatory frameworks and infrastructure, which can affect O^3dyn's performance and applicability. Therefore, the results may not be generalisable to other airports or different logistical contexts.

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Short Testing Duration: The empirical testing at Munich airport was conducted over a limited period of ten days. This brief timeframe may not have captured the full range of operational scenarios, including variations in cargo volumes, peak traffic times, seasonal differences and unexpected environmental conditions. Longer testing durations are essential to evaluate the system's performance under diverse and dynamic conditions, which are typical in air cargo operations.

Limited Operational Scenarios: The study primarily focuses on specific transport tasks between three warehouses, which restricts the diversity of the test scenarios. The absence of varied operational challenges, such as different cargo types, loading and unloading processes and interactions with a broader range of vehicles and personnel, limits the understanding of the system's robustness and adaptability.

Human Intervention Requirements: The findings highlight that the current O^{3}dyn system requires significant human intervention during operations. This reliance on human oversight raises questions about the level of autonomy achieved and the system's readiness for full integration into automated logistics processes.

Technology Limitations: The O^{3}dyn robot's current technological limitations include its ability to navigate complex environments and effectively detect and respond to dynamic obstacles. These challenges indicate that while the system shows promise, further technological advancements are necessary to improve its operational capabilities and reliability.

Regulatory and Infrastructure Constraints: The implementation of autonomous systems in airport environments is subject to strict regulatory requirements and existing infrastructure limitations. These constraints may hinder the scalability and adaptability of the O^{3}dyn system across different airport settings.

The outlined limitations underscore the need for further research involving multiple airports, extended testing periods and a broader range of operational scenarios. Future investigations should also focus on enhancing the technology's autonomy and addressing the challenges identified during the testing phase to facilitate successful implementation in diverse logistics environments.

6. Outlook

This paper has outlined the empirical findings from the development and testing of O^{3}dyn at Munich Airport, emphasising the challenges and opportunities in integrating autonomous systems within air cargo logistics. The insights gained from these tests provide a framework for future research and advancements in automation technologies, aiming to enhance efficiency and operational effectiveness in the air cargo sector.

Given the outlined prototyping results, the following further research steps and insights are of great interest to researchers and managers in the air cargo setting:

(1) Further insights regarding the human-technology interaction angle according to the latest Industry 5.0 and human-centric process concepts. This is important given new dimensions regarding human well-being in operations (Corbett, 2023).

(2) Improvement of outdoor automation and autonomy functionalities, particularly regarding localisation and safety, as part of a holistic system-level optimisation approach for airports.

(3) Further dedicated development steps are required to bridge the gap between technical proof and practical application for the air cargo handling business case (e.g. larger containers, increased loading capacity, fleet approach and different airports).

(4) Detailed operational and management issues must be further explored, such as process times (averages and minimum/maximum values), process costs and comparisons with existing solutions, to improve the investment case calculation.

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By carefully describing the setup, the modifications and the results of the O^3dyn development and tests, this paper suggests recommendations for both further vehicle development in air cargo handling as well as the definition of suitable test and implementation sites at airports.

The empirical data gathered over 10 days of operation offer a rare perspective on the practical challenges and operational dynamics faced by autonomous systems in a complex airport environment. Unlike previous studies that may focus solely on theoretical frameworks or controlled laboratory settings, this research bridges the gap between theory and practice by showcasing the robot's performance under real-world conditions. Thus, the findings from this project could serve as a foundation for future advancements in robotic technologies, ultimately leading to more efficient and automated air cargo logistics processes.

Within the DTAC project, a new robot is currently being developed based on the existing O^3dyn platform and collected test experiences at Munich Airport are described in this paper. This new robot shall transport ULDs, which are larger, heavier and more diverse than EPALs, along the entire airport process flow between road access and aircraft positions. The process will include both indoor and outdoor operations, as well as public and restricted roads, warehouse and apron areas and the respective links between these. The new robot is expected to be fully developed and deployed for airport tests in autumn 2026.

Altogether, this highly relevant example for the air cargo transport segment has outlined the impact and importance of automated solutions in complex logistics process environments. It highlights the need for both research and management to pursue further empirical studies that inform generalised frameworks applicable to multiple contexts in transportation and logistics. Core elements in this regard would include economic considerations in the form of specified investment calculations, as presented here in draft mode, along with conceptual elements that facilitate successful human-technology interaction, thereby enhancing overall process effectiveness.

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Manuel Wehner specialises in aviation logistics at the Fraunhofer Institute for Material Flow and Logistics (IML) in Frankfurt. He oversees the development of autonomous robotic systems for air cargo operations at the Digital Testbed Air Cargo (DTAC). Wehner studied Management and Technology (M.Sc.) in Munich and Mexico and Aviation Management (B.Sc.) in Frankfurt and Saudi Arabia. He is a lecturer and co-founder of the Institute for Aviation and Tourism (IAT). In a previous role as a project manager for Fraport AG, he led the test operation of autonomous minibuses at Frankfurt Airport in 2017.

Christian Blesing is a computer scientist specialising in localisation and navigation of automated guided vehicles at the Fraunhofer IML in Dortmund. He studied Technical Computer Science (M.Sc.) at the Westphalian University of Applied Sciences and has been active in applied research for 10 years. In addition, Blesing has worked on AI-based object detection and classification, multi-agent systems, the coordination of heterogeneous robot fleets and the creation of semantic environment maps. His contribution to the DTAC includes software development in the area of localisation and navigation.

Niklas Ullrich is a mechanical engineer and research associate at the Fraunhofer IML in Dortmund. He specialises in developing, designing and prototyping robotic transport systems for intralogistics. Ullrich played a pivotal role in creating O^3dyn within the Silicon Economy project, focusing on comprehensive vehicle concepts and mechanical design. His contributions to the DTAC encompass developing vehicle concepts, mechanical design, operational strategies and safety technology.

Max Gössner is a mechanical engineer and works as a research associate at Fraunhofer IML in Dortmund. He specialises in developing, designing and prototyping robotic transport systems for intralogistics. Gössner was part of the O^3yn design team as part of the Silicon Economy project with a focus on vehicle design concepts and mechanical and pneumatical design. His contributions to the DTAC include developing vehicle concepts, mechanical design and testing equipment.

Matthias Klumpp has a research focus on human–technology integration and digital automation issues in operations, logistics and supply chain management. He is affiliated with Politecnico di Milano (School of Management) and the University of Bremen.

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Notes

1. Funded by the German Federal Ministry for Digitalization and Government Modernisation (BMDS), DTAC seeks to explore the feasibility and efficiency of autonomous systems in the air cargo logistics sector. Alongside consortium leader Fraunhofer IML, scientific partner Frankfurt University of Applied Sciences, insurance company KRAVAG-Logistic Versicherungs-AG and industrial partners at Munich Airport (Cargogate, CHI, DB Schenker and Sovereign Speed) were directly involved in the airport tests. DTAC includes seven additional industry partners, namely Lufthansa Cargo, LUG, as well as the operators of Cologne/Bonn, Düsseldorf, Frankfurt (Fraport), Leipzig and Stuttgart airports.
2. For further details, visit: https://openlogisticsfoundation.org/licenses/(search word: "DGPS").
3. Munich Airport hosted 41.6 million passengers in 2024 and processed 311,000 tons of cargo with a total of 327,000 aircraft movements. See also: https://www.munich-airport.com/traffic-figures-263342.
4. Air France Cargo and Alstef Group (formerly BA Systèmes) have deployed a fleet of 30 cargo robots at Paris Airport (CDG) in a large facility with one type of standardised loading unit as part of a facility redesign in 1996. See also: https://alstefgroup.com/project/air-france-cargo/.
5. Dnata and Lödige Industries are planning to deploy a fleet of seven cargo robots in a newly-built facility at Amsterdam Airport (AMS). See also: https://www.lodige.com/en-us/company/about-us/news/newsdetail/lodige-industries-to-equip-dnatas-new-fully-automated-system-at-amsterdam-airport-schiphol/.

Supplementary material

The supplementary material for this article can be found online.

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