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## Implementation of robotic workstations in internal enterprise logistics: analysis of efficiency, safety, and economic benefits in the context of Industry 4.0

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**Abstract:** The article addresses the implementation of robotic workstations in internal logistics with the aim of analysing the impact of automation on the efficiency of logistics processes and identifying key factors for the successful deployment of robotic systems. Contemporary logistics processes face increasing demands for flexibility, speed, accuracy, and cost reduction, while traditional material handling and transport methods based on manual labour often result in higher error rates, inefficient use of the workforce, and increased risk of occupational injuries. In the context of digitalisation and the Industry 4.0 concept, it is therefore necessary to reassess existing practices and adopt intelligent automated solutions. The research is based on the analysis of existing implementations of robotic systems in industrial enterprises and on evaluating their benefits in terms of productivity, safety, and economic efficiency. The study examines technologies such as automated storage systems, robotic manipulators, autonomous mobile robots (AMR), and automated guided vehicles (AGV), including their integration into existing logistics processes. The results indicate a significant increase in the performance and reliability of internal transport, a reduction in operating costs and material handling errors, and improvements in workplace safety. At the same time, the main barriers to implementation are identified, including investment intensity and the need for organisational changes. The article provides recommendations for the effective integration of robotic technologies aimed at enhancing the competitiveness and sustainability of industrial enterprises.

### 1 Introduction

The rapid development of automation and digitalisation has significantly transformed industrial production and logistics systems. Internal logistics, which ensures the flow of materials, components, and information within enterprises, is increasingly recognised as a critical factor influencing productivity, responsiveness, and operational efficiency. Traditional material handling systems based on manual labour are often characterised by limited flexibility, higher error rates, and increased safety risks, which makes them less suitable for highly dynamic production environments [1]. As a result, companies are increasingly adopting robotic and automated solutions to enhance efficiency and reliability.

The concept of Industry 4.0 has accelerated the integration of intelligent technologies into logistics systems, emphasising cyber-physical systems, real-time data exchange, and autonomous decision-making processes [2]. Within this framework, automated guided vehicles (AGVs) and autonomous mobile robots (AMRs) have become essential tools for optimising internal transport, enabling continuous material flow and reducing dependency on human operators [3]. Research shows that robotic transport systems can significantly reduce throughput times and increase operational stability, particularly in high-volume production environments [4].

Automated storage and retrieval systems (AS/RS) and robotic manipulators also play a key role in improving warehouse performance and order-picking accuracy [5]. Studies indicate that the integration of robotic handling technologies contributes to higher inventory accuracy, reduced labour costs, and improved workplace ergonomics [6]. Furthermore, simulation-based analyses demonstrate that the implementation of robotic workstations can enhance system throughput while minimising bottlenecks in production logistics [7].

Despite these advantages, the adoption of robotic solutions in internal logistics remains associated with several challenges. High initial investment costs, integration complexity, and the need for organisational change management are frequently identified as major barriers to implementation [8]. Moreover, successful deployment requires not only technological readiness but also process redesign and workforce adaptation [9]. Human-robot collaboration models are therefore increasingly explored as a means of balancing automation with operator flexibility and maintaining system resilience [10].

Recent studies also highlight the importance of data-driven optimisation and digital twins in evaluating the performance of automated logistics systems before their physical implementation [11]. Such approaches enable enterprises to predict economic returns, identify risks, and optimise system configuration, thereby improving investment decision-making [12]. In addition, safety analyses confirm that robotic systems can significantly reduce accident rates when properly integrated into logistics processes and supported by adequate control strategies [13].

Overall, the literature indicates that robotic workstations represent a promising pathway toward more efficient, reliable, and sustainable internal logistics systems. However, their successful implementation requires a comprehensive assessment of technical, economic, and organisational factors, as well as a systematic approach to integration within existing production environments.

## 2 Methodology

### 2.1 Definition of problem

Company ALFA s.r.o. specialises in the production of printed circuit boards (PCBs) (Figure 1), which represent a fundamental component of most electronic devices. The production system consists of several interconnected departments, including material receiving, surface-mount technology (SMT) assembly, soldering, optical inspection, and packaging. Efficient coordination between these units is essential to ensure continuous production flow, short lead times, and consistent product quality. However, the current internal material handling system is based exclusively on manual transport performed by workers using pallet trucks and platform carts, which has proven to be increasingly inadequate for the operational demands of modern electronics manufacturing. Similar limitations of manual material handling in high-mix electronics production environments have been identified in several industrial logistics studies [14].



Figure 1 Printed circuit boards (PCB) [15]

One of the most critical bottlenecks occurs at the SMT assembly line, where delays in the delivery of components lead to machine downtime. Interruptions in material supply reduce utilisation of high-value equipment and negatively affect production stability. Research confirms that insufficiently synchronised internal logistics is a common cause of production losses in automated manufacturing systems [16]. Similar inefficiencies arise in the transfer of assembled boards to inspection stations, where limited transport capacity may result in the accumulation of semi-finished products and missed delivery deadlines.

Manual transport also introduces quality and safety risks. Improper handling may lead to mechanical damage to sensitive electronic components or mixing of batches, resulting in rework and additional operational costs. Furthermore, the system is highly dependent on human resources, meaning that staff shortages or shift fluctuations directly influence logistics performance. Such dependence on manual transport has been shown to significantly reduce system robustness and scalability in industrial production environments [9].

Additional inefficiencies are linked to suboptimal warehouse navigation and the absence of transport prioritisation mechanisms, which increases handling time and reduces material flow transparency. At the same time, labour costs associated with internal transport remain substantial while competing enterprises increasingly adopt automated logistics solutions to improve efficiency and responsiveness.

Given these limitations, the current transport system cannot respond dynamically to real-time production requirements. This creates a need for a more automated and responsive solution. One potential approach involves the use of aerial transport supported by lightweight, protective transport containers designed for safe PCB handling. Such containers combine electrostatic protection, structural rigidity, and low weight, enabling safe automated transport while maintaining product integrity (Figure 2).



Figure 2 ESD euro crates with hinged lids [17]

## 2.2 Technical conditions of implementation

Based on the analysis of the current internal logistics system, a concept for implementing autonomous aerial drones was proposed as an alternative to manual transport of materials and semi-finished products within the production facility. The concept builds on the premise that modern smart factories increasingly utilise vertical space and cyber-physical logistics solutions to improve transport efficiency and reduce congestion in ground-level material flows [18]. The use of ceiling space for automated transport represents a promising approach, particularly in environments where floor routes are already saturated with operators, carts, and equipment.

The proposed drone transport system is intended for deployment in the main production hall, which represents the most transport-intensive area of the facility. The hall covers approximately 400 m<sup>2</sup> and accommodates the primary logistics flows between the warehouse, SMT assembly line, quality control stations, and shipping area. The spatial parameters of the hall (20 m × 20 m, ceiling height 5.5 m) enable the establishment of a dedicated flight corridor at 2.5–3.5 m above the working zone, ensuring safe coexistence of aerial transport with ongoing production activities. Research on indoor UAV logistics confirms that separation of operational layers significantly reduces collision risks and improves system reliability [19].

The digital and physical infrastructure of the hall already meets key requirements for autonomous drone deployment. Full Wi-Fi coverage, stable environmental conditions, and sufficient lighting create suitable conditions for visual navigation and sensor-based localisation. Planned charging stations located near the warehouse and dispatch zone will enable continuous operation of a small drone fleet. Such infrastructure integration is consistent with current approaches to intelligent intralogistics systems, where real-time communication and automated task scheduling are essential for ensuring efficient material flow [20].

From a logistics perspective, the production system generates approximately 130-150 transport cycles per day, associated with an output of around 3,000 PCBs daily. Manual transport currently requires 6.5-8.5 labour hours per day, indicating substantial potential for automation. Autonomous drones are expected to reduce transport time per route by up to 50%, while also minimising handling risks for sensitive electronic components through stabilised payload holders and controlled motion. Furthermore, aerial transport allows a physical separation of traffic layers, which improves workplace safety and reduces congestion in narrow aisles.

The broader facility layout also supports drone-based integration. The main production hall is connected to a central warehouse occupying approximately 400 m<sup>2</sup> with multi-level shelving. Limited manoeuvring space within this warehouse restricts the efficiency of ground-based automated vehicles, further strengthening the suitability of aerial transport solutions. The proposed system therefore represents not only a technological upgrade but also a spatially optimised logistics concept capable of enhancing efficiency, traceability, and operational flexibility of internal material flows.

*Table 1 Costs for the current situation [own processing]*

<b>Number of workers providing transport</b>	4 workers
<b>Monthly personnel costs for transportation</b>	4,400 €
<b>Annual personnel costs for transportation</b>	52,800 €
<b>Average number of forms of transport per day</b>	130
<b>Average length of one transport</b>	3 minutes
<b>Average daily workload of workers for transportation</b>	6.5 hours per day

*Table 2 Cost comparison: drones vs. employees [own processing]*

Initial investment costs	30,000 €	0 €
Annual operating costs	2,000 €	52,800 €
Estimated annual cost savings after implementation	50,800 €	-
Number of transports per day	150+	max. 130
Reliability	high	fluctuating (human factor)
Transport speed	20 – 40 seconds	2 – 4 minutes
Risks	technical failure	fatigue, errors, absence
Safety	predictable	variable

From the above data (Table 1, Table 2), the current system cannot effectively serve production needs. Dependence on employees, time losses, delays and the risk of component damage led to increased costs, lower efficiency and losses. Implementing drone transport can achieve:

- Significant cost reduction (savings of up to €50,000 per year),
- Faster and more predictable material movement,
- Better traceability and safety,
- Eliminating dependence on human resources at critical points.

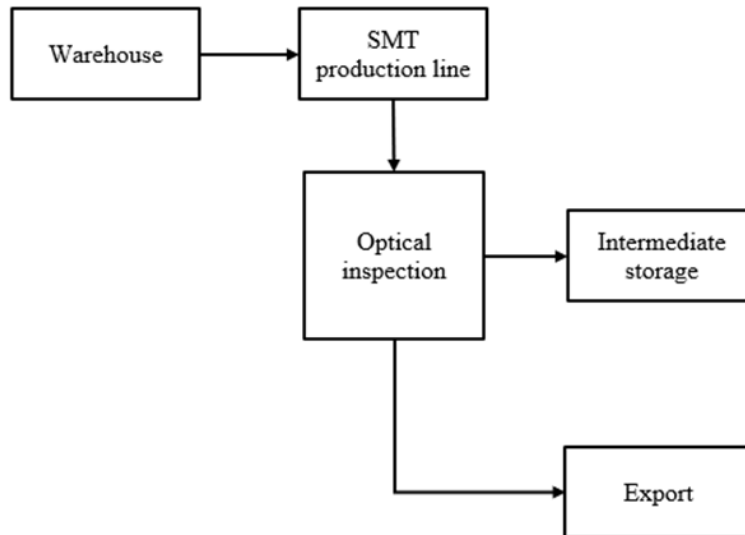


Figure 3 Current floor plan of the operation [own processing]

The methodological approach applied in this study follows a structured engineering framework consisting of five sequential steps: (1) analysis of the current internal logistics system, including data collection on transport flows, time consumption, and error rates; (2) identification of critical inefficiencies and technological limitations; (3) design of an innovative technological solution based on autonomous aerial transport; (4) technical and economic evaluation of the proposed system, including cost modelling and performance estimation; and (5) validation through comparison of key operational indicators before and after implementation. This methodology reflects standard approaches used in industrial engineering and technology design, where data-driven analysis is combined with simulation and system modelling to optimise logistics processes (Figure 3).

### 3 Implementation of the solution

Based on the analysis of material flows within the ALFA s.r.o. production hall, a concept for deploying a fleet of four autonomous indoor drones is proposed to ensure regular transport of materials between five key workstations: the warehouse, SMT assembly line, optical inspection, intermediate storage, and dispatch area. The operational model is designed as rotational, with two drones actively performing transport tasks while the remaining two remain in charging or standby mode (Table 3). Such redundancy-oriented fleet management is consistent with current approaches to autonomous logistics systems, where reliability and operational continuity are critical design criteria [21].

Table 3 Drone parameters [own processing]

<b>Max. load capacity</b>	5 kg
<b>Dimensions</b>	approx. 60 × 60 × 30 cm
<b>Flight height</b>	2 – 3.5 m above floor level
<b>Navigation</b>	visual (optical sensors) + QR points and routes on the floor
<b>Navigation accuracy</b>	±10 cm
<b>Safety features</b>	motion detection, automatic stop, software limits for height and route
<b>Average transport time</b>	20 – 40 seconds per section
<b>Flight speed</b>	1 – 2 m/s (taking into account safety near workers)
<b>Number of transports</b>	per day min. 150
<b>Battery life approx.</b>	2 – 15 minutes
<b>Charging</b>	Automatic charging in two docking stations (warehouse + expedition)
<b>Control system</b>	Central route planning, fleet monitoring, reporting

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Table 4 Drone maintenance costs [own processing]

Price of 1 drone	6,000 €
Price of the complete fleet (4 drones) including integration and software	30,000 €
Annual operating costs (maintenance, software updates, service)	2,000 €
Expected system life	5 years
After writing off the initial investment, the annual savings compared to manual transport are approximately 50,800 €	

The proposed solution introduces several technological and engineering innovations in the design of internal logistics systems. First, aerial transport significantly reduces transport time, with estimated transfer durations of 20–40 seconds compared to 2–4 minutes for manual handling. Studies on autonomous aerial logistics indicate that vertical transport layers can substantially increase throughput and reduce congestion in industrial facilities [22]. Second, sensitive electronic components are transported in stabilised holders, which minimises vibration-induced damage and handling errors. This aligns with findings that controlled robotic transport improves product integrity and reduces defect rates in electronics manufacturing logistics [23].

From a safety perspective, the drones operate in a dedicated height zone outside the reach of operators and ground vehicles. Equipped with obstacle detection sensors, emergency landing protocols, and predefined flight corridors, the system ensures safe coexistence with human workers. Modern indoor UAV systems commonly incorporate such layered safety architectures to meet industrial deployment requirements [24].

The technical configuration includes industrial indoor drones with payload capacities of up to 5 kg, combining optical positioning, QR-based localisation, LiDAR sensing, and inertial navigation to achieve centimetre-level positioning accuracy without GPS (Table 3, Table 4). Charging is ensured via automated docking stations placed near logistics nodes, enabling uninterrupted operation through rotational battery management. A central control platform manages task allocation, route optimisation, battery monitoring, and integration with manufacturing execution and warehouse systems, supporting real-time decision-making and traceability of material flows. The selected solution builds on commercially validated technologies, including systems deployed in logistics operations by companies such as IKEA and DSV. The drone platform chosen for the implementation is supplied by Verity AG (Figure 4), known for indoor autonomous inventory and transport solutions. Fleet coordination and automated docking are supported by the FlytWare control system developed by FlytBase, which enables scalable deployment and centralised fleet management.



Figure 4 An example of an industrial drone, from Verity AG, which will be added to the ALFA warehouse [25]

Through this configuration, the proposed system establishes the technological and organisational foundation for autonomous intralogistics based on aerial transport, emphasising operational efficiency, safety, and future scalability of the logistics infrastructure.

### 3.1 Expected benefits

The comparison of operational indicators (Figure 5) demonstrates not only a quantitative improvement but also a structural transformation of the internal logistics system. The reduction in transport time and increase in transport frequency indicate a shift from a labour-dependent system toward a capacity-stabilised and process-driven logistics model. Moreover, the observed cost reduction is not solely a result of workforce substitution but reflects improved utilisation of logistics resources and reduced process variability.

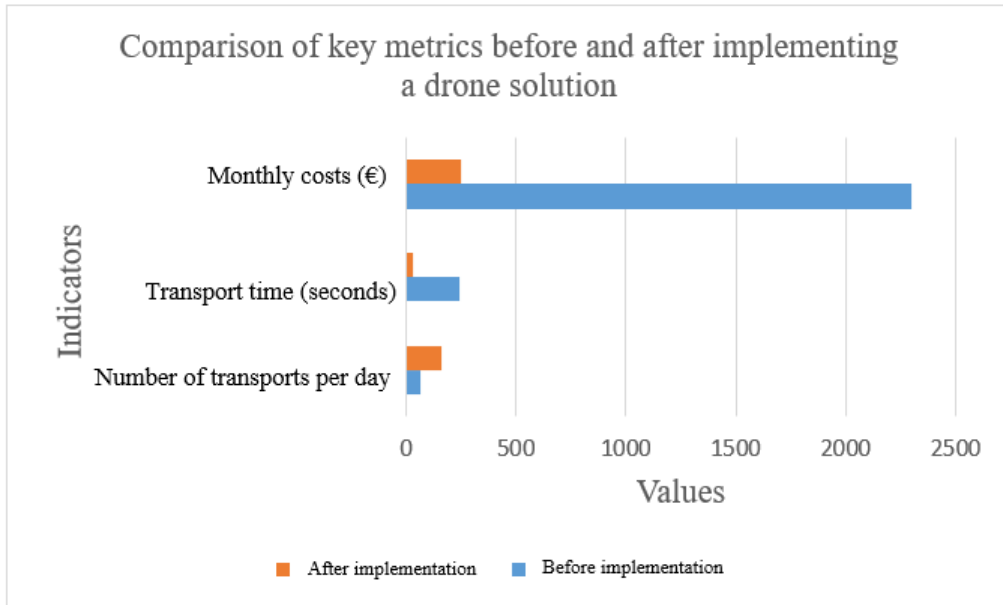


Figure 5 Comparison of operational indicators before and after drone implementation [own processing]

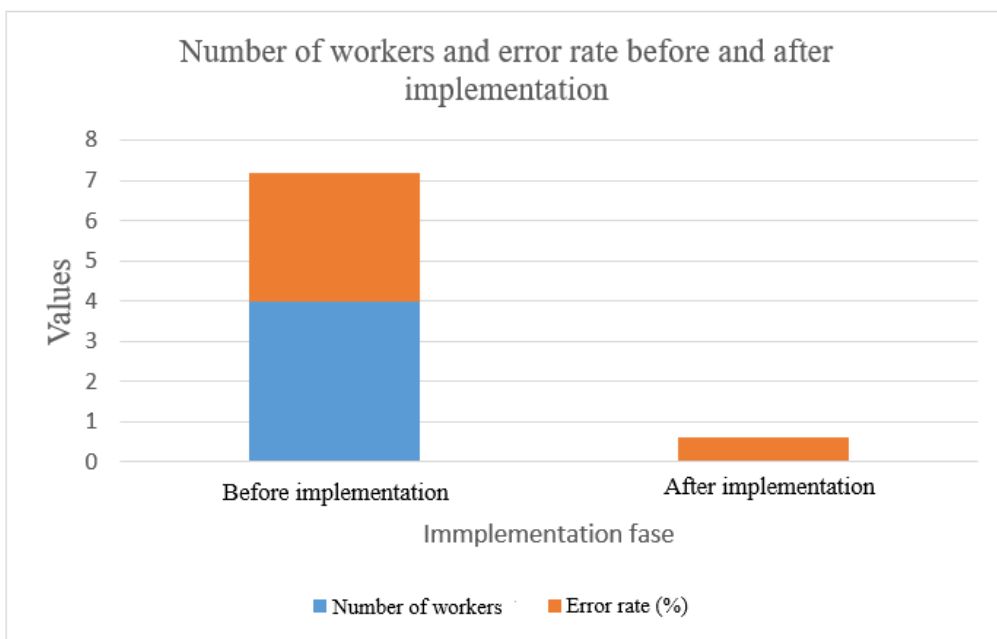


Figure 6 Change in the number of workers and error rates in transportation before and after the implementation of drones [own processing]

The reduction in error rate from approximately 3% to below 1% (Figure 6) suggests a significant improvement in process reliability, which can be attributed to the elimination of human-related variability in handling operations. The robotic transport systems in electronics manufacturing reduce defect occurrence primarily through standardisation of movement and minimisation of uncontrolled interactions with sensitive components. From a systems perspective, this improvement contributes not only to quality enhancement but also to the reduction of hidden costs associated with rework and production interruptions.

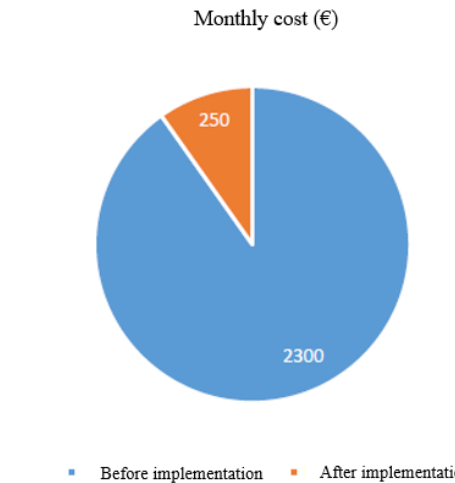


Figure 7 Reduction in labour costs after implementing drone transportation [own processing]

Figure 7 shows a comparison of monthly labour costs before and after the implementation of drone transport. The graph shows a significant reduction in labour costs due to the reduction in the need for human service.

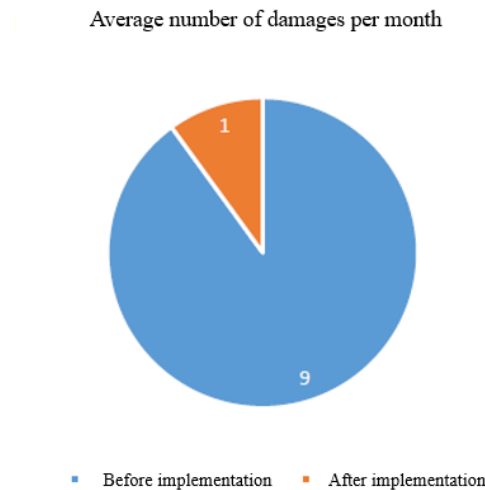


Figure 8 Reducing material damage during handling [own processing]

The decrease in material damage from an average of nine to one incident per month (Figure 8) represents a substantial improvement in handling quality. This reduction can be analytically linked to the controlled transport environment provided by drones, where predefined trajectories and stabilised payload systems minimise mechanical shocks. Similar effects have been observed in automated intralogistics systems, where the standardisation of transport conditions directly correlates with lower defect rates [23]. Importantly, this improvement has a multiplicative economic impact, as it reduces both direct material losses and indirect costs related to quality control and customer dissatisfaction.

#### 4 Results and discussion

The implementation of autonomous drones for internal material transport at ALFA s.r.o. represents a technological intervention whose effectiveness depends on a structured deployment strategy and continuous evaluation. The implementation process was therefore divided into five phases, each producing measurable outputs that enable both technical validation and organisational adaptation.

##### Phase 1: System Analysis and Design

The initial phase focused on a detailed audit of internal transport processes, including measurements of transport frequency, duration, and error rates. Such data-driven assessment is essential for successful automation projects, as empirical process mapping has been shown to significantly improve the design accuracy of autonomous logistics systems [26]. The resulting technical documentation defined drone specifications, docking infrastructure, digital architecture, and

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safe aerial corridors. This structured design approach corresponds with best practices in cyber-physical production systems, where early integration of hardware and software requirements reduces later deployment risks [27].

### Phase 2: Pilot Operation and Testing

A limited pilot deployment using one or two drones enabled verification of navigation precision, delivery reliability, and interaction safety with personnel. Experimental studies on indoor UAV logistics indicate that pilot testing significantly reduces operational uncertainty and improves path-planning algorithms through real-environment calibration [19]. The pilot phase provided quantitative performance indicators and enabled optimisation of flight routes and localisation markers before scaling the system.

### Phase 3: Employee Training

Successful automation depends not only on technical performance but also on human–system integration. Training employees in system monitoring, emergency procedures, and maintenance improves acceptance and operational reliability. Research on human-robot collaboration confirms that structured workforce preparation reduces resistance to automation and improves safety outcomes [28].

### Phase 4: Full Implementation

Following successful validation, the full fleet deployment enabled integration with enterprise and warehouse systems, providing real-time monitoring of material flows. Digital tracking of logistics operations improves transparency and decision-making efficiency, particularly when integrated with manufacturing information systems [29]. Continuous logging of transport activities also supports predictive maintenance and performance benchmarking.

### Phase 5: Operational Evaluation and Optimisation

The final phase focuses on long-term data analysis, route adjustments, maintenance scheduling, and scalability planning. Continuous optimisation is widely recognised as a core element of intelligent logistics systems, where feedback loops enhance reliability and return on investment over time [30].

## 4.1 Discussion of quantified benefits

The quantified benefits of the proposed drone system extend beyond simple time and cost savings and indicate a broader transformation of the internal logistics performance structure. The reduction of transport time from approximately three minutes to thirty seconds represents a nearly sixfold acceleration, which significantly improves production synchronisation and reduces the probability of machine idle time. Synchronisation is a critical factor influencing overall system throughput in automated manufacturing environments.

Furthermore, the reduction in labour dependency enhances system robustness by eliminating fluctuations associated with human availability, fatigue, and variability in task execution. This observation corresponds with the findings of [9], who identify workforce dependency as a key limitation of traditional logistics systems. The introduction of autonomous drones therefore not only improves efficiency but also increases predictability, which is essential for stable production planning. From an operational perspective, the system also introduces a new dimension of spatial optimisation by utilising vertical transport layers. This approach reduces congestion in ground-level logistics flows, a benefit highlighted in recent studies on UAV-based intralogistics systems [22]. As a result, the proposed solution contributes to both micro-level process improvements and macro-level optimisation of the production environment. From a broader technological perspective, the presented results confirm a growing trend in industrial logistics toward the integration of autonomous and cyber-physical systems. While previous studies have primarily focused on ground-based technologies such as AGVs and AMRs [3,9], the findings of this research extend the current knowledge by demonstrating the practical applicability of aerial transport systems in production environments with limited spatial capacity. This complements the work [22], highlight the untapped potential of UAV-based logistics in industrial applications.

Furthermore, compared to traditional automation approaches, the proposed solution introduces a higher level of system flexibility and scalability, which are key characteristics of modern Industry 4.0 technologies. In this context, the results contribute to the ongoing discussion on the role of technological innovation in enhancing production efficiency, supporting the argument that advanced transport technologies are not only operational tools but also strategic enablers of industrial competitiveness.

## 5 Conclusions

The research presented in this study demonstrates that the integration of autonomous aerial transport into internal production logistics represents a viable and effective pathway toward increasing operational efficiency in electronics manufacturing environments [31]. The analysis of the existing transport system in ALFA s.r.o. confirmed that manual handling of materials and semi-finished PCB products creates measurable inefficiencies manifested in transport delays, labour dependency, inconsistent material flow, and elevated risks of product damage. These findings are consistent with broader industrial observations that identify internal logistics as a critical bottleneck in high-precision manufacturing systems [32,33].

The proposed implementation of an autonomous drone-based transport system, supported by industrial solutions such as those developed by Verity AG and coordinated through fleet-management platforms similar to FlytBase, provides a

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technologically feasible response to these challenges. The designed model demonstrated clear performance improvements, most notably a reduction in transport cycle time from approximately 3–4 minutes to less than one minute. Such acceleration directly contributes to the minimisation of machine idle time and the stabilisation of production throughput, which are recognised determinants of manufacturing productivity in automated environments [34].

From an economic perspective, the results indicate a substantial potential reduction in labour-related logistics costs, exceeding 50% compared with the current manual system. Beyond direct savings, the system enhances cost predictability and operational resilience by reducing dependence on human availability and mitigating disruptions caused by workforce fluctuations. These outcomes reinforce existing research highlighting automation as a key driver of sustainable productivity growth in Industry 4.0-oriented enterprises [35].

Quality and safety benefits further strengthen the case for implementation. Controlled aerial transport with stabilised holders and predefined flight paths reduces the likelihood of mechanical shocks, mishandling, or component misplacement. This contributes to lower defect rates, reduced rework, and improved reliability of production output. Simultaneously, the removal of repetitive manual transport tasks reduces physical strain on workers and lowers occupational risk exposure, aligning with contemporary ergonomic and safety standards in smart factories [35].

Importantly, the proposed solution is not limited to isolated process optimisation but represents a scalable step toward comprehensive digital logistics integration. The system architecture allows future expansion through interoperability with AGV platforms, robotic handling systems, or digital production monitoring tools. Such compatibility ensures that the proposed approach supports long-term strategic transformation rather than a short-term technological upgrade.

In summary, the conducted research confirms that autonomous drone transport can significantly enhance the speed, reliability, safety, and economic efficiency of internal logistics in PCB manufacturing. The proposed implementation demonstrates strong alignment with modern trends in intelligent automation and digital manufacturing, offering a realistic pathway for companies seeking to strengthen competitiveness while improving operational sustainability.

From the perspective of technological development, the proposed solution represents an advanced application of autonomous systems within industrial engineering and production logistics (Figure 9). The integration of aerial transport technologies demonstrates how innovative technological design can enhance traditional manufacturing systems and contribute to the evolution of smart factories. This approach aligns with current trends in Industry 4.0, where the convergence of automation, digitalisation, and intelligent control systems forms the basis of next-generation industrial technologies.

These findings not only confirm the practical benefits of drone-based logistics but also contribute to the existing body of research by demonstrating the applicability of aerial transport systems in high-precision electronics manufacturing, a domain that has been only partially explored in current literature.

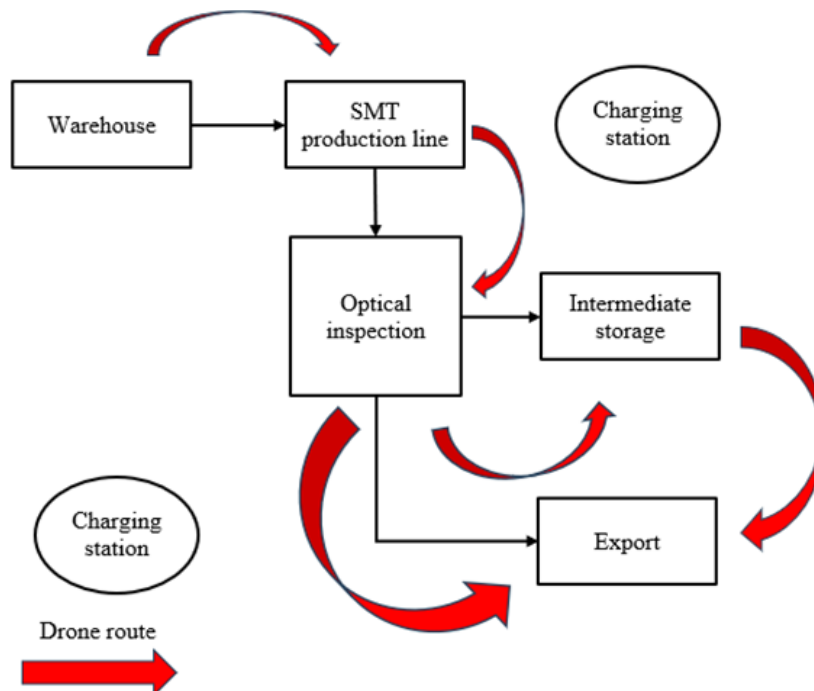


Figure 9 Floor plan of the room after the implementation solution [own processing]

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### Review process

Single-blind peer review process.