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Assessing the Applicability of Industry 4.0 Technologies in Optimizing Air Cargo Terminal Operations

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Abstract: The applicability of Industry 4.0 technologies in air cargo terminals was rigorously evaluated with a focus on optimizing operational processes. This study is motivated by the potential of these technologies to substantially enhance efficiency, safety, and the overall quality of logistics services within the air transport sector. To achieve a comprehensive assessment, Multi-Criteria Decision-Making (MCDM) methods were applied, notably the Best-Worst Method (BWM) for determining the prioritization of criteria, and Comprehensive Distance-Based Ranking (COBRA) for an in-depth analysis and ranking of the technologies. The evaluation encompassed critical criteria such as efficiency, productivity, financial sustainability, data security and privacy, integration, scalability, adaptability and flexibility, reliability and resilience, innovation, and the quality of logistics services. The findings indicate that autonomous mobile robots (AMR) emerged as the top-ranked technology, exhibiting superior performance across all key criteria. AMR technology demonstrated remarkable potential in efficiently integrating logistics operations, enhancing productivity, and ensuring high levels of data security and scalability. In addition to AMR, technologies such as the Internet of Things (IoT) and blockchain were identified as pivotal in improving operational processes in air cargo terminals, offering notable benefits in integration, security, and information transparency. The significance of applying Industry 4.0 technologies to transform operational processes in air cargo terminals is underscored, providing a deeper understanding of their capacity to enhance logistics operations in air transport. Further research is recommended to explore the implementation and optimization of these technologies.

Keywords: Air cargo terminal; Industry 4.0 technologies; Multi-Criteria Decision-Making (MCDM); Best-Worst Method (BWM); Comprehensive Distance-Based Ranking (COBRA)

1. Introduction

Intermodal transport involves the movement of goods using two or more modes of transport without unloading or reloading the cargo itself, utilizing loading units, or entire or partial road vehicles. The essence of intermodal transport lies in the use of standardized intermodal transport units (containers, swap bodies, parts of vehicles, or entire vehicles) that facilitate the easy transfer of cargo from one mode of transport to another. Intermodal transport offers multiple advantages, including efficiency and cost-effectiveness, by using the most suitable mode of transport for each part of the journey, reducing the negative environmental impacts of transport, and so on. Additionally, intermodal transport enhances safety, reduces the risk of cargo damage, provides flexibility and reliability in adapting to market changes, and thus enables global connectivity and easier access to international markets. All these benefits make intermodal transport crucial for optimizing resources, the efficiency of modern logistics, and the global economy. Intermodal transport includes specialized cargo handling units and transport vehicles adapted to them, terminals, terminal networks, transportation infrastructure, transport organizations and operators, logistics chain strategies, and telematics systems. All components of the intermodal transport system are highly interdependent, so any change in one segment can cause changes in other parts of the system.

Intermodal transport systems consist of specialized cargo-handling units, transport vehicles, transportation infrastructure, terminals, terminal networks, transport organizations, operators (associations), telematics systems, logistics chain strategies, and regulations. Specialized cargo-handling units can be pallets, containers, parts of vehicles, or entire vehicles. Standardized metal containers facilitate the easy transfer of cargo between water, rail, and road transport modes without the need for reloading. Pallets are platforms on which cargo is stacked for easier storage and handling. Transport vehicles, depending on the mode of transport, can be airplanes, trucks, trains, or ships. Transportation infrastructure includes all modes of transport routes where intermodal transport flows are realized. Multimodal corridors are integrated transport routes that connect different modes of transport, such as roads, railways, rivers, and sea routes, allowing efficient and coordinated transport of goods and passengers. Transport organization involves the coordination and cooperation of different participants to efficiently realize the transport process. The participants in the transport organization include the shipper, transport contractor, transport operator, carrier, and receiver. The shipper is a person or company that has goods and wants to send them to a specific destination. The transport contractor, or freight forwarder, acts as an intermediary between the shipper and the carrier and is responsible for organizing the entire transport process. The transport operator is a person or company that physically transports the goods using various types of transport vehicles, depending on the mode of transport. The role of the carrier is to transport the goods from point A to point B. The receiver is the person or company receiving the goods intended for them. Associations in the transport industry are organizations that gather carriers, freight forwarders, logistics companies, and other participants in the transport process. Examples of associations include National Rail and Transport Associations and specialized firms within associations such as Transfracht, Interfrigo, and Intercontainer. The International Union for Road-Rail Combined Transport (UIRR) manages the work of national societies and consists of 43 members from 17 countries. Telematics is an interdisciplinary field that combines telecommunications, informatics, and vehicle technology to improve efficiency, safety, and transport management.

The application of telematic systems aims to simplify operations, improve system productivity, optimize processes in terminals, and manage and control transport systems. Telematic systems are widely used in various aspects of the transport industry, including fleet management, shipment tracking, navigation, and road safety. Regulation encompasses legal and administrative guidelines that regulate operations and interactions between different modes of transport and their participants within the intermodal transport system. It ensures compliance with safety standards, customs regulations, environmental requirements, and other regulations to ensure efficiency, safety, and sustainability throughout the transport chain. Terminals are key parts of the logistics chain infrastructure where cargo handling, storage, and transshipment between different modes of transport occur. Terminals serve as exchange points within the same modal system, ensuring the continuity of transport flows. One of the fundamental characteristics of terminals is their convergence function. The geographical location of a terminal determines its accessibility to different transport routes and how effectively it can serve as a hub for gathering and redistributing resources. The three main characteristics of terminals are location, accessibility, and infrastructure. Terminal location is crucial as it enables efficient connectivity with key transport networks, reducing transportation costs and time. Moreover, a good location enhances delivery reliability and operational flexibility, enabling better responses to market needs and unforeseen situations. Accessibility of terminals is key to operational efficiency and speed, cost reduction in transportation, and increased delivery reliability. Well-connected terminals facilitate easier intermodal exchanges and operational flexibility, optimizing logistics routes and capacities, thus ensuring safety, sustainability, and competitiveness in business.

Terminals can be classified according to the type of transport, function in the logistics chain and technology, transport medium, and cargo-handling unit.

According to the type of transport, there are rail-road terminals, which facilitate the transshipment between rail and road transport, typically equipped with container terminals, ramps, and cranes. Rail-marine terminals connect rail transport with maritime transport, often located in ports, and use cranes for container transshipment. Marine-road terminals link maritime with road transport, enabling the swift transshipment of containers or bulk cargo from maritime transport vehicles to road transport vehicles. Rail-air terminals are located near airports and allow for the transshipment of cargo between rail and air transport modes. Air-road terminals connect air transport with road traffic, often including warehouses and fast transshipment systems. According to their function in the logistics chain, there are hub terminals, which serve as central points where large volumes of cargo are consolidated and distributed to various destinations. They usually have high transshipment and storage capacities. They are used to concentrate cargo from different locations, enabling more efficient transport to major consumption centers or industrial zones. Spreading terminals are used for distributing cargo to smaller places, often near final destinations or consumer centers. They facilitate the last phase of transport, enabling more efficient distribution of cargo to end-users or smaller warehouses. Transshipment terminals are used for transferring cargo from one mode of transport to another. They are crucial for connecting different modes of transport and ensuring the continuous flow of cargo through the logistics chain.

Hub and Spoke terminals are systems organized around a central terminal (hub), which serves as the main point for gathering, sorting, and distributing cargo from smaller terminals (spokes). Hub terminals typically have high storage and transshipment capacities, optimizing interregional transport and reducing operational costs. Spoke terminals collect cargo from local areas and efficiently distribute it to hub terminals, enhancing transport efficiency and coverage. This model is often used in air transportation, consumer goods logistics, and even postal services, where a centralized hub facilitates efficient sorting and distribution. Feeder terminals are smaller terminals used for gathering and distributing cargo from smaller ports or inland terminals to larger central terminals or hubs. They utilize smaller vessels, known as feeder ships, to transport cargo between smaller and larger ports. Feeder terminals are crucial for optimizing the capacity utilization of large ships, improving efficiency in maritime transport, providing access to smaller markets, and enhancing global transport coverage. Predominantly used in maritime transport, they enable smaller ports to access global transport networks through major hub terminals.

In terms of technology, transport medium, and cargo-handling unit, there are container terminals specialized in handling standard-sized containers (e.g., TEU, Twenty-foot Equivalent Unit). They utilize cranes, forklifts, and specialized trains for container manipulation. Bulk cargo terminals are designed for handling bulk goods such as grains, minerals, ores, construction materials, and chemical products. They are equipped with conveyor belts, elevators, and specialized cranes. General cargo terminals handle various types of cargo that are not in standardized containers, including palletized cargo, wood, steel, and other industrial products. They use forklifts, cranes, and other handling equipment. Air cargo terminals are essential parts of airport infrastructure and are specialized for efficient reception, handling, storage, and dispatch of air-transported cargo. These terminals are integral to the global supply chain, enabling rapid distribution of goods worldwide, and are often connected with other types of terminals, such as road terminals, for distributing cargo to final destinations. Huckepack (also known as "piggyback") terminals are specialized for combined rail-road transport. These terminals facilitate the transportation of truck trailers on railway wagons. Key features include the transshipment of truck trailers onto wagons, the use of specialized wagons, speed, and efficiency. They are frequently used in Europe, where intermodal transport is highly developed, enabling efficient connections between road and rail transport and reducing costs and CO_2 emissions. Ro-Ro (roll-on/roll-off) terminals are designed for transporting vehicles that can load and unload themselves from water, rail, or road transport vehicles. These terminals enable the transport of rollable cargo, such as cars, trucks, trailers, and other wheeled goods. Key features include vehicle loading and unloading, the use of specialized ships, and efficiency in cargo handling. They are used worldwide, especially in maritime transport, for efficient transportation of cars, trucks, and other vehicles across seas or along rivers and canals.

The network of terminals in logistics represents a system of interconnected terminals or nodes used for transshipment, storage, distribution, or handling of cargo. This network includes various types of logistics terminals, such as ports, airports, railway terminals, bus stations, distribution centers, etc. The primary goal of the terminal network is to enable the efficient distribution and handling of goods between different points in the logistics chain. By integrating different terminals into one coherent network, logistics processes become faster, more efficient, and less prone to errors. In practical terms, the terminal network allows organizations to optimize routes, reduce transportation and storage costs, and improve tracking and control of goods throughout their journey through the logistics chain.

The subject of this paper is the air cargo intermodal terminal and the application of Industry 4.0 technologies in air cargo terminals.

Air cargo terminals enable efficient reception, storage, processing, and distribution of cargo. These specialized facilities play a crucial role in international trade, ensuring fast and reliable transport of goods worldwide. As global trade increases and becomes more complex, the need for more efficient, secure, and faster cargo management becomes more pronounced. Therefore, Industry 4.0 technologies offer revolutionary opportunities to enhance operations within air cargo terminals. Industry 4.0, also known as the Fourth Industrial Revolution, brings the integration of advanced digital technologies such as the IoT, artificial intelligence (AI), big data analytics, automation, and robotics. Implementing these technologies in air cargo terminals can drastically improve efficiency, reduce costs, enhance security, and provide real-time insights into operations. Through the application of Industry 4.0 technologies, air cargo terminals can optimize cargo management processes, improve shipment tracking systems, increase prediction accuracy, and enhance the customer experience. For example, the use of IoT devices enables real-time monitoring of cargo temperature, humidity, and location, while AI and big data analytics enable predictive maintenance of equipment and optimization of delivery routes. Automated systems and robots can take over repetitive tasks, reducing the risk of human error and increasing productivity.

The aim of this paper is to evaluate and rank Industry 4.0 technologies in terms of their applicability in air cargo terminals. The paper is structured as follows: The second section presents a description of the concept of air cargo terminals as intermodal logistics centers. The following section provides an overview of Industry 4.0 technologies and their applications. Next, the subsequent section outlines a MCDM model for the applicability of Industry 4.0 technologies in air cargo terminals and ranks these technologies. The final section provides concluding remarks and directions for future research in this area.

2. Literature Review

In the first half of the twentieth century, air cargo transportation began to develop. Initially, airplanes were used for transporting mail and small packages of goods. After World War II, there was significant growth in air cargo traffic due to increasing demand for fast delivery of goods. The production of cargo aircraft such as the Boeing 747F and McDonnell Douglas DC-10F in the latter half of the twentieth century increased the efficiency and capacity of air cargo transportation. Today, there are numerous cargo aircraft specifically designed for transporting various types of goods. As the demand for air transport of different types of goods continues to grow, air cargo terminals have developed (Bañez et al., 2019).

An air cargo terminal is a specialized facility or zone within an airport where processing, storage, and handling of air cargo take place (Bañez et al., 2019; Bowen & Rodrigue, 2017). It is a key component in the intermodal transportation chain, facilitating the efficient transfer of goods between different modes of transport. An intermodal air cargo terminal serves as a central point in the logistics chain, integrating various types of transport and enabling a synchronized and coherent flow of goods from manufacturers to end users. This terminal optimizes transportation time and costs, reduces delays, and enhances overall process efficiency.

The key characteristics of air cargo terminals in intermodal transport include multimodal connectivity, technological infrastructure, operational efficiency, security measures, flexibility, and ecological sustainability. Multimodal connectivity refers to direct connections with rail, road, and maritime transport. Technological infrastructure involves the use of advanced technologies for cargo tracking, management, and security checks. Operational efficiency encompasses optimizing the processes of reception, storage, handling, and dispatch to reduce downtime. Security measures include stringent controls and procedures to ensure cargo and operational safety. Flexibility denotes the ability to adapt to various types of cargo and client needs. Ecological sustainability entails implementing environmentally friendly practices to minimize their impact on the environment (Bañez et al., 2019; Bowen & Rodrigue, 2017; Mishler & Hanley, 2019).

The functions of air cargo terminals in intermodal transport include cargo reception, storage, customs clearance, cargo handling, and distribution. Terminals are equipped with entry and exit ramps, parking facilities for road transport vehicles, and specialized cargo handling equipment to facilitate efficient reception of road transport-originated cargo and dispatch by air transport (Bañez et al., 2019; Mishler & Hanley, 2019; Rodrigue & Slack, 2013). Warehouse spaces in terminals serve for temporary storage of cargo pre- or post-flight, necessitating appropriate space and controlled conditions for various types of cargo, including standard, perishable, and special shipments. Specialized cargo handling equipment such as forklifts, conveyor belts, and container carriers enables quick and safe transfer of cargo between different transport modes and warehouse spaces. Terminals feature customs and inspection offices where cargo clearance and inspection occur, with high-level security measures to safeguard cargo. Cargo is sorted and prepared for onward transport, enabling swift and efficient handling of large volumes of cargo and reducing transport and delivery times. These terminals facilitate rapid cargo transport between different parts of the world, which is particularly crucial for transporting special types of goods such as medical supplies, perishable foods, high-value products, and hazardous materials. In emergency situations, air cargo terminals are vital for enabling the rapid delivery of humanitarian aid and medical supplies. Air cargo terminals play a crucial role in the intermodal transport chain, primarily due to their efficiency and speed. They facilitate the rapid transfer of cargo between aircraft and other transport modes, which is crucial for maintaining an efficient logistics chain and minimizing downtime. Their connectivity with major logistical hubs enables efficient transfer of cargo between different transport modes, ensuring smooth flow of goods through various transport modalities. Additionally, air cargo terminals offer specialized services such as refrigeration units for perishable goods, handling of hazardous materials, and storage of valuable cargo, ensuring the safety and preservation of cargo quality. Their ability to facilitate the global distribution of goods connects markets worldwide and supports international trade. The flexibility of air cargo terminals in logistics management allows for the for the adjustment of cargo quantities and types of transport according to market and client needs. Integration of advanced technologies such as automation, real-time cargo tracking, and digitization of documents further enhances efficiency and accuracy in air cargo terminals, optimizing the entire supply chain (Rodrigue & Slack, 2013).

The application of Industry 4.0 technologies in intermodal air cargo terminals has become a significant research topic in recent years. Numerous studies have focused on various aspects of Industry 4.0 technologies and their impact on efficiency, security, and management in air cargo terminals. In a study conducted by Spandonidis et al. (2022), various aspects of IoT technology application in air cargo terminals were analyzed. Their research demonstrated that such systems could advance technologies for cargo containers and air cargo operations. Shakhatreh (2020) conducted research focusing on the application of IoT technologies in transporting specific types of cargo, particularly pharmaceutical products. The aim was to design software and hardware solutions to enable monitoring of temperature conditions during transport. The study by Xu et al. (2014) illustrated that IoT implementation in manufacturing allows real-time monitoring and control of production processes. A study by Tubis et al. (2024) aimed to analyze the current state and identify the potential for implementing AR systems in air cargo terminals. The study conducted by Stoltz et al. (2017) focuses on the possibilities of applying AR technologies in warehouses. According to Ke et al. (2005), AR technologies are used for training workers and supporting complex assembly processes. Poleshkina (2021) focused on the application of blockchain technologies in air cargo terminals, aiming to address transparency issues in air cargo transportation information. Kshetri (2018) demonstrated that blockchain technology can enhance security and transparency in supply chains. Fragapane et al. (2022) provided a better understanding of the role of AMR technologies in manufacturing processes. This study supported decision-makers in the process industry, showing how AMR systems can improve productivity, flexibility, and reduce costs. The study by Karabegović et al. (2015) examined the introduction of AGV service robots for internal transport processes.

Veljović et al. (2024) conducted research aimed at applying and ranking Industry 4.0 technologies in last-mile logistics. MCDM methods were used to rank technologies in this study. Miškić et al. (2023) aimed at applying Industry 4.0 technologies in a logistics center and ranking technologies using MCDM methods. Broniewicz & Ogrodnik (2021) analyzed the application of various MCDM methods in the field of transportation and logistics, focusing on evaluating different transport routes, inventory management technologies, and distribution. Ferraro et al. (2023) demonstrated the application of various technologies to achieve sustainable development goals within logistics, as well as ranking technologies using MCDM methods.

The BVM method is a MCDM approach developed by Rezaei (2020). This method can be used to assess alternatives against criteria and determine the importance (weights) of criteria used in finding solutions aimed at satisfying the main problem. The BVM method brings several significant values, including identifying the best and worst criteria or alternatives and using two paired comparison vectors based on two opposite references (best and worst) in one optimization model. The advantages of the BVM method include its simplicity in application and interpretation of results, the ability to incorporate subjective assessments of importance and undesirableness, and flexibility in comparing alternatives based on multiple criteria. However, drawbacks of the BVM method include the need for a clear definition of the importance and undesirability of each criterion, which can be subjective; the requirement for a sufficiently large sample of expert or user ratings; and potential sensitivity to the order of choice of elements (best and worst). BWM has recently been used for solving problems from various fields (Alsanousi et al., 2024; Barasin et al., 2024), but also for evaluating the potential implementation of Industry 4.0 technologies, primarily in manufacturing processes (Eldrandaly et al., 2022; Javaid et al., 2023), but also in cargo terminals (Krstić et al., 2023).

The COBRA method is a MCDM method based on ranking alternatives according to their distance from positive and negative ideal solutions. This method was developed by Krstić et al. (2022b). The main advantage of this method is its comprehensiveness. Alternatives are ranked based on the comprehensive distance of each alternative from three types of solutions: positive ideals, negative ideals, and average solutions. The COBRA method can be used with various types of criteria and alternatives, making it applicable in different domains. Additionally, this method effectively manages complex, MCDM problems. The complexity of the COBRA method presents both an advantage in its use and its main drawback. In addition to three types of solutions, this method requires obtaining four groups of distances: distance from a positive ideal solution, distance from a negative ideal solution, positive distance from an average solution, and negative distance from an average solution, as a combination of two different types of distance measurements, as well as comprehensive distances that integrate all of the above. Therefore, the method requires more resources, especially time, to obtain results. The COBRA method, although recently developed, has been applied for solving various problems (Asker, 2024; Popović et al., 2022), including the selection of the most efficient Industry 4.0 technology for developing a smart reverse logistics system (Krstić et al., 2022a).

3. Applicable Industry 4.0 Technologies in Air Cargo Terminals

Industry 4.0, also known as the Fourth Industrial Revolution, represents the integration of modern technologies into industrial processes to increase automation, efficiency, and interconnectedness. This transformation is revolutionizing manufacturing, logistics, and other sectors, enabling the creation of smart factories and the enhancement of supply chains. By applying technologies such as the IoT, advanced robotics, augmented reality (AR), virtual reality (VR), and blockchain, Industry 4.0 enables innovative approaches to business.

The following sections of this work provide an overview of these technologies, an analysis of their characteristics, possible applications, and their impact on logistics processes in air cargo terminals.

3.1 IoT

The introduction of new technologies in the field of aviation has significantly improved the efficiency and safety of operations, especially in the context of air cargo terminals. One of the key innovations is the application of IoT technology (T1), which enables the connection of various devices and systems into a network for the purpose of collecting and exchanging data in real-time. This technology has found widespread application in air cargo terminals due to its ability to enhance shipment tracking, optimize cargo handling processes, and increase security (Baláž et al., 2023). IoT allows for automated monitoring of storage conditions, such as temperature and humidity, as well as the position of cargo at any given time, thereby reducing the risk of damage or loss of shipments. The implementation of these technologies not only contributes to operational efficiency but also reduces costs and improves customer service.

Air cargo terminals are central hubs for managing and handling cargo in the aviation industry, and effective management of these processes depends on the use of various technologies and devices. One of the most important elements in this system are ULD containers, which enable secure and organized storage and transport of cargo. To ensure maximum efficiency and safety in handling ULD containers, increasing attention is being paid to the use of sensors for tracking these devices. Sensors enable continuous monitoring of location, temperature, humidity, and the condition of cargo within ULD containers, which is vital for air cargo terminal operations. There are four different types of sensors installed within ULDs: smoke detectors, contact switches, piezoelectric sensors, and position sensors. In this way, IoT technology helps reduce the risk of cargo damage or loss, optimize logistics processes, and increase overall terminal efficiency. ULDs, or unit load devices, are an integral part of air cargo transportation.

IoT technologies can be applied to the problem of tracking ULDs to increase the efficiency and safety of the cargo itself (Revina et al., 2019). The Remote Monitoring System (RMS) provides information on the precise location and condition of ULDs. The system consists of four parts: sensors for monitoring status and condition, a robotic platform that loads cargo into the aircraft, the Remote Monitoring Control (RMC) system located inside the ULD that collects and transmits data to the fourth part of the system, which is the Human-Machine Interface (HMI) via a Wi-Fi network. Each ULD receives a unique ID code that is generated and sent to the interface, which is then transmitted via Wi-Fi to the robotic platform. The status of the ULDs is periodically sent in the form of reports. In this way, the robotic platform tracks the ULD from the moment of loading, through the locking location in the aircraft, during the flight, and until unloading. The status data of the ULDs is provided to the captain and crew members. The RMC system, thanks to the data generated by the Human-Machine Interface, can control, in addition to tracking ULDs, the locking status of ULDs and fire detection systems.

In addition to using various types of sensors placed inside containers, there is another solution for tracking ULDs, which is the use of a traceable e-seal. The traceable e-seal is a smart electronic seal that serves to lock the container and enable real-time tracking. This device uses IoT technology to collect and transmit data about the status and location of the container during delivery.

Key features of the smart electronic seal include security, real-time tracking, temperature monitoring, communication with the application, and a long-lasting battery. The MiTraceable application is directly connected to the traceable e-seal via IoT technology, allowing continuous tracking and management of containers during transport. The traceable e-seal sends information about the container's location, door status (open/closed), and the temperature inside the container if appropriate sensors are installed. Users (such as transport companies, logistics operators, or cargo recipients) can access this data through the MiTraceable application on their mobile devices or computers. The application provides users with an interface to monitor and view all relevant information about the container in real-time. The MiTraceable application allows users to receive notifications about important events during transport, such as temperature changes or unauthorized door openings. Additionally, users can manage application settings to customize how they receive notifications or perform data analysis. The integration of the traceable e-seal with the MiTraceable application provides better cargo security during transport, as users can respond promptly to potential risks or issues. Furthermore, transparency regarding the location and status of the cargo contributes to better logistics management and increases trust between participants in the supply chain. The MiTraceable application provides users with a simple and intuitive way to track all relevant information about cargo in transit, which is especially important for dynamic logistics operations that require quick decision-making.

Tracking cargo within air cargo terminals is crucial for various aspects such as cargo security, operational efficiency, supply chain transparency, data use for optimization, and the management of specific cargo requirements. Tracking allows terminals to continuously monitor the location and status of each shipment. This helps prevent theft, loss, or unauthorized manipulation of cargo, which is particularly important in complex logistics networks and during transitions between different transport modes. Additionally, tracking enables terminals to optimize scheduling and resource management. Accurate information about cargo location allows for faster and more precise handling, reducing processing time and operational costs. Tracking enables transparency in the flow of goods in the supply chain. This increases trust among all participants in the supply chain (manufacturers, retailers, transporters, and recipients), reduces misunderstandings, and facilitates problem resolution that may arise during transport. Data collected during tracking allows for performance analysis and the identification of potential improvements in logistics processes.

3.2 AR Technology

AR (T2) is one of the primary tools of Industry 4.0. This technology provides the ability to use real-time information in the form of text, graphics, sound, and other virtual enhancements (Ke et al., 2005). AR technology allows users to experience the real world enriched with additional digital information or elements, expanding their perception and interaction with the environment in a new and innovative way. AR technology has also found applications in logistics processes through the system of smart glasses.

The implementation of smart glasses positively impacts the following areas:

- Visualization - Displaying information directly in the operator's field of view reduces the time required to complete tasks by eliminating unnecessary head and body movements. It also enables the documentation of all operator actions, continuous monitoring, natural user attention guidance, and the provision of additional information.
- Interaction - Building a safer and more productive work environment by promoting the useful application of technology for people, improving interaction between people and their environment, and enhancing human perception for more efficient task execution.
- User convenience - Smart glasses are comfortable to wear, do not obstruct workers, and allow hands-free access to information.
- Navigation - The ability to move quickly along optimized paths, precise determination and tracking of position at all times, and easy location of physical targets.

Handheld devices are mobile devices, such as smartphones and tablets, that can display information, images, or videos in the real world using their cameras and screens. These devices use AR technology to enrich the user's view of the world with additional digital information. Handheld devices can be very useful at air cargo terminals. They can enhance efficiency, accuracy, and safety in various aspects of cargo handling. They can be used for navigation and guidance of workers, identification and tracking of shipments, inspection and verification of cargo, training and education, planning and optimization of storage space, repair and maintenance of equipment, and connection with Warehouse Management Systems (WMS). Workers in terminals can use AR devices to navigate through large storage areas.

Arrows and instructions can be displayed on the device's screen, guiding them to specific locations within the terminal, thus reducing the time needed to find specific shipments. AR devices can display information about shipments when workers point the camera at the cargo. For example, information about the contents, weight, dimensions, destination, and status of the shipment can be displayed directly on the device's screen. Workers can use AR for inspection and verification of cargo. For example, they can use it to check the integrity of packaging or to identify damage to the cargo. AR can display instructions for the proper handling and storage of cargo. AR technology can be used for training new workers. Through interactive AR simulations, workers can learn how to properly handle cargo, use equipment, and follow safety protocols without the need for a physical instructor. AR applications can help in planning and optimizing storage space. Workers can use AR devices to visualize the arrangement of cargo and optimize space utilization, which can reduce handling time and increase warehouse capacity. AR devices can assist technicians in the repair and maintenance of equipment. For example, the device can display 3D models and instructions for repairing specific machines or devices, making it easier to identify problems and perform necessary repairs. AR devices can be integrated with existing WMS to provide real-time information about inventory status, shipment locations, and other relevant data.

Spatial Augmented Reality (SAR) systems use technologies that project digital information directly onto physical objects and surfaces in the environment, as opposed to wearable devices such as smartphones or AR glasses. SAR systems often utilize projectors, cameras, sensors, and computer algorithms to create interactive and informative displays that integrate with the physical world. These systems can be applied in air cargo terminals for navigation and orientation, cargo information, handling instructions, equipment maintenance, training and education, and storage space optimization.

SAR systems can project arrows and signs on the floor or walls of a terminal to guide workers to specific locations within the warehouse or terminal. When cargo is placed in a designated spot, the SAR system can project key information about the cargo directly onto the boxes, including destination, contents, weight, and status. SAR can project instructions for proper handling and storage of cargo directly onto the cargo or in the workspace, reducing the possibility of errors and increasing efficiency. Technicians can use SAR systems to project diagrams, repair instructions, and maintenance guidelines directly onto the equipment being repaired, facilitating the repair and maintenance process. SAR systems can provide interactive training simulations for training new workers. These systems can project cargo handling scenarios and safety procedures directly into the workspace, allowing for realistic and hands-on training experiences.

SAR can assist in planning cargo layout within a warehouse by projecting optimal storage layouts and routes for cargo storage and retrieval, which can enhance efficiency and space utilization.

Head-mounted displays (HMDs) are wearable devices that allow users to view digital information or AR directly within their field of view. These devices often come in the form of glasses or helmets and can display real-time information, making them valuable in various industrial applications, including air cargo terminals. HMDs can be used in air cargo terminals for navigation and orientation, cargo information, handling instructions, equipment maintenance, education and training, and integration with WMS. Workers can use HMDs to receive navigation instructions throughout the terminal, including routes to specific shipments or storage locations. HMDs can display cargo information when the user focuses on a particular package. Information such as weight, dimensions, contents, and destination can be shown directly in the user's field of view. HMDs can provide step-by-step handling instructions for specific types of cargo or equipment, reducing the possibility of errors and improving efficiency. Technicians can use HMDs to view diagrams, instructions, and other information directly on the equipment they are servicing, facilitating maintenance and repair processes. New workers can use HMDs for interactive training simulations that guide them through cargo handling procedures, safety protocols, and other important operations. HMDs can be connected to WMS to provide real-time information on inventory status, shipment locations, and other relevant data.

The application of AR technology in air cargo terminals significantly enhances operational efficiency and safety (Glockner et al., 2014). Smart glasses enable workers to quickly access relevant information, such as cargo handling instructions and logistical data, without interrupting their workflow or using their hands. This reduces processing time for cargo, minimizes errors, and improves coordination among teams. Additionally, AR technology allows for real-time monitoring and documentation of all actions, thereby increasing transparency and operational safety.

3.3 Blockchain Technology

Air cargo transport involves various stakeholders, including airlines, airports, customs, shippers, consignees, and handling companies. Goods transported by air generate around thirty different documents. The use of electronic freight documentation (e-freight) reduces the time required for document exchange among all interested parties. The most demanding operation, in terms of electronic freight documentation, is verifying the correctness of the documents, especially electronic air waybills (eAWB), labels, and certificates of origin.

Blockchain (T3) is a database that is not located in one place but consists of smaller databases (blocks) that are digitally interconnected, containing information about digital transactions. The use of blockchain technology in air cargo transport would enable the verification of the origin and correctness of goods for transport (Goudarzi et al., 2018). Additionally, blockchain technology reduces the volume of documentation exchange between stakeholders in air transport due to distributed data storage and increased shipment transparency.

Blockchain technology has improved booking services for shippers, enabling air transport reservations and a faster acceptance and delivery process. Blockchain can provide automatic data verification and the virtual integration of additional services from other providers, such as customs brokerage. Booking cargo capacity involves three steps:

1. Booking cargo space is only possible after agreeing with the carrier on the feasibility of transporting a specific type of goods (documents: air waybill, safety declaration);
2. Passing a phytosanitary/veterinary inspection (document: phytosanitary/veterinary certificate);
3. Obtaining customs clearance for cargo transport (document: customs declaration).

Integrating blockchain technology reduces the possibility of errors in the system and speeds up the process of booking and delivering cargo.

Blockchain technology can also be applied to tracking and recording goods, data security, customs procedures and regulations, financial transactions, inventory management, and logistics process optimization. Blockchain enables transparent tracking of goods from the moment they are picked up to delivery, with immutable records of all transactions and movements. It can be used for automatically executing contracts when certain conditions are met, such as receipt confirmation or fulfillment of customs requirements. Due to its decentralized nature, blockchain prevents unauthorized data modification, increasing security and trust among participants. All participants can be assured of each other's identity through cryptographic methods. Cargo information can be automatically verified and confirmed, reducing customs clearance time. All compliance-related data can be stored on the blockchain, facilitating tracking and verification. Blockchain enables faster transactions without intermediaries, reducing costs and time needed for financial operations. All financial transactions are transparently recorded, reducing the risk of fraud. Blockchain can provide real-time data on inventory status, allowing better planning and reduction of excess stock. It allows tracking the origin and movement of all components within the terminal, increasing efficiency in inventory management. Smart contracts and automatic tracking enable faster and more efficient cargo handling. Document digitization reduces paperwork and speeds up cargo processing. Implementing blockchain technology in air cargo terminals can result in significant improvements in efficiency, security, and transparency, providing a competitive advantage and enhancing the customer experience.

3.4 AMR

AMRs (T4) are robots that navigate their environment independently using sensors, cameras, and advanced navigation algorithms. These robots are designed to perform multiple tasks simultaneously. They can maintain a level of quality and productivity and carry out tasks that humans cannot or should not do. Using various sensors, cameras, and sophisticated algorithms, these robots adjust their routes in real-time to avoid obstacles and efficiently complete tasks. Their applications are diverse: from transporting cargo within terminals, organizing and sorting goods, to interacting with other systems such as WMS and cargo tracking.

AMRs are typically equipped with various sensor technologies that provide input data for autonomous navigation. Integrated laser scanners such as Light Detection and Ranging (LIDAR), 3D cameras, accelerometers, and gyroscopes provide information about wheel positions to calculate the distance traveled by the robot. Additionally, integrated laser scanners collect and transmit large amounts of data about the AMR's immediate environment. Sensing the surroundings enables AMRs to cooperate and communicate with humans and machines. Real-time navigation support technology (SLAM) provides information on activities such as creating detailed maps of the surroundings and calculating the AMR's position on the map. Movement planning is part of the guidance system based on environmental overview and equipment manipulation. Movement planning algorithms provide speed commands as well as actuator and wheel rotation commands on the vehicles. SLAM technology and sensors enable path tracking and provide feedback for returning the AMR to the desired path. In a dynamic environment, the movement planner can adjust the AMR to traffic or congestion by reducing speed or even stopping the vehicle. If the planned path becomes unfeasible due to obstacles, a new path will be generated to avoid collisions.

AMR can also be applied to cargo transport within terminals, inventory management and storage, aircraft loading and unloading, security and inspection, waste management, improving working conditions, integration with IT systems, and optimizing logistics processes. AMR robots can pick up and move pallets and containers from one area of the terminal to another, reducing the need for manual labor and speeding up the process. They can be used for distributing cargo to appropriate storage or shipping areas, reducing the risk of errors and cargo loss.

AMR robots can automatically scan barcodes and RFID tags on cargo, updating inventory in real-time. This enables precise inventory tracking and simplifies inventory checks. They can be used for optimal cargo placement within warehouses, maximizing available space utilization. AMR robots can assist in loading and unloading cargo from airplanes, reducing the time required for these operations and increasing safety. AMR robots can work in coordination with workers, taking on heavier or more repetitive tasks and allowing workers to focus on more complex operations. They can patrol the terminal, performing security checks and detecting potential threats or irregularities. AMR robots can inspect cargo using built-in sensors and cameras, checking its condition and compliance with regulations. AMR robots can be responsible for collecting waste, transporting it to appropriate recycling or disposal sites, and maintaining terminal cleanliness and hygiene. They can monitor and report on environmental conditions within the terminal, such as air quality or noise levels. By taking on heavy and repetitive tasks, AMR robots reduce the physical strain on workers, thereby decreasing the risk of injuries and increasing productivity. Given that AMR robots can operate 24/7 without needing rest, the overall efficiency and productivity of the terminal significantly increase. AMR robots can be integrated with WMS systems to automate and optimize warehouse management tasks. Information collected by AMR robots can be directly transmitted to central tracking and analysis systems, enabling faster decision-making. AMR robots use dynamic route planning algorithms, allowing for optimal and quick cargo delivery within the terminal. They can quickly adapt to changes in working conditions or requirements, such as changes in flight schedules or urgent deliveries.

The implementation of AMR robots in air cargo terminals can significantly enhance operational processes, reduce costs, and increase safety and precision. In this way, terminals become more efficient and competitive in the market.

3.5 Criteria for Evaluation and Ranking of Industry 4.0 Technology Applicability

In assessing the applicability of Industry 4.0 technologies in an air cargo terminal, several key criteria can be defined:

Efficiency and Productivity (C1): This criterion evaluates process automation and reductions in processing time to increase terminal efficiency and productivity.

Financial Sustainability (C2): Consideration of implementation costs and operational expenses.

Data Security and Privacy (C3): This criterion emphasizes the technology's ability to ensure data privacy and protection, preventing unauthorized access, data leaks, and misuse of information, as well as safeguarding infrastructure and operations from cyber threats, including protection against hacking attacks, viruses, and other forms of cyber threats.

Integration (C4): This criterion assesses the ability of new technologies to integrate with existing terminal infrastructure and systems.

Scalability (C5): Scalability evaluates the technology's capacity to adapt to the growth and increasing complexity of the terminal.

Adaptability and Flexibility (C6): This criterion pertains to the technology's ability to adjust to changes in the environment, market demands, and business objectives.

Reliability and Resilience (C7): This criterion concerns the stability and reliability of the technology in operation, its ability to avoid or quickly resolve errors, and its ability to reduce downtime.

Innovation (C8): The technology's ability to introduce new functionalities, enhance operational processes, and contribute to advanced solutions. Innovation is crucial as it can provide the terminal with a significant competitive advantage, enabling continuous improvement in efficiency, productivity, and service quality.

Quality of Logistics Services (C9): Focuses on operational aspects of the terminal, such as accuracy, speed, efficiency, and reliability in cargo handling. This criterion is critical for optimizing the operational performance of the terminal.

4. Methodology

MCDM models represent a set of methods and approaches used for decision-making in situations where there are multiple conflicting criteria. MCDM models enable the analysis of multiple criteria simultaneously, providing a better understanding of all aspects of the problem. These models can use both quantitative and qualitative data, encompassing a broader range of information relevant to decision-making.

In this study, a hybrid MCDM model was used to address the evaluation and ranking of Industry 4.0 technologies in terms of their applicability in air cargo terminals. The model combines the BWM for criterion weighting and the COBRA method for determining the final rank of alternatives (technologies).

The model consists of four steps:

Step 1: Define the decision problem structure by identifying alternatives and a set of criteria relevant to their evaluation.

Step 2: Define the evaluation scale. Evaluations of criteria and alternatives can be quantitative or qualitative. Quantitative assessments can be generalized to obtain a qualitative form, but not vice versa. Considering this, a qualitative scale is more general and universally applicable. Additionally, a qualitative scale better suits the nature of human thinking, as decision-makers feel more comfortable providing descriptive assessments. Based on the above, the general form of the proposed model assumes the application of a qualitative scale using linguistic terms and their corresponding numerical values. In this study, a nine-point scale was used for assessments, as presented in Table 1. Decision-makers evaluate criteria and alternatives using linguistic terms, which are then transformed into numerical values suitable for the MCDM model.

Step 3: Calculate criterion weights using the BWM method.

Step 4: Rank alternatives using the COBRA method.

Table 1. Evaluation scale

Linguistic Evaluation	Abbreviation	Numerical Value
None	N	1
Very Low	VL	2
Low	L	3
Fairly Low	FL	4
Medium	M	5
Fairly High	FH	6
High	H	7
Very High	VH	8
Extremely High	EH	9

4.1 The BVM Method

The BWM relies on comparing pairs of identified best and worst criteria against all other relevant criteria for a given problem. Criterion weights (importances, values) are determined by solving a maximization task. Unlike other methods that rely on pairwise comparisons of elements (criteria or alternatives), such as AHP and ANP, the BWM method requires fewer data (pairs of comparisons), provides a higher degree of consistency, yields more reliable results, allows for less total deviation, minimizes duplication, and is more consistent with other MCDM methods.

To obtain criterion weights using the BWM, the following steps need to be followed:

Step 1: Identify the best criterion B and the worst criterion W (least desirable or least important);

Step 2: Evaluate the preferences (e_{bj}) of the best criterion B relative to all other criteria (j) using the previously defined scales shown in Table 1. The result is expressed as a vector of best-to-other assessments, denoted as $E_b = (e_{b1}, e_{b2}, \ldots, e_{bm})$, where each element e_{bj} indicates the preference of the best criterion B compared to criterion j.

Step 3: Evaluate the preferences (e_{jw}) of all criteria (j) compared to the worst criterion W using the scale shown in Table 1. The result is expressed as a vector of assessments of others relative to the worst, denoted as $E_w =$

$(e_{1w}, e_{2w}, \dots, e_{mw})$, where each e_{jw} indicates the preference of criterion compared to the worst criterion W.

Step 4: To calculate the weights w_j of criteria, solve the linear programming problem as follows:

$$\min \xi \tag{1}$$

$$\left| w_b + e_{bj} w_j \right| \leq \xi, \forall_j = 1, \dots, m, \tag{2}$$

$$\left| w_j + e_{jw} w_w \right| \leq \xi, \forall_j = 1, \dots, m, \tag{3}$$

$$\sum_{j=1}^{m} w_j = 1, \tag{4}$$

$$w_j \geq 0, \forall_j = 1, \dots, m, \tag{5}$$

4.2 The COBRA Method

The COBRA method used to determine the final ranking of alternatives consists of several steps:

Step 1: To determine the evaluations a_{ij} of alternatives $i\ (i = 1, \dots, n)$ relative to criteria j, forming the decision matrix A:

$$A = \left[\begin{pmatrix} a_{11} & \cdots & a_{jm} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nm} \end{pmatrix} \right], \tag{6}$$

where, n is the total number of criteria, and m is the total number of the alternatives taken into consideration.

Step 2: Formulate the decision matrix Δ:

$$\Delta = \left[\alpha_{ij} \right]_{n \times m} \tag{7}$$

$$\alpha_{ij} = \frac{a_{ij}}{\max_i a_{ij}} \tag{8}$$

where,

Step 3: Formulate the weighted normalized decision matrix Δ_w as follows:

$$\Delta_w = \left[w_j \times \alpha_{ij} \right]_{n \times m} \tag{9}$$

where, w_j is the relative weight of criterion j.

Step 4: For each criterion function determine the positive ideal PIS_j, negative ideal NIS_j and average solution AS_j as follows:

$$\begin{aligned} PIS_j &= \max_j \left(w_j \times \alpha_{ij} \right), \forall_j = 1, \dots, mzaj \in J^B \\ PIS_j &= \max_j \left(w_j \times \alpha_{ij} \right), \forall_j = 1, \dots, mzaj \in J^C \end{aligned} \tag{10}$$

$$\begin{aligned} NIS_j &= \max_j \left(w_j \times \alpha_{ij} \right), \forall_j = 1, \dots, mzaj \in J^B \\ NIS_j &= \max_j \left(w_j \times \alpha_{ij} \right), \forall_j = 1, \dots, mzaj \in J^C \end{aligned} \tag{11}$$

$$AS_j = \frac{\sum_{i=1}^{n} \left(w_j \times \alpha_{ij} \right)}{n}, \forall_j = 1, \dots, mzaj \in J^B, J^C \tag{12}$$

where, J^B is the set of benefit and J^C the set of cost criteria.

Step 5: For each alternative determine the distances from the positive ideal $\left(\mathrm{d}\left(\mathrm{PIS}_j \right) \right)$ and negative ideal

$\left(d\left(NIS_j\right)\right)$ solutions, as well as the positive $\left(d\left(AS_j^+\right)\right)$ and negative $\left(d\left(AS_j^-\right)\right)$ distances from the average solution as follows:

$$d\left(S_j\right) = dE\left(S_j\right) + \sigma \times dE\left(S_j\right) \times dT\left(S_j\right), \forall_j = 1, \dots, m \tag{13}$$

where, S_j represents any solution (PIS_j, NIS_j, AS_j), σ is the correction coefficient obtained as follows:

$$\sigma = \max_i dE(S_j)_i - \min_i dE(S_j)_i \tag{14}$$

$$dE\left(PIS_j\right)_i = \sqrt{\sum_{j=1}^m \left(PIS_j - w_j \times \alpha_{ij}\right)^2}, \ \forall_i = 1, \dots, n, \forall_j = 1, \dots, m, \tag{15}$$

$$dT\left(PIS_j\right)_i = \sum_{j=1}^m \left|PIS_j - w_j \times \alpha_{ij}\right|, \ \forall_i = 1, \dots, n, \forall_j = 1, \dots, m, \tag{16}$$

for the negative ideal solution obtained as follows:

$$dE\left(NIS_j\right)_i = \sqrt{\sum_{j=1}^m \left(NIS_j - w_j \times \alpha_{ij}\right)^2}, \ \forall_i = 1, \dots, n, \forall_j = 1, \dots, m, \tag{17}$$

$$dT\left(NIS_j\right)_i = \sum_{j=1}^m \left|NIS_j - w_j \times \alpha_{ij}\right|, \ \forall_i = 1, \dots, n, \forall_j = 1, \dots, m, \tag{18}$$

for the positive distance from the average solution obtained as follows:

$$dE\left(AS_j\right)_i^+ = \sqrt{\sum_{j=1}^m \tau + \left(AS_j - w_j \times \alpha_{ij}\right)^2}, \ \forall_i = 1, \dots, n, \forall_j = 1, \dots, m, \tag{19}$$

$$dT\left(AS_j\right)_i^+ = \sum_{j=1}^m \tau + \left|AS_j - w_j \times \alpha_{ij}\right|, \ \forall_i = 1, \dots, n, \forall_j = 1, \dots, m, \tag{20}$$

$$\tau^+ = \begin{cases} 1 \ ako \ AS_j < w_j \times \alpha_{ij} \\ 0 \ ako \ AS_j > w_j \times \alpha_{ij} \end{cases} \tag{21}$$

and for the negative distance from the average solution obtained as follows:

$$dE\left(AS_j\right)_i^- = \sqrt{\sum_{j=1}^m \tau - \left(AS_j - w_j \times \alpha_{ij}\right)^2}, \ \forall_i = 1, \dots, n, \forall_j = 1, \dots, m, \tag{22}$$

$$dT\left(AS_j\right)_i^- = \sum_{j=1}^m \tau - \left|AS_j - w_j \times \alpha_{ij}\right|, \ \forall_i = 1, \dots, n, \forall_j = 1, \dots, m, \tag{23}$$

$$\tau^- = \begin{cases} 1 \ ako \ AS_j > w_j \times \alpha_{ij} \\ 0 \ ako \ AS_j < w_j \times \alpha_{ij} \end{cases} \tag{24}$$

Step 6: Rank the alternatives according to the increasing values of the comprehensive distances (dC_i) obtained using:

$$dC_i = \frac{d\left(PIS_j\right)_i - d\left(NIS_j\right)_i - d\left(AS_j\right)_i^+ + dE\left(AS_j\right)_i^-}{4}, \ \forall 1 = 1, \dots, n, \tag{25}$$

5. Ranking Industry 4.0 technologies in Terms of Applicability in Air Cargo Terminals

The first step of the model described in the previous chapter involves establishing the problem structure. This structure is set by introducing various Industry 4.0 technologies as alternatives and multiple criteria for their evaluation, as described in earlier chapters. The second step of the model entails using the evaluation scale previously defined in Table 1 to assess criteria and alternatives. It is necessary to identify the best and worst criteria, i.e., those criteria that most and least influence their applicability, and to assess the remaining criteria in relation to these using the linguistic assessments provided in Table 1. By solving the linear programming problem (1) in accordance with (2)-(5), criterion weights w_j are obtained. The best and worst criteria, their assessments, and the criterion weights obtained using the BWM method are presented in Table 2.

Table 2. Criteria weights obtained by using the BWM method

Criterion	Best/Worst	Best over Other	e_{bj}	Other over Worst	e_{jw}	w_j
C1	B	/	/	EH	9	0.221
C2	W	FL	4	/	/	0.092
C3		H	7	FH	6	0.053
C4		VH	8	VH	8	0.046
C5		FH	6	H	7	0.061
C6		M	5	M	5	0.074
C7		VL	2	L	3	0.184
C8		L	3	VL	2	0.024
C9		N	1	FL	4	0.245

Next, it is necessary to evaluate alternatives relative to all criteria. The assessments are shown in Table 3. Using the criterion weights presented in Table 1 and applying Eq. (9), the weighted normalized decision matrix Δ_w is formed. By applying Eqs. (10)-(12), positive ideal solutions $\left(PIS_j\right)$, negative ideal solutions $\left(NIS_j\right)$, and average solutions for each criterion function $\left(AS_j\right)$ are obtained. Subsequently, for each alternative, distances from the positive ideal solutions $\left(d\left(PIS_j\right)\right)$ are obtained using Eqs. (13)-(16). Distances from the negative ideal solutions $\left(d\left(NIS_j\right)\right)$ are obtained using Eqs. (13), (14), (17), and (18). Positive distances from the average solution $\left(d\left(AS_j^+\right)\right)$ are obtained using Eqs. (13), (14), and (19)-(21), while negative distances from the average solution $\left(d\left(AS_j^-\right)\right)$ are obtained using Eqs. (13), (14), and (22)-(24). Finally, the ranking of technologies is achieved by sorting the comprehensive distances $\left(dC_i\right)$ of each technology obtained by Eq. (25) in ascending order. The results obtained using the COBRA method for ranking the applicability of Industry 4.0 technologies in an air cargo terminal are presented in Table 4.

Table 3. Evaluations of the technologies in relation to the criteria

	IoT - T1	AR - T2	Blockchain - T3	AMR - T4
C1	VH 8	M 5	FH 6	EH 9
C2	H 7	H 7	FL 4	FH 6
C3	M 5	FL 4	EH 9	H 7
C4	FL 4	FH 6	H 7	VH 8
C5	EH 9	VH 8	VH 8	M 5
C6	VL 2	EH 9	L 3	FL 4
C7	L 3	L 3	M 5	L 3
C8	FH 6	VL 2	N 1	N 1
C9	N 1	N 1	VL 2	VL 2

Table 4. The results of COBRA method application for ranking the Industry 4.0 technologies

	T1	T2	T3	T4
$d(PIS)$	0.164	0.182	0.101	0.094
$d(NIS)$	0.092	0.074	0.155	0.167
$d(AS^+)$	0.033	0.039	0.085	0.080
$d(AS^-)$	0.069	0.082	0.039	0.026
dC	0.027	0.038	-0.025	-0.032
Rank	3	4	2	1

6. Discussion

This analysis examines the applicability of Industry 4.0 technologies in air cargo terminals, using BWM and COBRA methods for ranking. Key criteria include efficiency and productivity (C1), financial sustainability (C2), data security and privacy (C3), integration (C4), scalability (C5), adaptability and flexibility (C6), reliability and resilience (C7), innovation (C8), and the quality of logistics services (C9). The technology ranking shows the following order: AMR (T4) is the first, Blockchain (T3) is the second, IoT (T1) is the third, and AR (T2) is the fourth. The BWM and COBRA methods enable a comprehensive evaluation based on nine key criteria. Each technology is rated on a scale of 1 to 9 (Table 1), with unique scores for each criterion, providing an objective identification of the positive and negative aspects of each technology.

The analysis results indicate that AMR technology has the highest potential for improving efficiency and productivity in air cargo terminals, thanks to its high score in the efficiency and productivity category (C1). Despite challenges in adaptability (C6) and quality of logistics services (C9), its overall advantage in key operational aspects makes it the most suitable for implementation. Blockchain technology is ranked second, with high scores for data security and privacy (C3) and scalability (C5), making it ideal for contexts where data protection is crucial. However, high initial costs may be a barrier that needs careful consideration. IoT technology, ranked third, offers significant advantages in efficiency (C1) and scalability (C5) but faces challenges in adaptability (C6) and quality of logistics services (C9). These weaknesses should be addressed through further innovations and adjustments. AR technology, ranked fourth, has potential for improvement in several criteria, but its low score in innovation (C8) and financial sustainability (C2) suggests the need for further research and development before it becomes a competitive option.

Thus, the analysis results point to AMR technology as the most suitable for implementation in air cargo terminals, with a high potential for enhancing efficiency and productivity. Further evaluation and implementation of AMR technology are recommended to confirm its advantages in real-world conditions. Blockchain technology also represents a significant option for improving data security, while IoT technology can be used to enhance tracking and operational scalability. Further research and development are needed to optimize AR technology to improve its applicability in the future.

7. Conclusion

The aim of this paper is to explore the applicability of Industry 4.0 technologies in air cargo terminals, focusing on IoT, AR, Blockchain, and AMR technologies. Using MCDM methods, key criteria such as efficiency and productivity, financial sustainability, data security and privacy, integration, scalability, adaptability and flexibility, reliability and resilience, innovation, and quality of logistics services were analyzed.

AMR technology has been identified as the most promising technology for improving operational processes in air cargo terminals. High scores in categories such as efficiency and productivity, data security, integration, and scalability make it the most suitable for implementation. Its ability to automate and optimize workflows significantly enhances efficiency and reduces operational costs. Blockchain technology, ranked second, excels in data security and privacy. The transparency and immutability of data offered by Blockchain make it ideal for industries where information security is paramount. IoT technology, ranked third, offers real-time tracking and resource management, bringing significant advantages in efficiency and productivity. However, challenges in adaptability and quality of logistics services indicate the need for further innovation. AR technology, ranked fourth, offers potential improvements in several categories but requires further research and development to become a more competitive option in the industry.

Further evaluation and implementation of AMR technology in air cargo terminals are recommended to confirm its advantages under real working conditions. Blockchain technology should be further explored and developed for implementation, especially in data security. Additional innovations and adjustments in IoT technology are necessary to overcome challenges in adaptability and quality of logistics services. Further research and development of AR technology can enhance its applicability and competitiveness in air cargo terminals.

The application of Industry 4.0 technologies has the potential to significantly improve operational processes at air cargo terminals. The use of MCDM models has enabled the identification of the most suitable technologies for implementation, providing clear guidelines for future development and research. Implementing these technologies can bring significant improvements in efficiency, safety, and the overall quality of services in the air cargo industry.

Author Contributions

Conceptualization, S.T. and M.K.; methodology, M.K.; software, S.T. and M.K.; validation, S.T., M.K., and D.S.; formal analysis, D.S. and L.V.; investigation, M.K. and D.S.; data curation, S.T. and M.K.; writing—original draft preparation, D.S. and L.V.; writing—review and editing, S.T. and M.K.; visualization, D.S.; supervision, S.T. and M.K. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the research findings are available from the corresponding author upon.

Conflicts of Interest

The authors declare no conflict of interest.

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