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# Method of Reducing Energy Consumption during Forklift Operator Training in Cargo Terminals Utilizing Virtual Reality

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**Abstract:** In the era of shrinking resources of traditional fossil fuels and the increasingly dominant sustainable development policy, actions are taken to reduce energy consumption as much as possible, assuming that we achieve identical operational goals. These activities are apparent in the industries with the most significant energy demand, i.e., the aviation industry. To achieve this, these industries implement modern technologies in all possible areas of operation. One of these areas is the area of operator training, especially the most energy-consuming devices and types of equipment. This article investigated the potential of virtual reality (VR) technology for energy optimization of forklift operating training in airport cargo terminals. The authors propose a method whose practical implementation in one of the cargo terminals reduced energy consumption by several times while training forklift operators. The added value is that the method is universal and, after appropriate modification, can be used to train operators of other devices. The study compared traditional training methods with a VR-based training approach, assessing their impact on energy consumption and overall efficiency of forklift operations in airport cargo terminals. The results prove that VR technology training can significantly reduce energy consumption while improving operational efficiency and can offer a sustainable and effective training solution for the entire logistics sector.

**Keywords:** forklift operators; training methods; energy consumption; virtual reality



**Citation:** Kierzkowski, A.; Ryczyński, J.; Kisiel, T. Method of Reducing Energy Consumption during Forklift Operator Training in Cargo Terminals Utilizing Virtual Reality. *Energies* **2024**, *17*, 1153. https://doi.org/10.3390/en17051153

Academic Editors: Tomasz Rokicki, Aneta Bełdycka-Bórawska and Bogdan Klepacki

Received: 23 January 2024
Revised: 21 February 2024
Accepted: 26 February 2024
Published: 28 February 2024



## 1. Introduction

Managing energy consumption in air transport and cargo terminal operations takes on special significance in the context of limited oil resources and the implementation of sustainable development policies. Airlines and cargo terminals face the challenge of optimizing their operations to minimize energy consumption and harmful emissions. In the aviation sector, initiatives such as the introduction of higher energy efficiency aircraft, the optimization of flight routes, and the use of advanced propulsion technologies are responses to these challenges. At the same time, in cargo terminals, electric forklifts are playing an increasingly significant role, allowing for a substantial reduction in harmful emissions to the atmosphere compared to traditional internal combustion vehicles. This enables a significant reduction in the carbon footprint associated with logistics operations at airports. However, this requires appropriate infrastructure and fleet management systems that ensure the efficient use of these vehicles. These actions are in line with global trends towards the decarbonization of the transport sector and are crucial for achieving sustainable development goals.

The specificity of work in airport cargo terminals, characterized by stringent safety regulations, requires forklift operators to have technical proficiency in forklift operation and complete knowledge and unconditional compliance with these regulations. The only way to achieve this proficiency is through effective training and improvement programs. The task of conducted training is to raise the skill level of individuals with little experience and to maintain a high level of training for experienced operators [1–4]. A high level of training directly translates into a reduction in accident risk and ensures the maintenance of logistic operations' fluidity according to the schedule [2]. Traditional training methods rely on the physical use of technical equipment or on teaching based on instructions, lectures, video presentations, or independent study of materials provided online. Traditional training is usually conducted in classrooms or at computers using internet communicators and video conferences. Although traditional forms of training play a fundamental role in reducing occupational risk and accidents at work, the literature points out several significant limitations. The most important include poor knowledge retention, lack of motivation, and low engagement, mainly resulting from a passive approach to learning [5–7]. Traditional training programs are also expensive to prepare because they require experienced trainers and the availability of appropriate space [8]. More importantly, knowledge of safety is usually insufficient to fully increase employee engagement in improving safety awareness at the workplace [9].

In response to these limitations, the possibility of using virtual reality environments for training purposes is becoming increasingly attractive for the aviation industry, including cargo terminals. VR training can significantly increase teaching efficiency, offering a more interactive and engaging experience than traditional methods [10–13]. With VR, forklift operators can be trained in virtually recreated, realistic work scenarios, allowing them to safely practice procedures and safety rules without the risk of accidents or equipment damage. This not only improves knowledge retention and increases participant engagement but also significantly enhances the level of safety, enabling practical exercises in a fully controlled environment [10,12]. Additionally, VR training can be tailored to the individual needs of participants, allowing for a more effective and personalized approach to learning. Despite the higher initial costs associated with implementing VR technology, long-term benefits such as reduced costs related to workplace accidents, equipment damage, and downtime can outweigh the initial investment. Furthermore, VR training offers the possibility of easy repetition and updating of training scenarios, which is especially important in the dynamically changing work environment of cargo terminals [10,13]. Moreover, virtual reality opens doors to training in areas that would be difficult or impossible to implement in everyday life, thereby offering a fuller range of skills and knowledge. Therefore, despite some limitations, such as the need for specialized software, the use of VR in forklift operator training appears to be a promising direction that can significantly contribute to improving safety and operational efficiency in cargo terminals.

Traditional forms of training are not only costly, due to the need to provide appropriate equipment and space, but also generate significant energy consumption. Keeping machines such as forklifts in continuous operational readiness for training purposes leads to a significant increase in operational costs and the carbon footprint of cargo terminals. In contrast, training using VR, by eliminating the need to use real equipment, allows for a significant reduction in both operational costs and those associated with energy consumption. Thanks to the use of virtual reality, it is possible to conduct intensive and efficient training that minimizes the consumption of fuel or electricity, translating into both financial savings and environmental benefits. Additionally, reducing costs associated with the physical use of equipment in VR training opens up opportunities for organizations to increase the intensity of training and create personalized skill training systems for operators, increasing the safety and efficiency of operations in cargo terminals.

Investments in green technologies, such as electric forklifts in cargo terminals, represent an important step towards increasing energy efficiency and reducing dependence on fossil fuels. Through such actions, the transport industry can significantly contribute to the protection of the environment and natural resources for future generations, underscoring its role in building a sustainable future.

The paper is divided into five chapters. Section 2 presents a detailed analysis of solutions regarding the advantages and limitations of simulation methods using VR in the training process, energy management problems, and reducing energy consumption in airports. A research gap was identified that justified the authors' research. Section 3 presents a proposal for a four-stage method of training forklift operators. Section 4 presents the research results on improving training effectiveness using the method described in the article. Section 5 presents, in the form of a comparative analysis, the results of research on energy consumption in training conducted using traditional methods and the method proposed by the authors using the VR environment. The paper is summarized with conclusions, discussing the limitations of the proposed method and directions for further research.

## 2. Literature Review

Due to the broad scope of the issues discussed in the article, the literature review was divided into two parts. The first part discussed the advantages and limitations of VR technology in conducting training, while the second part focused on the energy consumption problems in airports' operations.

### *2.1. Advantages and Limitations of Training Using Virtual Reality Simulators*

To overcome the limitations of traditional training methods, VR-based training is increasingly being implemented in high-risk sectors such as air transport. These training courses offer more effective learning by using interactive and contextual training content in a simulated virtual environment. This is especially important in industries where mistakes can have disastrous consequences [10]. The virtual environment, characterized by a visual interface, interaction, and immersion, allows participants to experience situations close to real ones, contributing to the formation of awareness and appropriate habits [11]. VR simulators allow participants to be exposed to controlled, virtually dangerous situations that are impossible to operate in actual work conditions and can provide practical experiences related to avoiding accidents or infrastructure damage [5,12].

VR training can contribute to lasting behaviour changes and can shape appropriate habits by providing unique experiences, such as immediate feedback, building empathy, or experiencing the consequences of dangerous behaviour [7]. The availability of low-cost head-mounted displays (HMDs) and VR games based on graphics engines such as Unity and Unreal Engine makes it possible to create cost-effective VR training programs [13–16].

Research has confirmed the higher effectiveness of VR training compared to traditional methods in various industrial fields, including processes supporting air transport [2,15–21]. Additionally, this research has led to an understanding of other factors that influence learning outcomes in VR training, such as psychological factors [14,18].

A key aspect of designing simulation-based training is how faithfully the simulator reflects reality. This fidelity affects systems' learning outcomes and cost-effectiveness [22–24]. High-quality simulators, equipped with realistic views and a 3D interface, are preferred, as they provide greater transferability of training to complex real-world situations [20]. However, higher fidelity in reflecting reality is associated with higher system development costs and the need to use more advanced devices and programming tools, which may reduce the economic profitability of such training [22].

There are ongoing debates in the literature about the optimal level of fidelity of VR systems that may contribute to better training outcomes [14,25–28]. In various fields, including aviation and military, it is argued that higher fidelity can contribute to the better transfer of training and learning outcomes [22]. However, it is unclear whether higher fidelity regarding training or training effectiveness is always desirable. Ragan et al. [29] showed that higher scenario fidelity in a VR training system for a visual scanning task did not lead to better transfer of skills learned in VR to the real world. Requirements for faithfulness to reality may vary depending on the training task and the intended learning outcomes [23].

In order to systematize knowledge about VR technology in the training process, Table 1 lists the advantages and limitations of this solution.

**Table 1.** Advantages and limitations of using VR in training.

| Advantages | Limitations |
|---|---|
| ○ Realistic environment—VR enables the creation of a realistic training environment that can mimic actual work conditions, without the risk associated with physical presence in a dangerous or costly environment. | ○ High initial costs—implementing VR training requires initial investments in equipment and software, which can be a barrier for some organizations. |
| ○ Safety—training in virtual reality eliminates the risk of accidents and injuries, which is particularly important for training with heavy equipment, such as forklifts. | ○ Need for specialized software—the development of personalized VR training scenarios requires access to virtual reality experts and may involve additional costs. |
| ○ Participant engagement—VR increases engagement and motivation among participants through immersive experiences that are more engaging than traditional training methods. | ○ Technological limitations—the quality and immersion of the VR experience can be limited by current technological capabilities, such as screen resolution or response time. |
| ○ Repeatability—VR training can be easily repeated, allowing participants to practice the same scenarios multiple times, which improves learning and knowledge retention. | ○ Possible "side effects"—some users may experience negative physiological reactions, such as dizziness or nausea, known as "virtual reality sickness". |
| ○ Personalized learning—VR programs can be tailored to the individual needs of the learner, allowing for the adjustment of the pace and difficulty level of the training. | ○ Lack of human interaction—training in VR may limit the possibilities for interaction and learning from other participants or instructors in the real world, which can affect the social aspects of learning. |
| ○ Cost reduction—over the long term, VR training can reduce costs associated with logistics, such as rental of training space, equipment rental, energy consumption and costs related to participant delegations. | ○ Limitations in practical teaching—although VR can simulate many scenarios, it does not fully replace the practical experience associated with physically manipulating equipment in the real world. |

One of the advantages of using VR technology in the training process is cost reduction (see Table 1), which is related to, among other things, reducing the consumption of electricity used in the training process. Training in a virtual environment eliminates the need to use heavy equipment that requires significant amounts of electricity. Transferring some training to the virtual world can, therefore, significantly reduce the demand for energy in the aviation sector, both in terms of training equipment operators and ground and cabin staff. This is particularly important in managing energy consumption in aviation operations, where every saving directly impacts reducing $CO_2$ emissions and other sustainable development goals.

In the context of energy consumption management in air transport, VR technology can play a crucial role in staff training and also in the analysis and optimization of operational processes. VR simulations can help identify areas where energy consumption is highest and propose solutions to minimize this consumption. This approach is consistent with current aviation energy management trends, which focus on energy efficiency and minimizing environmental impact. An overview of current trends in energy consumption management is presented in Section 2.2.

### 2.2. *Energy Consumption Management in Air Transport*

The process of optimizing energy consumption management in air transportation, aimed at its reduction, has been extensively analysed in scientific literature. A detailed discussion of this issue is found in [30]. Based on this analysis, supplemented by the latest research findings, a significant gap in research on energy consumption in the area of cargo terminal handling, especially in the context of transport operations in cargo terminals, is noticeable. There is a need to focus on energy consumption analysis to ensure efficient cargo handling while adhering to sustainable development principles. It is important to note that the studies presented in [30] covered the entire airport and terminal infrastructure, with particular emphasis on HVAC (Heating, Ventilation, Air Conditioning) systems [31–34]. Some research works have focused in detail on selected aspects. For example, Ma and colleagues [35] analysed the relationship between air flow and internal comfort within the terminal, while Parker and colleagues [36] aimed to reduce the carbon footprint by expanding a glass roof on a selected airport. Meanwhile, Gowresuunker and colleagues [37] assessed the effectiveness of displacement ventilation in the airport terminal. Numerous articles focus on predicting energy consumption in airport passenger terminals. Chen [38] applied a Markov model, Huang and colleagues [39] used neural networks, and Fan and colleagues [40] developed a model based on probability density functions. Mambo and colleagues [41] observed that the dynamic regulation of the internal environment, depending on flight schedules, could improve efficiency by up to 25%. Studies [41–44] highlighted the possibility of dynamically managing thermal comfort and lighting in different parts of the terminals. It must be strongly emphasized that only a few works in the literature discuss the energy intensity of terminal operations, and only three [45–47] directly correlate with the analysis of energy intensity through operational systems. However, these are operational systems of passenger terminals, not cargo terminals. In work [45], a simulation model was used to analyse the sensitivity of energy consumption by the airport baggage handling system to changes in resource allocation strategies. In work [46], a simulation model was developed, allowing for the simultaneous analysis of the efficiency of the airport security checkpoint and energy consumption per serviced passenger. In turn, in work [47], the authors deal with analyses in the field of energy consumption of processes, related to passenger luggage support during security control.

In summary, a critical research gap in the existing literature is the lack of studies documenting the energy intensity of transport operations conducted in cargo terminals. So far, researchers' attention has focused only on aspects related to direct passenger service. A comprehensive review of the literature on modelling passenger service processes is presented in [45]. The results of this review indicate that the main factors are process efficiency and passenger service quality. Recent studies, such as the stochastic model of passenger boarding developed to increase process efficiency [48], confirm that these elements remain key to research efforts. Uncertainty is also taken into account in planning terminal operations [49], with the goal being to optimize passenger service processes [50]. Optimal resource allocation is often used to increase process efficiency [51,52].

Managing energy consumption at airports is crucial both from an economic and ecological point of view. One of the challenges is that data on total energy consumption by airports are classified as sensitive information, limiting their public availability. Therefore, researchers and analysts must rely solely on estimated data to understand which airport processes consume the most energy.

Cargo handling is one area that requires special attention. It is a time-consuming and energy-intensive process, constituting a significant part of the total energy balance of the cargo terminal. Analyses [32,33,37] indicate that it may account for 21% to 35% of annual energy consumption in terminals, especially at large airports. Therefore, it is not a negligible value compared to the total consumption, indicating the purposefulness of undertaking analyses related to efficient management of the control process.

Nevertheless, aspects related to energy consumption during transport operations (loading and unloading) have been completely overlooked in the solutions developed so far. This article aims to fill this gap. The material includes a multi-aspect analysis of the impact of the level of training of forklift operators (the leading means of transport in cargo terminals) on the energy intensity of the entire cargo handling process.

A well-trained operator demonstrates significantly higher efficiency in forklift use, which directly translates into energy savings. Their ability to effectively plan travel routes, properly select forklift speeds, and precisely and consciously handle loads minimizes unnecessary movements and engine operating time. Additionally, skills related to the maintenance and ongoing monitoring of the technical condition of forklifts allow for keeping the equipment in a state ensuring optimal energy efficiency. Differences in training levels can be measured in simulation studies by monitoring energy consumption in various operational scenarios.

The article proposes detailed solutions for optimal management of the training process, allowing for the development of personalized training strategies for operators based on the principles of sustainable development and minimizing the energy intensity of the entire process. Well-trained operators not only minimize the risk of accidents but also increase the overall efficiency of operations. Therefore, a high level of training for forklift operators is a key element in managing the safety and energy efficiency of logistics operations [53] in the environment of airport cargo terminals.

## 3. Method

Improving the training level of a forklift operator in an airport cargo terminal using a virtual reality environment is a four-step process. The details are presented in Figure 1.

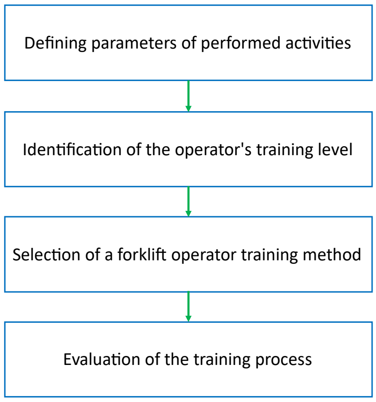


**Figure 1.** Stages of the process of improving the training level of a forklift operator in an airport cargo terminal using a virtual reality environment.

**Stage 1. Defining parameters of performed activities**

In the first step of the developed method, training parameters are set in terms of activities and the environment in which the training will occur.

First, three levels of difficulty are defined in the training process: easy, medium, and hard. For each level, the parameters of the environment in which the training will take place have been defined, as follows:

- EASY (basic) level: low traffic intensity of other participants in the handling process, a small number of shipments to be handled, and a large distance between shipments;
- MEDIUM level: average traffic intensity of other participants in the handling process, an average number of shipments to be handled, and an average distance between shipments;
- HARD (advanced) level: high traffic intensity of other participants in the handling process, a large number of shipments to be handled, and a small distance between shipments.

Table 2 presents descriptions of individual parameters of the freight terminal environment, depending on the level of training performed.

**Table 2.** Descriptions of individual parameters of the freight terminal environment, depending on the level of training performed.

| | Traffic Intensity | Number of Parcels | Distance between Parcels |
|---|---|---|---|
| Easy | Max. one forklift for 2000 $m^2$ of warehouse | Max. one parcel per 10 min | Even distribution of parcels over a maximum of 25% of the space |
| Medium | At least one forklift for 2000 $m^2$ warehouse and no more than one forklift for 200 $m^2$ of warehouse | At least one parcel per 10 min and no more than one parcel per 2 min | At least 25% of space occupied and no more than 75% |
| Hard | Min. one forklift for 200 $m^2$ of warehouse | Min. one parcel per 2 min | Even distribution of shipments over at least 75% of the space |

Secondly, the set of activities the forklift operator can perform is defined. These activities can be divided into three groups, related to transport, manipulation, and identification.

The set of activities related to transport includes the following:

- $D_1$—driving a forklift from the parking place to the collection point,
- $D_2$—driving a forklift from the parking space to the X-ray scanner,
- $D_3$—driving a forklift from the parking space to the warehouse with shipments checked for safety,
- $D_4$—driving a forklift from a parking space to the temporary storage space,
- $D_5$—driving a forklift from the place of pickup to the scale,
- $D_6$—driving a forklift from the scale to the temporary storage space,
- $D_7$—driving a forklift from the scale to the warehouse rack,
- $D_8$—driving a forklift from the temporary storage space area to the X-ray scanner,
- $D_9$—driving a forklift from the warehouse rack to the X-ray scanner,
- $D_{10}$—driving with an X-ray scanner to the warehouse for shipments checked for safety,
- $D_{11}$—driving from the warehouse of safety-checked shipments to the waiting area,
- $D_{12}$—driving a forklift at the weighing area,
- $D_{13}$—driving a forklift in the temporary storage area,
- $D_{14}$—driving a forklift within the X-ray scanner service area,
- $D_{15}$—driving a forklift from the temporary storage area to the picking area,
- $D_{16}$—driving a forklift from the temporary storage area to the waiting area,
- $D_{17}$—driving a forklift in the warehouse area of shipments checked for safety,
- $D_{18}$—driving a forklift from the warehouse of safety-checked shipments to the X-ray scanner,
- $D_{19}$—driving a forklift from the place of depositing the shipment to the conveyor transporting the construction of ULD (Unit Load Devices) pallets to the waiting place,
- $D_{20}$—driving a forklift from the place where the shipment is placed to the conveyor transporting the construction of ULD pallets to the X-ray scanner.

The set of manipulation activities includes the following:

- $M_1$—collecting the parcel from the collection point,
- $M_2$—placing the parcel on the scale,
- $M_3$—picking up the shipment from the scale,
- $M_4$—putting the parcel to the temporary storage area,
- $M_5$—picking up the parcel from the temporary storage area,
- $M_6$—placing the shipment on the shelf,
- $M_7$—picking up the shipment from the shelf,
- $M_8$—putting the shipment on the X-ray scanner,
- $M_9$—retrieving the shipment from the X-ray scanner,
- $M_{10}$—putting the shipment aside in a storage space in the shipment warehouse after security inspection,
- $M_{11}$—picking up the shipment at the warehouse in the parcel warehouse after security inspection,
- $M_{12}$—placing the shipment on the conveyor transporting shipments for the construction of ULD pallets,
- $M_{13}$—waiting for transport activities to be performed.

The set of activities related to identification includes the following:

- $I_1$—identification of the Air Waybill number of the shipment for which the handling process is carried out,
- $I_2$—identification of the type of shipment (e.g., dangerous, live animals, valuable, etc.) for which the handling process is carried out,
- $I_3$—identification of the weight and dimensions of the shipment.

The relationship between the defined types of errors and the activities in which they may occur is defined in Table 3.

**Table 3.** Types of errors and the activities in which they may occur.

| **Name of Activities** | **Errors** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Damage to the Transported Parcel** | **Damage to Third Party Parcel** | **Damage to Infrastructure Elements (e.g., Wall)** | **Scale Damage** | **Damage to a Warehouse Rack** | **Damage to the X-ray Scanner Components (e.g., Roller Conveyor)** | **Damage to Forklift Components** | **Incorrect Identification of the Shipment and Its Components** |
| Moving with a forklift | | | | | | | | |
| $D_1$ | | x | x | | | | x | |
| $D_2$ | | x | x | | | x | x | |
| $D_3$ | | x | x | | | | x | |
| $D_4$ | | x | x | | x | | x | |
| $D_5$ | x | x | x | x | | | x | |
| $D_6$ | x | x | x | x | | | x | |
| $D_7$ | x | x | x | x | x | | x | |
| $D_8$ | x | x | x | | | x | x | |
| $D_9$ | x | x | x | | x | x | x | |
| $D_{10}$ | x | x | x | | | x | x | |
| $D_{11}$ | | x | x | | | | x | |
| $D_{12}$ | x | x | x | x | x | | x | |
| $D_{13}$ | | x | x | | x | | x | |
| $D_{14}$ | | x | x | | | x | x | |
| $D_{15}$ | | x | x | | | | x | |
| $D_{16}$ | | x | x | | | | x | |
| $D_{17}$ | x | x | x | | | x | x | |
| $D_{18}$ | | x | x | | | x | x | |
| $D_{19}$ | | x | x | | | | x | |
| $D_{20}$ | | x | x | | | x | x | |
| Manipulative activities | | | | | | | | |
| $M_1$ | x | x | | | | | x | |
| $M_2$ | x | x | | x | | | x | |
| $M_3$ | x | x | | x | | | x | |
| $M_4$ | x | x | | | | | x | |
| $M_5$ | x | x | | | | | x | |
| $M_6$ | x | x | | | x | | x | |
| $M_7$ | x | x | | | x | | x | |
| $M_8$ | x | x | | | | x | x | |
| $M_9$ | x | x | | | | x | x | |
| $M_{10}$ | x | x | | | | | x | |
| $M_{11}$ | x | x | | | | | x | |
| $M_{12}$ | x | x | | | | | x | |
| $M_{13}$ | x | x | | | | | x | |
| Identification activities | | | | | | | | |
| $I_1$ | | | | | | | | x |
| $I_2$ | | | | | | | | x |
| $I_3$ | | | | x | | | | x |

The model of the shipment handling process in the airport cargo terminal is presented in Figure 2.

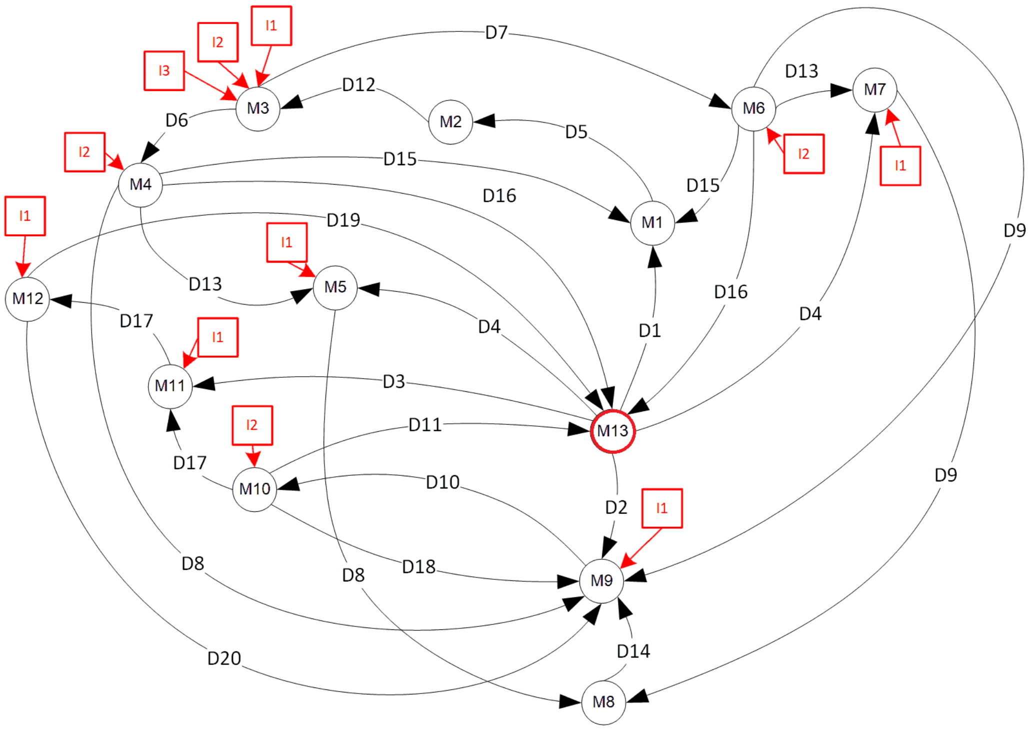


**Figure 2.** Model of the shipment handling process in the airport cargo terminal (start point—$M_{13}$).

For the developed model, activities related to manipulation were defined in the nodes, and activities related to shipment transportation were defined in the graph branches. The developed graph model defines all the possible consequences of actions performed by the operator and defines them for the virtual reality environment. In some graph nodes, identification activities must be performed as part of the virtual reality training have been defined.

**Stage 2. Identification of the operator's training level**

Identification of the training level of the forklift operator at the airport parcel handling terminal is carried out in accordance with the algorithm presented in Figure 3.

Identification of the operator's training level begins with the easy level, i.e., low traffic intensity of other participants in the handling process, a small number of parcels to be handled, and a large distance between parcels (parameters consistent with Table 1). The operator begins the process of 60 min identification of the training level, starting activities in the state of waiting for activities to be performed ($M_{13}$). Then, activities are set to be performed using the model of the shipment handling process in the airport terminal, with random durations of individual activities that are no longer than 15 s. The probabilities of changes in all states in the parcel handling process model in the airport terminal are uniformly distributed. Each activity generates at least one event (e.g., the passage of another forklift) that requires the forklift operator to perform the activity. Suppose the activity is performed correctly (driving from point A to point B or performing a manipulation operation) and correctly avoiding an externally generated situation (e.g., stopping and giving way to another forklift). In that case, the activity is considered to have been performed correctly. It is considered that the operator is trained at the easy level and can proceed to identify medium-level training if at least 80% of all activities, i.e., $D_1$ to $D_{20}$, $M_1$ to $M_{13}$, or $I_1$ to $I_3$, have been performed correctly. If the forklift operator has not achieved 80% of correctly performed activities, the training process is carried out by step 3. Medium- and hard-level training is identified similarly to the easy level by setting the appropriate parameters in Table 1, namely the length of the training session and the number of generated events. The level changes from medium to high after completing at least 80% of the tasks.

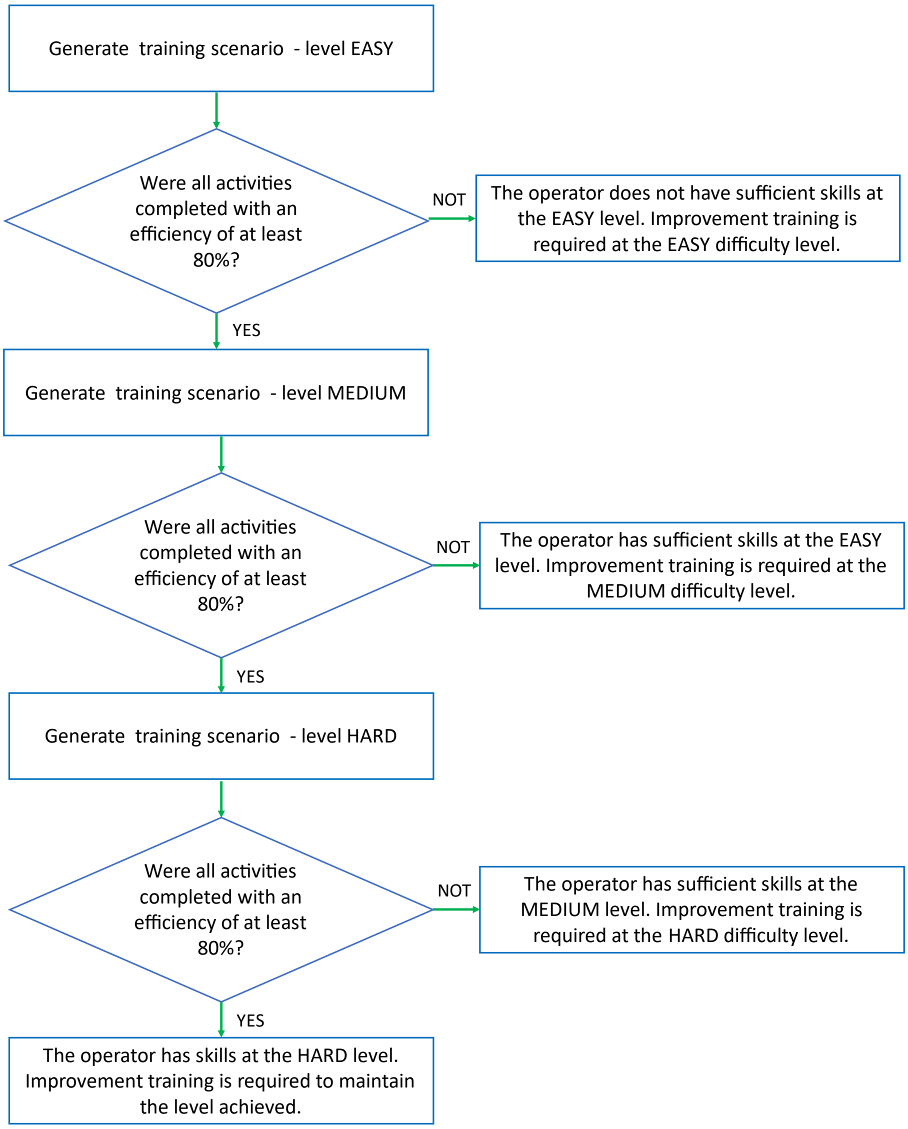


**Figure 3.** Algorithm for identifying the training level of a forklift operator in an air cargo terminal.

**Stage 3. Selection of a forklift operator training method**

The method of training a forklift operator in an airport parcel handling terminal is presented in Figure 4.

The operator's training level is defined in the method's first step. By default, it is defined as the correct performance of at least 80% of all activities performed. The next step of the method checks whether all activities were carried out with an efficiency of 80%. If the required level of training has not been achieved, a set of activities—operations for which the required level of 80% has not been achieved (e.g., {$D_4$; $D_{11}$; $M_1$; $M_2$; $I_3$})—is created. As part of the training session being created, the training system forces the intensity of operations defined in the set of operations as requiring improvement to be at least doubled compared to the session identifying the level of training. A 15 min improving session is then held. After the session, indicators of the level of training in performing individual operations are checked. If all operations have been completed with an efficiency of 80%, you can start further training at a medium level. If the required level of 80% is still not achieved, the set of activities requiring improvement is redefined, and the training session is conducted again.

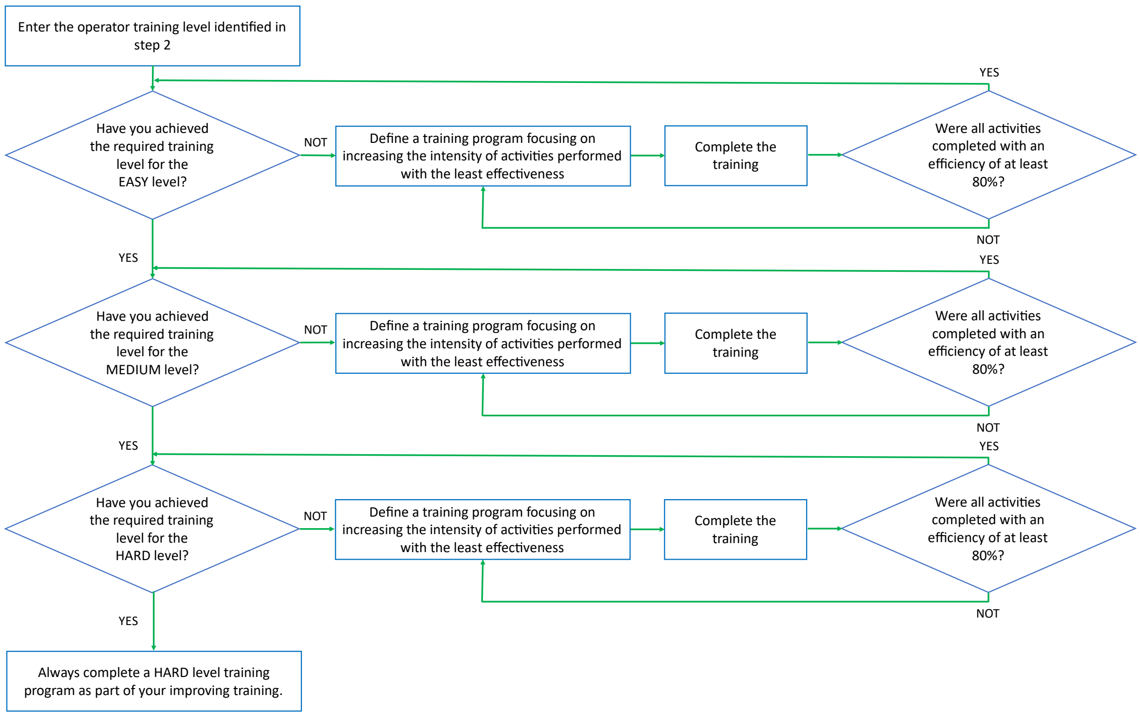


**Figure 4.** Algorithm of training a forklift operator in an airport cargo terminal.

**Stage 4. Evaluation of the training process**

The training process is assessed by estimating the parameters of a simple linear regression for the following:

- subsequent effectiveness indicators obtained for individual activity values: $D_1$ to $D_{20}$, $M_1$ to $M_{13}$ and $I_1$ to $I_3$;
- subsequent average values of all effectiveness indicators in the training process.

Suppose the forecasting effectiveness of the average values of all effectiveness indicators in the training process for training sessions n + 1, n + 2, and n + 3 is below 80%. In that case, the intensity of the training process should be increased. For an in-depth analysis, a detailed analysis of the simple linear regression parameters should be performed for individual activity values: $D_1$ to $D_{20}$, $M_1$ to $M_{13}$, and $I_1$ to $I_3$. If the forecast of the effectiveness of individual indicators for training sessions n + 1, n + 2, and n + 3 is below 80%, the intensity of these activities should be increased in the next training session.

Suppose all simple linear regression indicators (effectiveness index relative to the next training session) have a positive value. The training process went very well, and the forklift operator improved his skills in all activities.

## 4. Results

The research was carried out using an original solution developed as part of the project POIR.04.01.04-00-0072/20 "Use of the virtual reality environment in the training system for handling employees in the handling of goods transported by air". The visualization of the training station is presented in Figure 5.

The forklift operator training station consists of two main elements: virtual reality glasses (including the operating system and software) and the physical forklift operator station (operator's seat and control panel). The visualization of the virtual air cargo terminal system is presented in Figure 6.

The operator can perform the following activities: $D_1$ to $D_{20}$, $M_1$ to $M_{13}$, and $I_1$ to $I_3$ in the virtual air cargo terminal. This terminal reflects one of the regional parcel handling terminals. It has all the zones in a cargo airport terminal, e.g., the security control zone. The forklift control panel has all the standard functions of forklifts, i.e., raising and lowering the forks, fork shifting, and fork tilting. Additionally, the dashboard has a steering wheel, a button limiting the forklift's speed, a parking brake, a speedometer, a safety button, and a drive controller (front, rear). The forklift also has a dashboard that provides information about the shipment that needs to be handled. Figure 7 shows a photo from the training session.

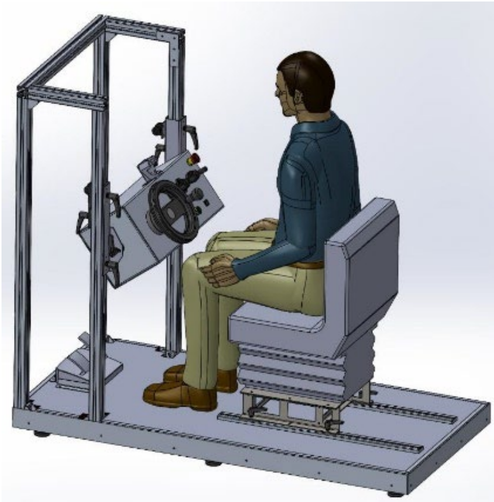

**Figure 5.** Visualization of the forklift operator training station.

**Figure 6.** Visualization of the virtual air cargo terminal system.

**Figure 7.** Training session on a VR forklift simulator.

The trained person carries out the training process on a simulator—the instructor has a real-time view on the monitor of all activities performed by the operator. The training included sessions for an operator with little experience in using a forklift (immediately after obtaining the license). The results of the training level identification process are presented in Table 4. Values in bold are lower than the minimum required to pass a given activity (the minimum is 80%).

**Table 4.** Identification of the forklift operator's training level.

| | **Operator 1** | | |
|---|---|---|---|
| | **Level *EASY*** | | |
| **ID** | **Total Number of Repetitions of the Activity (by ID) as Part of the Implemented Scenario** | **Number of Activities Performed Correctly** | **Effectiveness [%]** |
| $D_1$ | 11 | 10 | 90.90 |
| $D_2$ | 2 | 2 | 100.00 |
| $D_3$ | 3 | 3 | 100.00 |
| $D_4$ | 6 | 5 | 83.33 |
| $D_5$ | 17 | 14 | 82.35 |
| $D_6$ | 7 | 6 | 85.71 |
| $D_7$ | 10 | 9 | 90.00 |
| $D_8$ | 69 | 62 | 89.86 |
| $D_9$ | 10 | 8 | 80.00 |
| $D_{10}$ | 3 | 3 | 100.00 |
| $D_{11}$ | 10 | 9 | 90.00 |
| $D_{12}$ | 17 | 14 | 82.35 |
| $D_{13}$ | 5 | 5 | 100.00 |
| $D_{14}$ | 11 | 11 | 100.00 |
| $D_{15}$ | 6 | 5 | 83.33 |
| $D_{16}$ | 1 | 1 | 100.00 |
| $D_{17}$ | 53 | 47 | 88.68 |
| $D_{18}$ | 30 | 24 | 80.00 |
| $D_{19}$ | 10 | 8 | 80.00 |
| $D_{20}$ | 18 | 16 | 88.89 |
| $M_1$ | 17 | 13 | **76.47** |
| $M_2$ | 17 | 12 | **70.59** |
| $M_3$ | 17 | 14 | 82.35 |
| $M_4$ | 7 | 6 | 85.71 |
| $M_5$ | 3 | 2 | **66.67** |
| $M_6$ | 10 | 3 | **30.00** |
| $M_7$ | 8 | 3 | **37.50** |
| $M_8$ | 11 | 6 | **54.55** |
| $M_9$ | 66 | 34 | **51.52** |
| $M_{10}$ | 66 | 43 | **65.15** |
| $M_{11}$ | 28 | 19 | **67.86** |
| $M_{12}$ | 28 | 22 | **78.57** |
| $M_{13}$ | 22 | 22 | 100.00 |
| $I_1$ | 150 | 96 | **64.00** |
| $I_2$ | 100 | 78 | **78.00** |
| $I_3$ | 17 | 11 | **64.71** |

The training session showed that the forklift operator coped well with the activities performed during general forklift driving training. The effectiveness of all activities related to using a forklift, i.e., from $D_1$ to $D_{20}$, was above 80%. The operator achieved much worse results in the field of activities related to manipulation operations and activities related to parcel identification. The operator achieved the worst result with activities related to positioning or retrieving a shipment from a warehouse shelf or positioning or retrieving a shipment from an X-ray scanner. Activities related to loading or unloading a shipment from a warehouse rack require extensive operator experience acquired over time. Similarly, in the case of identification activities, all of these were completed with an efficiency of less than 80%. Problems in the initial stage of work as a forklift operator result from many regulations regarding shipment handling that must be followed (e.g., DGR, LAR regulations, etc.). The operator is, therefore, a beginner operator without basic training.

The intensity was changed in the second training session to achieve higher exercise frequency for low-performance activities. Since the identified low-efficiency activities are $M_6$, $M_7$, $M_8$, and $M_9$ (marked in dark grey in Table 5), using the graph (Figure 2), the training intensity was increased for $M_1$, $M_2$, $M_3$, $M_6$, $M_7$, $M_8$ Chains, $M_9$, $M_{10}$, and $M_{13}$ (light grey in Table 5). A comparative analysis of the results of both training sessions is presented in Table 5.

**Table 5.** Comparison of training levels between subsequent training sessions.

| ID | Total Number of Repetitions of the Activity (by ID) as Part of the Implemented Scenario | Number of Activities Performed Correctly | Effectiveness [%] | Total Number of Repetitions of the Activity (by ID) as Part of the Implemented Scenario | Number of Activities Performed Correctly | Effectiveness [%] | Change |
|---|---|---|---|---|---|---|---|
| | Session 1—Level *EASY* | | | Session 2—Level *EASY* | | | |
| $D_1$ | 11 | 10 | 90.90 | 19 | 18 | 94.74 | + * |
| $D_2$ | 2 | 2 | 100.00 | 4 | 4 | 100.00 | ~ |
| $D_3$ | 3 | 3 | 100.00 | 6 | 6 | 100.00 | ~ |
| $D_4$ | 6 | 5 | 83.33 | 14 | 12 | 85.71 | ~ |
| $D_5$ | 17 | 14 | 82.35 | 25 | 21 | 84.00 | ~ |
| $D_6$ | 7 | 6 | 85.71 | 13 | 11 | 84.62 | ~ |
| $D_7$ | 10 | 9 | 90.00 | 12 | 11 | 91.67 | ~ |
| $D_8$ | 69 | 62 | 89.86 | 54 | 48 | 88.89 | ~ |
| $D_9$ | 10 | 8 | 80.00 | 15 | 13 | 86.67 | + |
| $D_{10}$ | 3 | 3 | 100.00 | 4 | 4 | 100.00 | ~ |
| $D_{11}$ | 10 | 9 | 90.00 | 32 | 29 | 90.63 | ~ |
| $D_{12}$ | 17 | 14 | 82.35 | 25 | 22 | 88.00 | + |
| $D_{13}$ | 5 | 5 | 100.00 | 8 | 8 | 100.00 | ~ |
| $D_{14}$ | 11 | 11 | 100.00 | 21 | 20 | 95.24 | - |
| $D_{15}$ | 6 | 5 | 83.33 | 6 | 5 | 83.33 | ~ |
| $D_{16}$ | 1 | 1 | 100.00 | 4 | 4 | 100.00 | ~ |
| $D_{17}$ | 53 | 47 | 88.68 | 18 | 16 | 88.89 | ~ |
| $D_{18}$ | 30 | 24 | 80.00 | 7 | 6 | 85.71 | + |
| $D_{19}$ | 10 | 8 | 80.00 | 6 | 5 | 83.33 | ~ |
| $D_{20}$ | 18 | 16 | 88.89 | 6 | 6 | 100.00 | ++ |
| $M_1$ | 17 | 13 | **76.47** | 25 | 18 | **72.00** | ~ |
| $M_2$ | 17 | 12 | **70.59** | 25 | 17 | **68.00** | ~ |
| $M_3$ | 17 | 14 | 82.35 | 25 | 20 | 80.00 | ~ |
| $M_4$ | 7 | 6 | 85.71 | 13 | 11 | 84.62 | ~ |
| $M_5$ | 3 | 2 | **66.67** | 10 | 7 | **70.00** | + |
| $M_6$ | 10 | 3 | **30.00** | 12 | 6 | **50.00** | +++ |
| $M_7$ | 8 | 3 | **37.50** | 12 | 6 | **50.00** | +++ |
| $M_8$ | 11 | 6 | **54.55** | 21 | 12 | **57.14** | + |
| $M_9$ | 66 | 34 | **51.52** | 45 | 27 | **60.00** | ++ |
| $M_{10}$ | 66 | 43 | **65.15** | 45 | 32 | **71.11** | + |
| $M_{11}$ | 28 | 19 | **67.86** | 12 | 8 | **66.67** | ~ |
| $M_{12}$ | 28 | 22 | **78.57** | 12 | 10 | 83.33 | + |
| $M_{13}$ | 22 | 22 | 100.00 | 43 | 43 | 100.00 | ~ |
| $I_1$ | 150 | 96 | **64.00** | 116 | 80 | **68.97** | + |
| $I_2$ | 100 | 78 | **78.00** | 95 | 78 | 82.11 | + |
| $I_3$ | 17 | 11 | **64.71** | 25 | 17 | **68.00** | + |

*—slight decrease in efficiency. ~—maintenance efficiency at a similar level. +—efficiency levels improved slightly. ++—significant improvement. +++—very strong improvement.

The second training session brought about the expected results. As part of activities $M_6$, $M_7$, $M_8$, and $M_9$, the operator achieved greater efficiency in the operations performed. Only in the case of one activity ($D_{14}$) did the operator achieve a slight decrease in effectiveness from 100% to 95%.

Another six training sessions were conducted in which changes in the training intensity of individual activities were modified by the above principle. The effectiveness values of the activities performed for individual activities in subsequent training sessions, along with the determined function of simple linear regression, are presented in Table 6.

**Table 6.** Comparison of training levels between subsequent training sessions.

| ID | Effectiveness [%] | | | | | | | | Regression Function |
|---|---|---|---|---|---|---|---|---|---|
| | No. of Session—Level *EASY* | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| | $s_{No.}$ | | | | | | | | |
| $D_1$ | 90.90 | 94.74 | 94.63 | 96.51 | 94.77 | 97.08 | 95.32 | 97.69 | $E_{D1} = 0.67s_{No.(D1)} + 92.20$ |
| $D_2$ | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | $E_{D2} = 100$ |
| $D_3$ | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | $E_{D3} = 100$ |
| $D_4$ | 83.33 | 85.71 | 85.63 | 85.42 | 85.39 | 85.25 | 85.31 | 85.69 | $E_{D4} = 0.16s_{No.(D4)} + 84.50$ |
| $D_5$ | 82.35 | 84.00 | 84.03 | 86.07 | 87.2 | 84.19 | 87.15 | 86.47 | $E_{D5} = 0.55s_{No.(D5)} + 82.71$ |
| $D_6$ | 85.71 | 84.62 | 84.5 | 84.64 | 84.82 | 85.18 | 83.41 | 81.35 | $E_{D6} = -0.41s_{No.(D6)} + 86.12$ |
| $D_7$ | 90.00 | 91.67 | 91.51 | 93.34 | 91.18 | 94.97 | 91.09 | 93.03 | $E_{D7} = 0.31s_{No.(D1)} + 90.68$ |
| $D_8$ | 89.86 | 88.89 | 88.74 | 89.06 | 88.96 | 89.07 | 89.15 | 89.22 | $E_{D8} = -0.03s_{No.(D8)} + 89.24$ |
| $D_9$ | 80.00 | 86.67 | 86.83 | 86.68 | 84.5 | 89.06 | 86.75 | 89.15 | $E_{D9} = 0.82s_{No.(D9)} + 82.51$ |
| $D_{10}$ | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | $E_{D10} = 100$ |
| $D_{11}$ | 90.00 | 90.63 | 90.68 | 90.96 | 92 | 87.17 | 89.2 | 87.06 | $E_{D11} = -0.44s_{No.(D11)} + 91.71$ |
| $D_{12}$ | 82.35 | 88.00 | 87.81 | 90.84 | 91.21 | 88.23 | 88.47 | 88.72 | $E_{D12} = 0.58s_{No.(D12)} + 85.60$ |
| $D_{13}$ | 100.00 | 100.00 | 100 | 100 | 100 | 100 | 100 | 100 | $E_{D13} = 100$ |
| $D_{14}$ | 100.00 | 95.24 | 95.42 | 95.32 | 93.66 | 96.84 | 95.88 | 94.87 | $E_{D14} = -0.36s_{No.(D14)} + 97.52$ |
| $D_{15}$ | 83.33 | 83.33 | 83.28 | 84.45 | 83.64 | 86.96 | 85.82 | 84.68 | $E_{D15} = 0.38s_{No.(D15)} + 82.72$ |
| $D_{16}$ | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | $E_{D16} = 100$ |
| $D_{17}$ | 88.68 | 88.89 | 88.92 | 90.86 | 92.10 | 87.43 | 93.37 | 90.23 | $E_{D17} = 0.36s_{No.(D17)} + 88.45$ |
| $D_{18}$ | 80.00 | 85.71 | 85.74 | 87.66 | 88.01 | 85.83 | 90.64 | 87.71 | $E_{D18} = 0.94s_{No.(D18)} + 82.17$ |
| $D_{19}$ | 80.00 | 83.33 | 84.32 | 86.37 | 83.40 | 84.49 | 87.31 | 83.18 | $E_{D19} = 0.47s_{No.(D19)} + 81.93$ |
| $D_{20}$ | 88.89 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | $E_{D20} = 0.93s_{No.(D20)} + 94.45$ |
| $M_1$ | **76.47** | **72.00** | **72.99** | **73.06** | **75.99** | **77.90** | 82.07 | 81.90 | $E_{M1} = 1.26s_{No.(M1)} + 70.87$ |
| $M_2$ | **70.59** | **68.00** | **68.30** | **70.28** | **72.31** | **74.34** | **78.58** | 83.87 | $E_{M2} = 1.98s_{No.(M2)} + 64.39$ |
| $M_3$ | 82.35 | 80.00 | 80.35 | 84.41 | 88.79 | 86.07 | 83.19 | 81.49 | $E_{M3} = 0.37s_{No.(M3)} + 81.65$ |
| $M_4$ | 85.71 | 84.62 | 84.47 | 84.64 | 84.49 | 84.32 | 84.71 | 85.04 | $E_{M4} = -0.06s_{No.(M4)} + 85.01$ |
| $M_5$ | **66.67** | **70.00** | **70.09** | **73.44** | **75.36** | **76.52** | 80.47 | 81.49 | $E_{M5} = 2.11s_{No.(M5)} + 64.76$ |
| $M_6$ | **30.00** | **50.00** | **55.98** | **64.29** | **73.09** | **75.44** | **79.31** | 83.63 | $E_{M6} = 7.01s_{No.(M6)} + 32.41$ |
| $M_7$ | **37.50** | **50.00** | **52.84** | **55.08** | **60.99** | **65.3** | **72.42** | 80.26 | $E_{M7} = 5.41s_{No.(M7)} + 34.94$ |
| $M_8$ | **54.55** | **57.14** | **57.17** | **66.29** | **71.46** | **75.76** | **77.77** | 82.83 | $E_{M8} = 4.31s_{No.(M8)} + 48.48$ |
| $M_9$ | **51.52** | **60.00** | **62.09** | **64.03** | **60.4** | **60.78** | **60.96** | **61.15** | $E_{M9} = 4.10s_{No.(M9)} + 50.65$ |
| $M_{10}$ | **65.15** | **71.11** | **73.92** | **74.15** | **78.11** | 81.37 | 84.55 | 87.91 | $E_{M10} = 3.01s_{No.(M10)} + 63.49$ |
| $M_{11}$ | **67.86** | **66.67** | **68.64** | **72.48** | **77.63** | 81.45 | 82.81 | 84.88 | $E_{M11} = 2.89s_{No.(M11)} + 62.26$ |
| $M_{12}$ | **78.57** | 83.33 | 83.7 | 83.62 | 83.47 | 83.76 | 83.71 | 83.98 | $E_{M12} = 0.47s_{No.(M12)} + 80.89$ |
| $M_{13}$ | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | $E_{M13} = 100$ |
| $I_1$ | **64.00** | **68.97** | **74.79** | **76.91** | **77.01** | 80.93 | 82.19 | 84.44 | $E_{I1} = 2.71s_{No.(I1)} + 63.96$ |
| $I_2$ | **78.00** | 82.11 | 82.45 | 82.55 | 82.37 | 82.46 | 82.34 | 82.31 | $E_{I2} = 0.37s_{No.(I2)} + 80.15$ |
| $I_3$ | **64.71** | **68.00** | **71.3** | **76.21** | **78.5** | 81.49 | 84.87 | 86.68 | $E_{I3} = 3.23s_{No.(I3)} + 61.95$ |

The effectiveness of forklift driving activities ($D_1$ to $D_{20}$) in each training session met the minimum level. The operator implemented them with an efficiency of at least 80%. Only a few linear regression functions, the relationship between the level of effectiveness and the number of subsequent sessions, show a slope coefficient smaller than zero (marked in blue in Table 6). This means that the operator obtained lower effectiveness values over a longer time horizon with subsequent training sessions. For activity $D_8$, this decrease is small—it oscillates around 0.03% effectiveness per session. For activities $D_6$, $D_{11}$, and $D_{14}$, this decrease ranges from 0.36% to 0.44% per session. In subsequent training sessions, attention should be paid to the implementation of training in $D_6$ forklift driving activities because, during the last training session, the success rate was 81.35% and was only slightly higher than the minimum required. After completing the eighth training session, the forklift operator met the requirements to achieve the required level of effectiveness. For activities $M_{12}$, the operator obtained the minimum level of training after the second training session, and for activities $M_{10}$ and $M_{11}$ during the sixth training session. Training a forklift operator to the minimum level for $M_1$ manipulation activities (seventh training session) and $M_2$, $M_6$, $M_7$, $M_8$, and $M_9$ activities (eighth training session) took slightly longer. Only one linear regression function of the relationship between the level of effectiveness and the number of subsequent sessions shows a slope coefficient smaller than zero. For the $M_4$ activity, this decrease is small because it oscillates around 0.06% effectiveness per session. During the last session, the forklift operator achieved an efficiency of $M_4$ activity of 85.04%. The results of the obtained effectiveness should be monitored in subsequent training sessions. Regarding identification activities, the minimum level of training was achieved for activities $I_2$ during the second training session and for activities $I_1$ and $I_3$ during the sixth training session. For all shipment identification activities, the slope of the simple linear regression is greater than zero. This means that in the long term, continuous improvement of these activities takes place.

The results of empirical research indicate the high training effectiveness of the prepared solution. The next chapter will show how the solution proposed by the authors affects energy consumption compared to traditional training methods for forklift operators.

## 5. Comparative Analysis of Energy Consumption Using Traditional Methods of Training Forklift Operators and the Proposed Training Method (Using Virtual Reality)

As already mentioned, the aim of the developed training method for forklift operators is to reduce energy consumption in airport cargo terminals and, consequently, to more fully implement the principles of sustainable development.

The author's method was implemented in one of the cargo terminals in southern Poland. The research program examined 60 operators divided into three groups: beginners, intermediate, and advanced. The article presents results for only nine operators, due to space limitations of the material. The results presented in the article are representative (i.e., they describe the tendencies) of individual groups.

To illustrate the differences in energy consumption, research was conducted on a group of nine forklift operators with different years of experience in their positions (from 2 to 39 months) and, therefore, with different levels of training. The group was selected so that each level of training had three operators (beginner—EASY—experience: 0–10 months, intermediate—MEDIUM—experience: 11–23 months, and advanced—HARD—experience: over 24 months). The first step of the research was to determine (confirm) the assumed level of training of each operator according to the algorithm presented in Figure 3. Next, each operator implemented the training scenario prepared by the authors (covering the scope given in Table 2) on three different forklifts (differing in the power of the electric motor) and additionally on the VR training simulator shown in Figure 4. The prepared scenarios had the same difficulty level for each operator (the operator's level of training determined in the first step of the study did not matter). The operators repeated the test scenario twice: the first time with the truck set to ECO mode (lower energy consumption), and the second time in NORMAL mode. The exam was supervised by experienced driving instructors, who ultimately decided whether a given activity was passed and whether the operator could move on to the next one. In order to eliminate the phenomenon of rote learning and remembering of the implemented scenarios by the operators, the order of activities performed within the scenario was changed with each subsequent approach. The study measured the total time needed to perform all activities included in the scenario: the operator repeated the activity until the instructor passed it and only then moved on to the next one. Next, energy consumption during the entire exercise was calculated based on the time obtained. The technical data of the tested forklifts along with their energy consumption are presented in Table 7, and the experimental results are presented in Table 8.

**Table 7.** Energy consumption of the test's forklifts.

| | YALE ERC 16VA | YALE ERC 16VA | YALE ERP 55VM6 | Simulator VR |
|---|---|---|---|---|
| Energy consumption [kWh/h] (ECO mode) | 4.52 | 5.22 | 13.42 | 0.62 |
| Energy consumption [kWh/h] (NORMAL mode) | 6.50 | 6.67 | 17.56 | |

**Table 8.** Results of tests.

| | Mode | YALE ERC 16VA | YALE ERC 20VA | YALE ERC 50VM | Simulator VR |
|---|---|---|---|---|---|
| | | Energy Consumption [kWh] | | | |
| Operator 1 (Easy) | Eco | 1.58 | 2.20 | 6.38 | 0.22 |
| | Normal | 1.70 | 2.27 | 6.73 | |
| Operator 2 (Easy) | Eco | 1.50 | 2.20 | 5.87 | 0.19 |
| | Normal | 1.80 | 2.13 | 6.33 | |
| Operator 3 (Easy) | Eco | 1.35 | 1.80 | 5.88 | 0.20 |
| | Normal | 1.80 | 2.40 | 6.45 | |
| Operator 4 (Medium) | Eco | 0.90 | 1.20 | 3.40 | 0.13 |
| | Normal | 1.20 | 1.60 | 4.34 | |
| Operator 5 (Medium) | Eco | 0.98 | 1.30 | 3.68 | 0.13 |
| | Normal | 1.10 | 1.47 | 3.67 | |
| Operator 6 (Medium) | Eco | 1.05 | 1.30 | 3.97 | 0.11 |
| | Normal | 1.10 | 1.47 | 3.67 | |
| Operator 7 (Hard) | Eco | 0.60 | 0.80 | 2.27 | 0.09 |
| | Normal | 0.70 | 0.93 | 2.33 | |
| Operator 8 (Hard) | Eco | 0.53 | 0.70 | 1.98 | 0.10 |
| | Normal | 0.70 | 0.93 | 2.31 | |
| Operator 9 (Hard) | Eco | 0.45 | 0.60 | 1.70 | 0.09 |
| | Normal | 0.60 | 0.93 | 2.27 | |

Analysing the data presented in Table 8, it is visible that the factor that has a crucial impact on energy consumption is the level of operator training. It is in this area that potential sources of savings should be sought. It can be seen that the least experienced operators participating in the study used almost three times more energy than those with the most experience. The greater the power of the electric motor driving the wheelchair, the more significant the difference. Additionally, higher energy consumption was observed when the forklift operated in the NORMAL mode, i.e., in a mode that used all the forklift's capabilities without any speed limits. Details are presented in Figure 8.

In the case of the most experienced operators, great fluency and precision in the forklift technique were visible. In contrast, inexperienced operators had to repeat the activities several times for them to be passed by the instructor. However, paying attention to the values in the last column of Table 8 is essential. These results show the energy consumption of each operator when implementing the same scenario (which was implemented on physical electric wheelchairs) using a VR-supported simulator. These results are almost seven times lower than for the physical forklifts used in the study. In the case of the simulator, the operating modes (ECO and NORMAL) were not forced especially, as it worked in one mode—however, if it was necessary to reduce the speed of the trolley, the operator independently changed the trolley mode to "slow" (so-called "turtle") using a physical button available on the simulator cockpit. This shows the clear advantage of simulators over other solutions at the stage of skill improvement. When discussing this aspect, one more issue should be mentioned: losses caused by inexperienced operators at the stage of improving their skills. During the research, despite the supervision of the entire process by instructors, physical damage to two other shipments and one shelf was located in the hall where the research occurred. This type of event is eliminated by the improvement training process conducted on simulators.

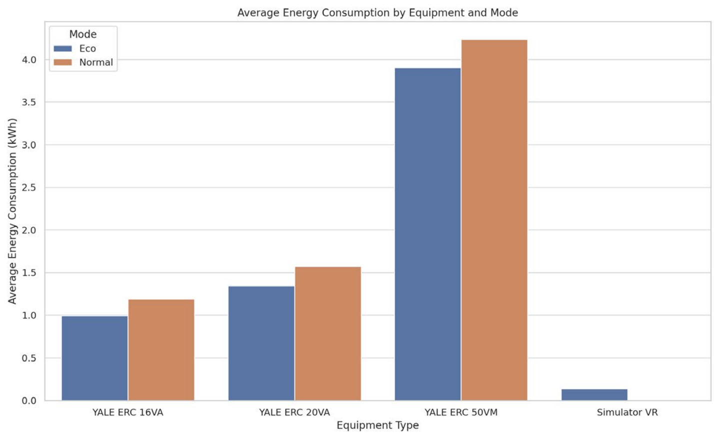


**Figure 8.** Average values of energy consumption by equipment and mode.

In the second stage of the research, improvement training was carried out using the method described in Section 3. The study focused primarily on the least trained operators from the EASY and MEDIUM groups to make an approximate calculation of energy consumption when operators achieved subsequent levels of training during real forklift training and on the simulator. Of course, the authors are aware that a lot depends on the psychophysical and individual predispositions of the trainee, but it seems possible to point out a certain tendency.

Operators realised improvement training until the scenario implementation efficiency was achieved at a given level of at least 80%. Due to time constraints related to the availability of the hall, it was decided to use two instead of three electric forklifts (with the lowest and highest power engines), namely YALE ERC 16VA and YALE ERC 50VM. The entire forklift training took place in one scenario: the operator repeated activities not approved by the instructor until the required level of performance was achieved at a given level. The time needed for the operator to implement the scenario with a satisfactory result (at least 80% effectiveness) was measured. The total energy consumption was then calculated on this basis. The simulator training looked slightly different. They were highly personalized. The improvement session on the simulator lasted 15 min each time. After its completion, the instructor independently prepared a scenario for the next 15 min session, focusing the student primarily on those elements in which the required effectiveness was not achieved. The 15 min sessions were repeated until a cumulative success rate of at least 80% was achieved for a given level. After the last session, the operator's energy consumption during training was calculated. Details are presented in Table 9.

**Table 9.** Results of tests.

| | Level of Training Implemented | YALE ERC 16VA | YALE ERC 50VM | Simulator VR | |
|---|---|---|---|---|---|
| | | Energy Consumption [kWh] | | | |
| Operator 1 (Easy) | Easy | 1.63 | 4.83 | 2 * | 0.31 |
| | Medium | 2.89 | 7.87 | 3 | 0.47 |
| | Hard | 5.33 | 9.66 | 7 | 1.09 |
| Operator 2 (Easy) | Easy | 1.41 | 3.78 | 2 | 0.31 |
| | Medium | 3.11 | 5.56 | 3 | 0.47 |
| | Hard | 5.82 | 8.15 | 7 | 1.09 |

**Table 9.** *Cont.*

| | Level of Training Implemented | YALE ERC 16VA | YALE ERC 50VM | Simulator VR | |
|---|---|---|---|---|---|
| | | Energy Consumption [kWh] | | | |
| Operator 3 (Easy) | Easy | 1.55 | 4.12 | 2 | 0.31 |
| | Medium | 2.12 | 4.92 | 2 | 0.31 |
| | Hard | 5.21 | 8.31 | 6 | 0.93 |
| Operator 4 (Medium) | Medium | 1.23 | 2.55 | 2 | 0.31 |
| | Hard | 2.88 | 3.16 | 4 | 0.62 |
| Operator 5 (Medium) | Medium | 1.67 | 2.87 | 1 | 0.16 |
| | Hard | 3.12 | 3.89 | 4 | 0.62 |
| Operator 6 (Medium) | Medium | 1.56 | 2.39 | 1 | 0.16 |
| | Hard | 3.08 | 4.11 | 3 | 0.47 |
| Operator 7 (Hard) | Hard | 0.64 | 2.11 | 1 | 0.16 |
| Operator 8 (Hard) | Hard | 0.81 | 1.82 | 1 | 0.16 |
| Operator 9 (Hard) | Hard | 0.59 | 1.77 | 2 | 0.31 |

* The number of repetitions of improvement sessions to achieve 80% effectiveness at a given level.

The analysis of the research results presented in Table 9 shows a significant difference in energy consumption when training using traditional methods and the method proposed by the authors using a VR simulator. The lower the operator's training level, the greater the observed differences. In the case of operators with the least experience in the position, trained using traditional methods on the equipment, energy consumption is from five (in the case of a lower-power forklift) to even ten times (in the case of a higher-power forklift) greater than in the case of personalized simulator training. It should be noted that in the case of the least experienced operators, although they relatively quickly reached the MEDIUM level on the simulator (from two to three personalized improvement sessions), as many as six/seven repetitions of specialized training were required to reach the HARD level. Despite this, energy consumption was several times lower than in the case of training conducted using traditional methods.

Figure 9 presents details regarding the distribution of energy consumption when achieving individual levels of training using traditional methods and the simulator method proposed by the authors.

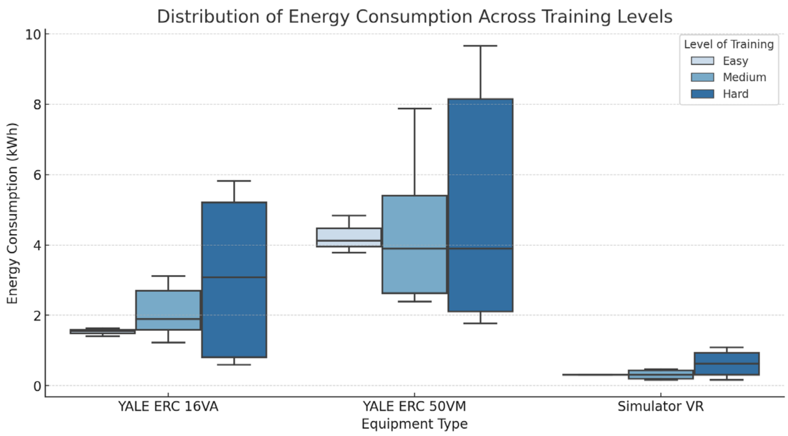


**Figure 9.** Distribution of energy consumption, when achieving individual levels of training using traditional methods and the VR simulator method.

## 6. Conclusions and Discussions

Modern training methods are an essential step towards sustainable development, contributing to reducing energy consumption and minimizing the risk of damage to infrastructure and transported goods.

The simulation training method using the VR environment proposed by the authors consists of four stages: determining the parameters and environment for the contractor, determining the operator's training level, proposing a training method, and assessing and evaluating the training process. This approach allows for personalized training, directly translating into improved operational and energy efficiency.

The research has shown that the level of training of forklift operators is one of the most important factors influencing the total energy consumption in airport cargo terminals because the main activity of these terminals is transport. Poorly trained operators used almost three times more energy to perform the same tasks than their more experienced colleagues. Moreover, the research revealed additional losses in damage to warehouse infrastructure elements. Using simulation training allowed us to achieve similar training effects with an almost tenfold reduction in energy consumption and eliminate unfavourable phenomena related to additional, hidden, and unpredictable training costs (damage and losses).

One of the most essential advantages of the proposed solution is the ability to personalize the training process by adapting it to each operator's individual needs and skill level. In turn, continuous monitoring and optimization of training processes by adjusting training intensity and analysing linear regression parameters are critical factors in achieving better results. The advantage of the proposed solution is that it is highly universal. As part of the project, the authors built further stations for training operators of other airport equipment, e.g., snow blowers or high-loaders. The developed method, after some modifications (adapting the algorithms to the specificity of the device), is also successfully used in these cases.

The authors are still working on improving the proposed solution. The greatest challenge for future research is to prepare a scale assessing the errors made by operators. The most important limitation of the prepared method is that, currently, the effectiveness of the training scenario implementation is calculated so that each error made by the operator is taken into account in the final result with the same weight (importance). Errors should be assessed because a mistake involving driving over the line marking the track of a forklift in a warehouse has an entirely different impact on the functioning of the entire system than, for example, damage to other shipments or the warehouse infrastructure itself.

Companies operating in the logistics industry should promote sustainable development as part of their corporate strategy, and simulation training using the VR environment is an essential element of such a strategy, contributing to reducing their carbon footprint and improving energy efficiency.

**Author Contributions:** Conceptualization, J.R., T.K. and A.K.; methodology, J.R.; software, T.K.; validation, J.R., T.K. and A.K.; formal analysis, A.K.; investigation, J.R.; resources, T.K.; data curation, J.R.; writing—original draft preparation, J.R. and A.K.; writing—review and editing, J.R. and A.K.; visualization, T.K.; supervision, A.K.; project administration, J.R. and T.K.; funding acquisition, T.K. and A.K. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** Data are contained within the article.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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