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Key Aspects of Workplace Safety and Efficiency Based on Dynamic Forklift Testing in the Context of Industry 4.0

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Abstract:

Purpose: *The research aimed to solve the problem of accidents involving forklifts in warehouses, logistics centers, and production plants. The research focused on comparing the efficiency of frontal forklifts and autonomous forklifts. A bibliometric review of thematic publications was also conducted using the Scopus database.*
Design/Methodology/Approach: *The methods adopted to solve the research problems were bibliometric analyses and my own research. The research focused on comparing the efficiency of frontal forklifts and autonomous forklifts.*
Findings: *The research methods adopted to support the work and solve the research problems were a literature search and own research. The research focused on comparing the efficiency of frontal forklifts and autonomous forklifts. The obtained data, generated using the WMS system, were analyzed and evaluated. The study assessed factors such as the time of the order-picking process, working time, and waiting time for orders.*
Practical implications: *As a result of the research on the efficiency of the trucks, the hypothesis was verified positively. Autonomous forklifts showed a better result in the order execution time, with an average of 10 minutes. In contrast, in the case of the front forklift, the average value of the order execution time is 15 minutes. The data on the waiting time for the order are comparable; this factor also depends on the Internet speed and the computing power of the computers used. In the case of autonomous trucks, the data is sent directly to the truck, so it can start working immediately after receiving the orders. On the other hand, front forklifts performed better in the total working time, the average of which was 5 hours. This is a better result than the autonomous forklift, whose average total working time during the day was 4 hours.*
Originality: *Based on the measurements and research results obtained, it can be concluded that many accidents involving forklifts are caused by excessive speed or by neglecting factors*

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that may affect the occurrence of an accident at work, which may lead to significant material losses or loss of life or health.

Keywords: *Forklift, automation, Industry 4,0.*

JEL classification: *L15, M10, M16, R49.*

Paper type: *Research article.*

1. Introduction

The fourth industrial revolution has led to the adoption of a manufacturing model called Industry 4.0 through feedback between automation, data processing and exchange, and modern manufacturing techniques. It is a general term for organizations, techniques, and value chain principles that jointly use or utilize cyber-physical systems, the Internet of Things, and cloud computing (Masłowski *et al.*, 2024; Chew *et al.*, 2021; Sinclair *et al.*, 2021; Dittes *et al.*, 2019).

According to this concept, Industry 4.0 is the realization of the vision of the smart factory. The transformation of the production plant by the fourth industrial revolution is to lead to radical optimization through (Piccarozzi *et al.*, 2018; Shahbaz *et al.*, 2019; Pałęga *et al.*, 2023; Zhang and Xiao, 2020):

- improving productivity,
- improving efficiency,
- increasing the degree of knowledge sharing and cooperation,
- flexibility and agility,
- facilitating compliance,
- improving customer service,
- reducing costs,
- expanding the scope for creating, developing, and implementing innovations,
- increasing turnover and revenue,
- increasing profitability,
- consolidating or increasing the importance of the product/company brand and better recognition in local and global markets.

The dissemination of cooperation between all participants in the production process using Industry 4.0 technologies leads to the complete optimization of the economy (Sawa *et al.*, 2022; Pałęga, 2020; Dallasega *et al.*, 2018; Skowrońska *et al.*, 2024).

The term (originally Industrie 4.0) comes from a draft strategy of the German government promoting the computerization of manufacturing processes and was first used at the Hanover Fair in 2011. In October 2012, a working group led by Siegfried Dais from Robert Bosch GmbH presented a set of implementation recommendations

for the concept to the federal government (Widyotriatmo 2019; Węgrzyn et al., 2024; Szala and Walczak 2024).

Table 1. *Industrial revolutions*[9]

Industrial revolutions				
Nr	Conventional beginning	**A distinctive invention**		**Characteristics**
I	late 18th century	The Age of Steam	Mechanical weaving loom (1784)	Mechanical production supported by steam and water power.
II	early 20th century	The Age of Electricity	Production line (1870)	Mass production using electricity.
III	1970s	The Age of Computers	Programmable logic system (1969)	Automation of industrial production using ICT.
IV	2010s	The Age of Fusion of Physical and Virtual Reality	Internet (1991)	Smart factories with cyber-physical production systems in the environment of: people (employees and contractors) Internet of things Internet of services Internet of data

Source: *Own study.*

On April 8, 2013, the group presented its final report. In the case of the fourth industrial revolution, great emphasis is placed on the interpenetration of the physical and digital worlds. The efficiency of manufacturing processes is of great importance and cannot be maximized without advanced information systems (Skowrońska *et al.*, 2024a; Pałęga 2021; Słodkowski 2022; Yoshida 2021). In recent years, the topic of research on automation within Industry 4.0 has become increasingly popular. The novelty of the topic raised by the authors is the fact that there is a lack of systematic research on the current state of knowledge.

According to bibliometric data, the most significant number of thematic publications was recorded in 2022. The largest number of publications from the bibliometric research area (158 articles) in the Scopus database was Lecture Notes in Mechanical Engineering (LNME), which publishes the latest achievements in mechanical engineering. The research aimed to solve the problem of accidents involving forklift trucks in warehouses, logistics centers, and production plants. The research focused on comparing the efficiency of front forklift trucks and autonomous forklift trucks.

A bibliometric review of thematic publications was also conducted using the Scopus database (Szczucka-Lasota et al., 2024; Skowrońska 2024b). As a result of the research on the efficiency of forklift trucks, the hypothesis was verified positively.

[9]*Own elaboration based on the literature review.*

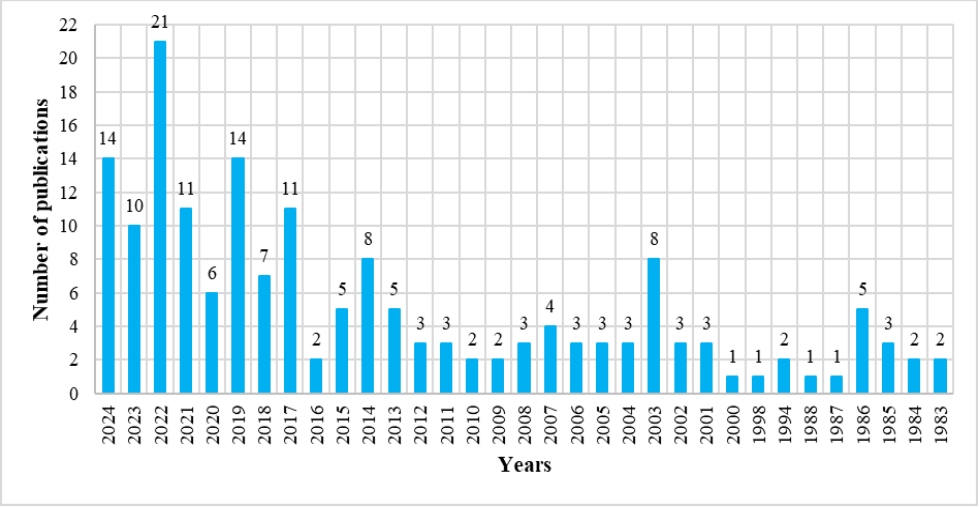
Based on the measurements and research results, it can be stated that many accidents involving forklift trucks are caused by excessive speed or by neglecting factors that may affect the occurrence of an accident at work, which may lead to significant material losses or loss of life or health (Lewczuk and Żuchowicz 2024; Węgrzyn *et al.*, 2024; Pałega and Krause, 2020). The article consists of five parts. The first part is an introduction, the second part presents a literature review, the third part is analytical and presents a comparative analysis of dynamic tests on the example of forklift trucks, the fourth part of the article presents a discussion, and the fifth part contains conclusions.

2. Literature Review

The attribute of the fourth industrial revolution was the use of modern technologies that redefined production and improved work methods. The invention of the steam engine defined the three previous revolutions: the production line and the computer. Industry 4.0 defines the direction of changes in the social, industrial, and technological areas caused by the digital transformation of industry.

The derivative of the implemented changes is the new face of automation and monitoring of the supply chain, thanks to intelligent technologies in industry (Szczucka-Lasota *et al.*, 2023; Pałęga *et al.*, 2024; Sładkowski and Pamuła 2016). The Figure 1 below analyzes the bibliographic data of the Scopus database in terms of the number of publications covering the topic of forklift automation in the years 1983-2024.

Figure 1. *Number of thematic publications in the years 1983-2024*[10]



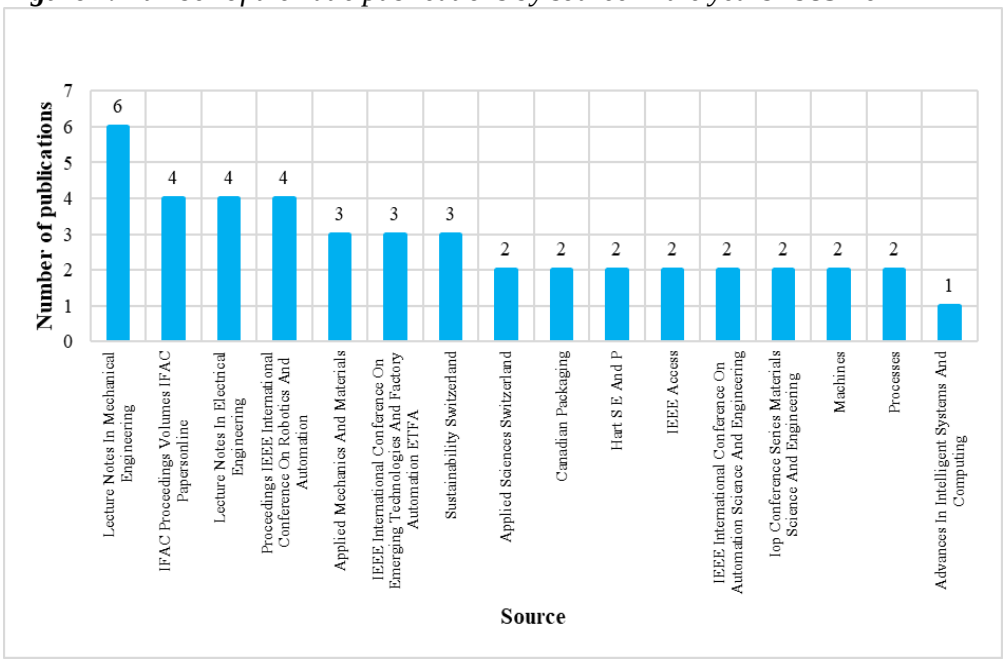
Source: *Own study.*

[10]*Own study based on Scopus - Analyze search results.*

As many as 158 authors who addressed the subject of forklift automation in scientific publications were noted. The most significant scientific activity can be safely associated with the fourth industrial revolution dating back to the beginning of the 21st century.

Moreover, statistically, we can observe an increase in the thematic publication output. The following Figure 2 shows the number of thematic publications by source from 1983-2024.

Figure 2. *Number of thematic publications by source in the years 1983-2024*[11]



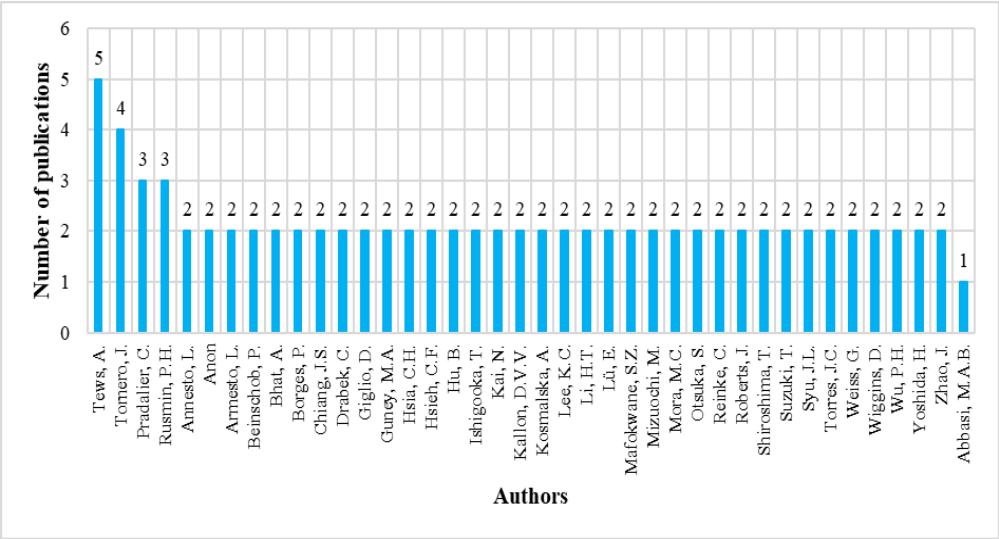
Source: *Own study.*

The journal with the most significant number of publications from the bibliometric research area in the Scopus database is Lecture Notes in Mechanical Engineering (LNME), which publishes the latest achievements in mechanical engineering (Ko *et al.*, 2021; Adam *et al.*, 2017).

The research areas of the journal are Mechanical structures and stress analysis, engine technology, aviation technology, astronautics, nanotechnology and microengineering, nanotechnology, control, robotics, and mechatronics (Figure 3). As many as 158 authors have been noted to address the topic of forklift automation in scientific publications, of which only 39 authors publish in the Scopus database during bibliometric research at the level of 2 publications or more.

[11]*Own study based on Scopus - Analyze search results.*

Figure 3. *Number of thematically leading publications by author in the years 1983-2024*[12]



Source: *Own study.*

3. Comparative Analysis of Dynamic Tests on the Example of Forklifts

Using highly developed and intelligent technologies, autonomous vehicles can move independently from the starting point to the destination without human intervention. Supported by artificial intelligence, for example, through radars, GPS systems, or environmental recognition systems (López *et al.*, 2022; Iinuma *et al.*, 2020). This allows for the collection of data from the environment, which is used to determine the correct route and to determine specific work assumptions, such as, adjusting speed, detecting and avoiding obstacles, so that the passage of the truck does not endanger other vehicles and people nearby.

Unlike regular forklifts, the autonomous truck is not equipped with forks but with a scissor lift, which allows for lifting pallets from the ground and lifting them to a height of one meter. This solution allows for cargo transport from point a to point b without using any external infrastructure, such as platforms on which the pallet would have to be placed, in the case of platform trucks. The truck automatically creates a map where the appropriate zones for picking up and putting down pallets should be placed, and the robot's mission should be calibrated accordingly.

Autonomous forklifts can connect to systems such as WMS or ERP, thanks to which the truck's operation can be monitored more precisely. Manufacturers of autonomous trucks place great emphasis on safety, which is why they are equipped with several sensors and laser scanners that allow them to detect obstacles to avoid them

[12]*Own study based on Scopus - Analyze search results.*

appropriately or stop safely. Safety is important when picking up and putting down a pallet. The truck has proximity sensors on the ends of the forks and a laser rangefinder between the blades, thanks to which the robot will stop when it detects an obstacle between the truck and the pallet being put down. The autonomous forklift can work independently or in a fleet, together with other autonomous trucks, thanks to which the trucks synchronize information about obstacles, safely avoiding each other.

When picking up a pallet, the truck scans the QR code or barcode located on the pallet, and based on it, the truck can be sent to a specific rack. It can also transport pallets from specially prepared buffer zones, where shipments are prepared for customers, and transport them to loading docks. By placing a QR code or barcode on the pallet, you can define the exact dock the truck should drive (Hussain *et al.*, 2023).

Many direct and indirect factors contribute to the occurrence of an accident. Direct factors influencing accidents include, among others, failure to comply with occupational health and safety regulations, excessive speed, and lack of experience in operating equipment. Indirect factors result from, for example, too fast a pace of work, lack of concentration, poor well-being, and stress.

The Central Statistical Office states that among the causes of accidents in the workplace, the most common factor that contributed to an accident was the employee's improper behavior. The capabilities of autonomous forklifts can contribute to reducing the number of accidents in the workplace by not affecting indirect factors. Despite this, when an accident occurs, e.g., when shelves collapse, the forklift remains damaged.

4. Discussion

The research aimed to solve the problem of accidents involving forklifts in warehouses, logistics centers, and production plants. The research focused on comparing the efficiency of front forklifts and autonomous forklifts. The obtained data, generated using the WMS system, were analyzed and assessed. The study assessed factors such as the time of the order-picking process, working time, and waiting time for orders. Reference was made to work safety, as many accidents can end in serious injuries or death.

The travel time of the autonomous truck and front forklift was measured. The study involved transporting a load from point A to point B along a previously designated route. The task of both trucks was to achieve the best possible travel time and avoid an obstacle in the form of a pallet, which narrows the travel lane and does not allow the entire route to be traveled at maximum speed. Before each pass, the pallet position was changed because this would be an excellent convenience for the autonomous forklift, which collected information about the route and obstacles

during each pass and then saved it in the database. The results of the tests are presented in Table 2.

Table 2. *Research results regarding the efficiency of front-wheel drive trucks*[13]

Date	Day	Order processing time	Waiting time for orders	Total completion time
04.09.2024	Monday	14 minutes	2 minutes	4 hours
05.09.2024	Tuesday	18 minutes	1 minutes	5 hours
06.09.2024	Wednesday	10 minutes	2 minutes	4 hours
07.09.2024	Thursday	14 minutes	2 minutes	4 hours
08.09.2024	Friday	21 minutes	3 minutes	6 hours
09.09.2024	Saturday	9 minutes	1 minutes	3 hours
11.09.2024	Monday	20 minutes	3 minutes	5 hours
12.09.2024	Tuesday	19 minutes	2 minutes	5 hours
13.09.2024	Wednesday	24 minutes	3 minutes	3 hours
14.09.2024	Thursday	13 minutes	2 minutes	4 hours
15.09.2024	Friday	20 minutes	3 minutes	4 hours
16.09.2024	Saturday	10 minutes	2 minutes	3 hours
18.09.2024	Monday	16 minutes	2 minutes	6 hours
19.09.2024	Tuesday	15 minutes	2 minutes	5 hours
20.09.2024	Wednesday	8 minutes	1 minutes	6 hours
21.09.2024	Thursday	14 minutes	2 minutes	4 hours
22.09.2024	Friday	10 minutes	2 minutes	5 hours
23.09.2024	Saturday	11 minutes	2 minutes	2 hours
25.09.2024	Monday	19 minutes	3 minutes	4 hours
26.09.2024	Tuesday	15 minutes	2 minutes	4 hours
27.09.2024	Wednesday	18 minutes	3 minutes	3 hours
28.09.2024	Thursday	14 minutes	2 minutes	4 hours
29.09.2024	Friday	16 minutes	2 minutes	5 hours
30.09.2024	Saturday	13 minutes	2 minutes	3 hours
02.10.2024	Monday	18 minutes	3 minutes	4 hours
03.10.2024	Tuesday	15 minutes	2 minutes	3 hours
04.10.2024	Wednesday	12 minutes	2 minutes	5 hours

Source: *Own study.*

The first factor referred to the duration of the order completion time per day. The next factor was the waiting time for the order, which reflected the time it took to send the order from the system to the operator's scanner, and the total working time represented the total number of hours worked by the front-end forklift operator. The average order completion time ranges between 15 and 20 minutes per month. The average waiting time to receive an order is 2 minutes. Every month, the forklift's

[13] *Based on research results.*

highest average number of hours worked occurs on Friday, Monday, and Wednesday. The fewest hours worked by the forklift occur on Saturday.

The data on the order completion time, waiting time for the order, and the total working time of the front-end forklift were compared with the data on the efficiency of the autonomous forklift. A comparative analysis was conducted to select the best solution. Table 3 presents the data on the efficiency of the autonomous forklift.

Table 3. *Research results on the efficiency of the autonomous forklift*[14]

Date	Day	Order processing time	Waiting time for orders	Total completion time
02.08.2024	Wednesday	8 minutes	1 minutes	2 hours
03.08.2024	Thursday	7 minutes	1 minutes	4 hours
04.08.2024	Friday	10 minutes	1 minutes	3 hours
05.08.2024	Saturday	8 minutes	2 minutes	2 hours
07.08.2024	Monday	11 minutes	1 minutes	4 hours
08.08.2024	Tuesday	10 minutes	2 minutes	4 hours
09.08.2024	Wednesday	7 minutes	1 minutes	4 hours
10.08.2024	Thursday	8 minutes	1 minutes	3 hours
11.08.2024	Friday	10 minutes	1 minutes	4 hours
12.08.2024	Saturday	7 minutes	1 minutes	2 hours
14.08.2024	Monday	10 minutes	2 minutes	3 hours
15.08.2024	Tuesday	12 minutes	1 minutes	2 hours
16.08.2024	Wednesday	8 minutes	2 minutes	2 hours
17.08.2024	Thursday	9 minutes	1 minutes	3 hours
18.08.2024	Friday	11 minutes	1 minutes	4 hours
19.08.2024	Saturday	7 minutes	2 minutes	2 hours
21.08.2024	Monday	12 minutes	1 minutes	4 hours
22.08.2024	Tuesday	9 minutes	2 minutes	4 hours
23.08.2024	Wednesday	13 minutes	1 minutes	2 hours
24.08.2024	Thursday	10 minutes	1 minutes	3 hours
25.08.2024	Friday	11 minutes	2 minutes	4 hours
26.08.2024	Saturday	8 minutes	1 minutes	3 hours
28.08.2024	Monday	9 minutes	1 minutes	3 hours
29.08.2024	Tuesday	12 minutes	1 minutes	3 hours
30.08.2024	Wednesday	9 minutes	1 minutes	4 hours
31.08.2024	Thursday	10 minutes	1 minutes	2 hours
01.09.2024	Friday	11 minutes	1 minutes	3 hours
02.09.2024	Saturday	7 minutes	2 minutes	1 hour

Source: *Own study.*

[14] *Based on research results.*

The data shows the monthly performance of both trucks, which affects work efficiency. The autonomous forklifts showed a better result in the order processing time, which averages 10 minutes, while in the case of the front forklift, the average order processing time is 15 minutes.

The data on the waiting time for an order are comparable; this factor also depends on the speed of the Internet and the computing power of the computers used. In the case of autonomous trucks, data is sent directly to the truck so it can start working immediately after receiving the orders. On the other hand, the front forklifts performed better in total working time, averaging 5 hours. This is a better result than the autonomous forklift, whose average total working time during the day was 4 hours.

Many accidents involving forklifts are caused by excessive speed or by neglecting factors that can affect the occurrence of an accident at the workplace, which can lead to significant material losses or loss of life or health.

5. Conclusions

The study aimed to measure the travel time of a front-end forklift and an autonomous forklift. During the journey, a Euro pallet was placed on a previously designated route, which was 42 meters. The pallet's task was to narrow the travel path so that the truck would slow down and pass between the pallet and the wall without damaging the pallet.

During the journey, the position of the pallet was changed 3 times because, during each journey, the autonomous trucks sent data regarding the journey and information about obstacles that occurred. Each truck had 3 attempts to achieve the best possible time. Based on the measurements, the analysis and evaluation of the research results were performed.

Table 4. *Results of the measurements of the front-end and autonomous forklift journeys*[15]

Truck type	Passage 1	Passage 2	Passage 3
Autonomous truck	1,45	1,42	1,42
Front-end forklift	1,49	1,42	1,48

Source: *Own study.*

The results obtained by the autonomous forklift are slightly better compared to the front forklift. During the measurements in the last approach, the front forklift operator clipped the pallet to obtain the best time, resulting in a worse result than in the previous approach. In the case of the autonomous forklift, changing the pallet position 3 times did not result in making the same mistake as in the case of the front

[15] *Based on research results.*

forklift. During the test, both the front and autonomous forklift achieved the worst time during the first run. In the case of the operator, this could have been caused by route adaptation and the lack of willingness to take risks to avoid making a mistake on the first attempt. After a general evaluation of the test results and observations, it can be concluded that the autonomous forklift achieved better results. Despite narrowing the lane through the pallet, the truck completed the route without any complications.

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