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Overall Forklift Effectiveness: The Proposal of A Model for Measuring Productive Efficiency in Forklifts

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ABSTRACT

Rising competitiveness in logistics has increased the need for efficient operations in distribution centers (DCs), where forklifts play a key role in material handling and cost management. This study proposes the Overall Forklift Effectiveness (OFE) model, an adaptation of the Overall Equipment Effectiveness (OEE) framework, designed to capture variables specific to forklift operations such as empty movements, battery replacement, and load adjustments. Developed through a Design Science Research (DSR) approach, the model was validated in a Brazilian DC over 10 business days using a mobile application for data collection. Results demonstrate that the OFE provided higher measurement precision by capturing operational losses overlooked by the OEE baseline. When applied in practice, the OFE enabled managers to identify that 75% of downtime was caused by unscheduled stops, allowing targeted actions to reduce idle time. Compared with the OEE baseline, the OFE model revealed a 49.5% occupancy rate and an overall efficiency of 14%, highlighting improvement opportunities that were invisible under the traditional metric. The empirical evidence shows that decisions supported by OFE can lead to more accurate resource allocation and enhanced equipment utilization, contributing to operational efficiency in logistics centers. The model offers logistics managers a structured tool to improve decision-making, while advancing the literature by extending OEE applications to material handling equipment.

Keywords: ***Productive efficiency, Forklift, Measurement efficiency, Model, OEE, OFE***

1. INTRODUCTION

The continued growth of competition between companies impacts supply chains, requiring more efficient operations without compromising the quality of product distribution (Choudhury, 2000; Sellitto *et al*., 2018; Shahram fard & Vahdani, 2019; Tortorella *et al*., 2018). Logistics has become essential in supply chain management, facilitating the movement of products, information and materials to consumers. Distribution centers (DCs) act as links between upstream (production) and downstream (distribution) members, which demands greater operational efficiency (Lee *et al*., 2019). The performance of operations in these centers affects productivity and costs, and process-based management is essential to improve efficiency and the level of customer service, in addition to reducing delivery times and operating costs (De Koster *et al*., 2017; Dixit *et al*., 2019). It is necessary to establish efficiency targets for DC resources and use methods that allow real-time performance assessment. Operational efficiency is directly affected by material handling management, with equipment such as forklifts playing a crucial role in this efficiency. Therefore, it is essential to analyze the movements of materials using this equipment (Abideen & Mohamad, 2020; Halawa *et al*., 2020; Kamali, 2019; Radaev & Leventsov, 2018).

Since forklifts are the most widely used mobile resources for moving materials in distribution centers and warehouses) (Bidot *et al*., 2017; Burinskiene, 2011; Halawa *et al*., 2020) the global forklift market surpassed US$ 90 billion in 2020 and is expected to grow at over 9% at the compound annual growth rate (CAGR) between 2021 and 2027. Global industry shipments are projected to exceed two million units by 2027 (Jadhay & Mutreja, 2021). The topic of efficiency measurement is regularly addressed in research. Efficiency is a multifaceted concept; that is, there are several efficiencies (of people, equipment, systems, etc.) to be measured. This research will specifically address the efficiency of equipment, in this case, forklifts. In order to make the best decisions, managers must establish appropriate metrics for these measurements (Binti Aminuddin *et al*., 2016). Proposed by Nakajima (Antunes *et al*., 2008; Cheah *et al*., 2020; Kamali, 2019; Nakajima, 1988; Schnorrenberger & Nunes, 2019), Overall Equipment Effectiveness (OEE) presents an index with several applications in measuring equipment in industries around the world. Research on the efficiency of material handling equipment is still scarce (Nunes, 2024a; Rose *et al*., 2021). Due to this complexity and the future scenario of these operations, the need for the evolution of DCs and the challenges of productivity and efficiency increase, so new technologies and new methods must be considered in the necessary changes to logistics (PwC, 2019; Taliaferro & Guenette, 2016).

The topic of measuring efficiency in forklifts was presented by Nunes (2024) in a study of indicators applied to operations in Brazilian Distribution Centers (DCs). In this research, the scarce measurement of productive efficiency in these environments was observed, and a model for measuring the efficiency of forklifts was not found in the literature. Studies only present the measurement of use through the measurement of hours worked and collected by hour meters or by telemetry systems installed in this equipment (Halawa *et al*., 2020; Nunes, 2024a). In their research, Nunes *et al*., (2025) presented an SLR on models and methods, available in the Scopus and Web of Science databases, applied to measure the efficiency of the most widely used material handling equipment in logistics environments, forklifts. The results of this SLR revealed a significant gap in measuring the efficiency of forklifts. In this SLR, the studies analyzed are limited to simple indicators, such as hours worked or use rate. This approach does not consider more complex metrics, such as productivity, sustainability, or environmental impact, which are essential for efficient management in dynamic logistics environments. Variables such as operating times with load, underutilization of equipment through empty movements, and unplanned stops are neglected, thus limiting practical applicability to improve the overall efficiency of this operations system. The lack of consolidated models for this function can be attributed to the complexity of logistics operations. Therefore, most studies prioritize indicators that are easy to measure, ignoring the specificities of each operation. From this, the need for adaptable models that integrate variables and provide a holistic view of forklift performance is imminent (Nunes *et al*., 2025).

In this context, this paper aims to answer the following research question: How can the productive efficiency of forklifts in the warehousing process be identified? To address this gap, this study builds upon the widely used Overall Equipment Effectiveness (OEE) metric, originally proposed by Nakajima (1988), which serves as the baseline for equipment efficiency measurement. Based on the OEE, we propose two adapted models for forklift operations. The first, called Model 0 (M0), incorporates operational characteristics specific to forklifts, such as empty movements and distinct categories of planned and unplanned downtimes. During field testing, additional loss factors emerged—namely battery replacement and load adjustments—which led to the development of Model 1 (M1). Thus, while OEE provides the conceptual foundation, M0 represents the first adapted version for forklift contexts, and M1 refines the model further by integrating additional empirical evidence from the instantiation. This progression from OEE to M0 and M1 clarifies the evolution of the proposed metric and its incremental contributions.

The general objective of this study is to adapt the concept of Overall Equipment Effectiveness (OEE), proposed by Nakajima (1988) to analyze the productive efficiency of forklifts in the warehousing operation of a logistics distribution center in Brazil. This article is divided into five sections: (i) this introduction; (ii) the theoretical review on the themes efficiency (Agarwal & Sarkar, 2019; Kukanja & Planinc, 2019), OEE (Antunes *et al*., 2008; Nakajima, 1988; Nunes, in press; Stamatis, 2010), forklifts (Burinskiene, 2011, 2015; Frazelle, 2016; Kamali, 2019); (iii) the research method applied in conducting this research, or the Design Science Research (Strassburguer *et al*., 2023); (iv) instantiation, the practical application of the proposed model in a Logistics Distribution Center (LDC) and its results; and (v) conclusions and suggestions for future research.

2. LITERATURE REVIEW

The following are the themes of Efficiency, Overall Equipment Effectiveness, and Forklifts used in the literature review for this research.

2.1 Efficiency

The performance of organizations is the result of the activities, operations, and routines carried out, as well as the capabilities and use of their resources in their operating systems (Lam & Hentenryck, 2016). To this end, must expand the measurements of this performance through measures of quality, processing times, flexibility, productivity, use, efficiency, and resource capabilities (Eidelwein *et al*., 2016). Efficiency means doing more with fewer resources or maximizing current resources (Al Yami *et al*., 2021). Resources are tangible and intangible assets that have capabilities. Goldtratt describes these capabilities (Antunes *et al*., 2008; Goldratt, 1984) as (a) productive capacity, which represents the actual capacity used by the resource in meeting demands; (b) protective capacity, which deals with excessive capabilities in non-restrictive resources that aim not to interrupt the flows of restrictive operations (bottlenecks); and (c) idle capacity, which represents the difference between available capacity and productive and protective capabilities. Operational performance measurements aim to minimize direct costs, high capacity use, and resource efficiency (Antunes *et al*., 2008; Nakajima, 1988). One of the most widely applied models for measuring equipment efficiency is the OEE applied to performance measurement developed by Seiichi Nakajima with the aim of analyzing the results from TPM (Total Productive Maintenance) (Cheah *et al*., 2020).

2.2 Overall Equipment Effectiveness (OEE)

OEE is an indicator recognized as essential for measuring equipment productivity and performance (Corrales *et al*., 2020; Sathler *et al*., 2023; Schnorrenberger & Nunes, 2019). It focuses on the efficiency with which resources are used in operations and thus enables performance evaluation and comparison between resources (Cheah *et al*., 2020; Stamatis, 2010). OEE can reduce operational time and identify waste and potential gains to optimize the equipment it measures (Kennedy, 2018; Stamatis, 2010). To analyze OEE, based on time and its losses, the model shown in Figure 1 is observed.

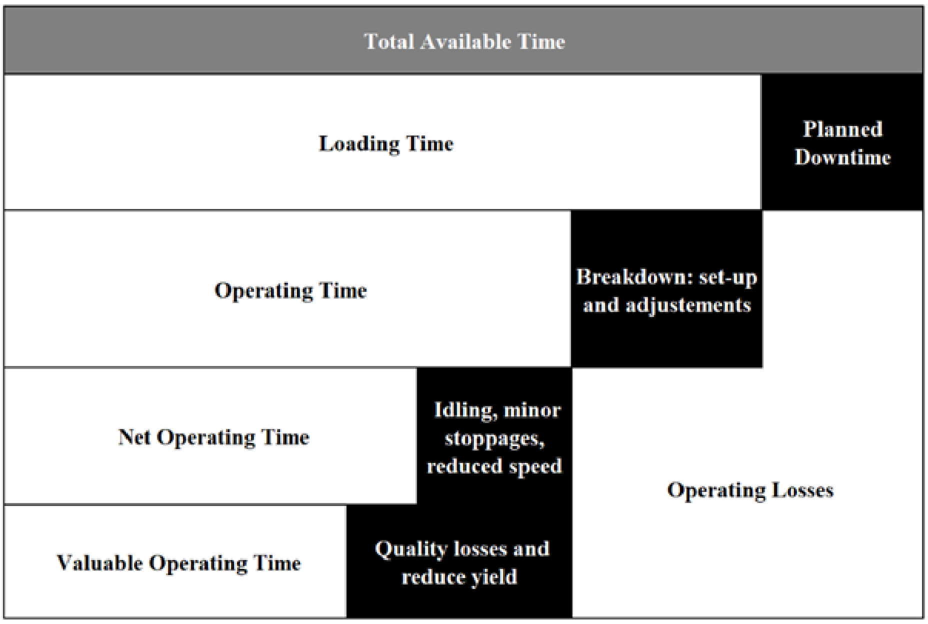

Figure 1 Times to be used in the OEE analysis
Source: Adapted from Antunes *et al*. (2008), Stamatis (2010) and Kennedy (2018)

The concepts of time available for equipment include Total Available Time, which is the time an asset can operate, and Loading Time, which reflects the period scheduled for operation, discounting planned downtime. Operating Time is the time spent in operation, considering unscheduled stops. Net Operating Time is the time remaining after deducting stops and performance losses, while Valuable Operating Time is the time that adds value after all interruptions and losses are considered (Kennedy, 2018; Stamatis, 2010). These times generate indexes that make up the OEE equation. Thus, the measurement of OEE is based on three main factors that consist of availability, performance, and quality (Kennedy, 2018; Nakajima, 1988; Stamatis, 2010). To ensure consistency and clarity in mathematical formulation, all variables and abbreviations used in the proposed models are summarized in table 1. This notation serves as a reference throughout the methodological section, avoiding ambiguity in the interpretation of OEE equations and figures

The availability factor considers availability losses, which encompasses events that interrupt the planned operation for a period and include planned and unplanned shutdowns (Equation 1). The availability factor (A) considers losses caused by both planned and unplanned.

Table 1 Notation used in the OEE models.

Symbol	Definition
TAT	Total Available Time: is production crew time (normal rostered time plus any overtime by the entire crew for production). Example: 24h/day, 7 days/week etc.
LT	Loading Time: Loading time is the working time minus planned downtime, where downtime is the stoppage time loss due to breakdowns, setup and adjustments.
OT	Operating Time: time in which the equipment operation, excluding all breakdowns.
NOT	Net Operation Time: represents the time when the machine is running at its fastest possible speed, but before any quality defects are accounted for.
VOT	Valuable Operating Time: when equipment is producing good quality products at the optimal or fastest possible speed, excluding all planned and unplanned stops and defects .
A	Availability factor: measures how much of the scheduled production time a machine or process was actually running.
P	Performance factor: measures a piece of equipment's production speed compared to its ideal or maximum theoretical speed.
Q	Quality factor: takes into account manufactured parts that do not meet quality standards, including parts that need rework.
OEE	Overall Equipment Effectiveness: a metric used in manufacturing to measure how efficiently equipment or a process is performing, expressed as a percentage of perfect production.
TEEP	Total Effectiveness Equipment Performance: metric that measures how effectively equipment and production lines perform over all available time (24/7), not just scheduled production time

Source: Adapted from Stamatis (2010) and Kennedy (2018).

stops. It is calculated as the ratio between Operating Time (OT) and Loading Time (LT), formulated as:

$$\text{Availability} = (\text{OT} / \text{LT}) \times 100 \quad (1)$$

Where OT is the time the forklift moved effectively, and LT is the total planned operating time.

The performance factor considers the losses that include the elements that make the resource operate during execution at a speed lower than the maximum possible (Equation 2).

$$\text{Performance (P)} = (\text{NTO} / \text{OT}) \times 100 \quad (2)$$

The quality factor considers quality losses, disregarding the time in which non-conforming items were produced (Equation 3).

$$\text{Quality (Q)} = (\text{NTO} / \text{OT}) \times 100 \quad (3)$$

Thus, to calculate the OEE, it must multiply by the three elements: availability, performance, and quality. And a benchmarking value for OEE, according to Nakajima (1988) is 85%. (Cheah *et al*., 2020; Sathler *et al*., 2023). (Equation 4).

$$\text{Overall Equipment Effectiveness (OEE)} = (\text{A} \times \text{P} \times \text{Q}) \times 100 \quad (4)$$

In addition to OEE, it is also possible to measure the Total Effective Equipment Productivity (TEEP). TEEP is the index that shows the performance of the equipment, considering losses and production rates. TEEP shows how well the equipment performs the production process and how excellent the equipment the company uses is(Antunes *et al*., 2008; Sathler *et al*., 2023). TEEP is related to restrictive assets (bottlenecks) (Nakajima, 1988; Vaccaro & Korzenowski, 2015), which are resources that have less capacity than demand (Gopalakrishnan *et al*., 2019; Omar & Plapper, 2020). TEEP can be calculated using Equation 5.

$$\text{Total Effectiveness Equipment Performance (TEEP[1])} = (\text{A} \times \text{P} \times \text{Q}) \times 100 \quad (5)$$

2.3 *Forklift*

A forklift is an industrial vehicle that has a toothed device attached, which can be lowered or raised, on which a load can be placed (Jadhay & Mutreja, 2021) . These industrial vehicles are used to move and lift different types of loads in loading and unloading and storage operations in factories, warehouses, ports, stores, and distribution centers (d'Apolito & Hong, 2019) and play an important role in the modern supply chain. There are different types of electric forklifts: internal combustion, order pickers, retractable, for narrow aisles, lateral, and trilateral. The use of the appropriate forklift for the operations to be performed is an important decision regarding the productivity of this equipment (Paksoy *et al*., 2019). The short distances to be covered by forklifts and their use in relation to the loads moved must be considered because the less loaded a forklift is, the less efficient it becomes (Pashkevich *et al*., 2019). These types of equipment are regularly measured by their costs in relation to the workforce, forklift drivers, who are an important part of a storage system, maintenance costs and their use (hours worked), based on the reading of the hour meters inserted in the forklifts (Ghalehkhondabi & Masel, 2018; Zou *et al*., 2019). Utilization is defined as putting the forklifts into use in a way that achieves maximum productivity with the minimum movements or with lower costs. The use of the forklift should be considered to avoid excessive investments in the movement of materials. The routes taken by the forklifts to store and keep materials in an available location require the return of the empty forks (Bartholdi & Hankman, 2011; Halawa *et al*., 2020). Based on the use estimate, managers can identify the causes of time losses and try to reduce them. In the supply of materials for supplies in manufacturing operations, when based on forklifts, they have a low level of equipment use, as redundancy is necessary to ensure that a forklift is available when needed (Hanson & Finnsgård, 2014).

The indicators commonly used by companies for storage management focus on external performance, measuring activities that have a direct impact on customers, neglecting the aspects that measure the performance of material handling equipment (Nunes, 2024a). Thus, a technique for identifying individual equipment performance is OEE, making it possible to measure equipment productivity to identify losses that impact performance and reduce downtime. In the supply chain, the activities that make storage are its central point, being essential to ensure storage efficiency and generate a competitive advantage that the equipment selected for each activity is carefully selected from the design of the process to be developed in the warehouse, evaluating the appropriate equipment for each activity, avoiding premature wear and the improper allocation of resources, also helping in the efficient occupation of spaces. The project also involves the development of efficient flows. OEE metrics are based on three pillars that assess the availability, performance and quality of equipment, serving as a diagnostic tool to increase efficiency and productivity and minimize downtime. To optimize forklifts, it is crucial to adopt preventive maintenance methods, establishing targets to be met at fixed intervals, which reduces failures and extends the useful life of the equipment. Accurate data collection on failures and downtime is essential; if the information is incomplete or inaccurate, it will not be possible to make improvements. By measuring all failures, it is possible to implement effective corrective actions, based on historical data. However, many methods used by companies to evaluate the efficiency of material handling equipment do not demonstrate relevance in terms of resources (Kamali, 2019).

3. METHODOLOGY

To develop this research, we used the Design Science Research (DSR) (Vaishnavi *et al*., 2015). It enables the creation of alternative solutions and the development of knowledge about the advantages and disadvantages of each of the solutions raised (Strassburguer *et al*., 2023). Through artifacts, researchers intend to respond to real problems, contributing new knowledge to the body of scientific evidence. Therefore, artifacts are crucial for this scenario (Hevner, 2022; Vaishnavi *et al*., 2015). DSR has been applied in several scientific works that aim to develop

[1] The difference between the OEE equation and Total Available Time is the application of Total Available Time instead of Loading Time.

artifacts for problem-solving (Strassburguer *et al.*, 2023). Figure 2 presents a method for developing a model to measure the operational efficiency of a forklift.

3.1 Efficiency

Literature analysis: In defining the research topic, Nunes (2024) addressed the indicators used in the management of efficiency in forklift fleets in Brazilian distribution centers. In this research, we observed that the companies surveyed do not measure the efficiency of forklifts in their operations, and no model for measuring forklift efficiency was found in the literature. In addition, the research by Nunes *et al*. (2025) presents an SLR on the measurement of efficiency in forklift activities in material handling operations. The results show the scarcity of research on the topic, as well as a gap in this topic and thus the need to propose a model for this measurement. Studies present the measurement of this equipment by measuring the hours worked, which are collected by the hour meter devices attached to this equipment. Thus, the need to measure the efficiency of this equipment is a research gap that needs to be broadened in the discussion of the topic of operational efficiency in material handling equipment. Based on the identification of this research gap, the research problem and objective presented in the introduction of this research were elaborated.

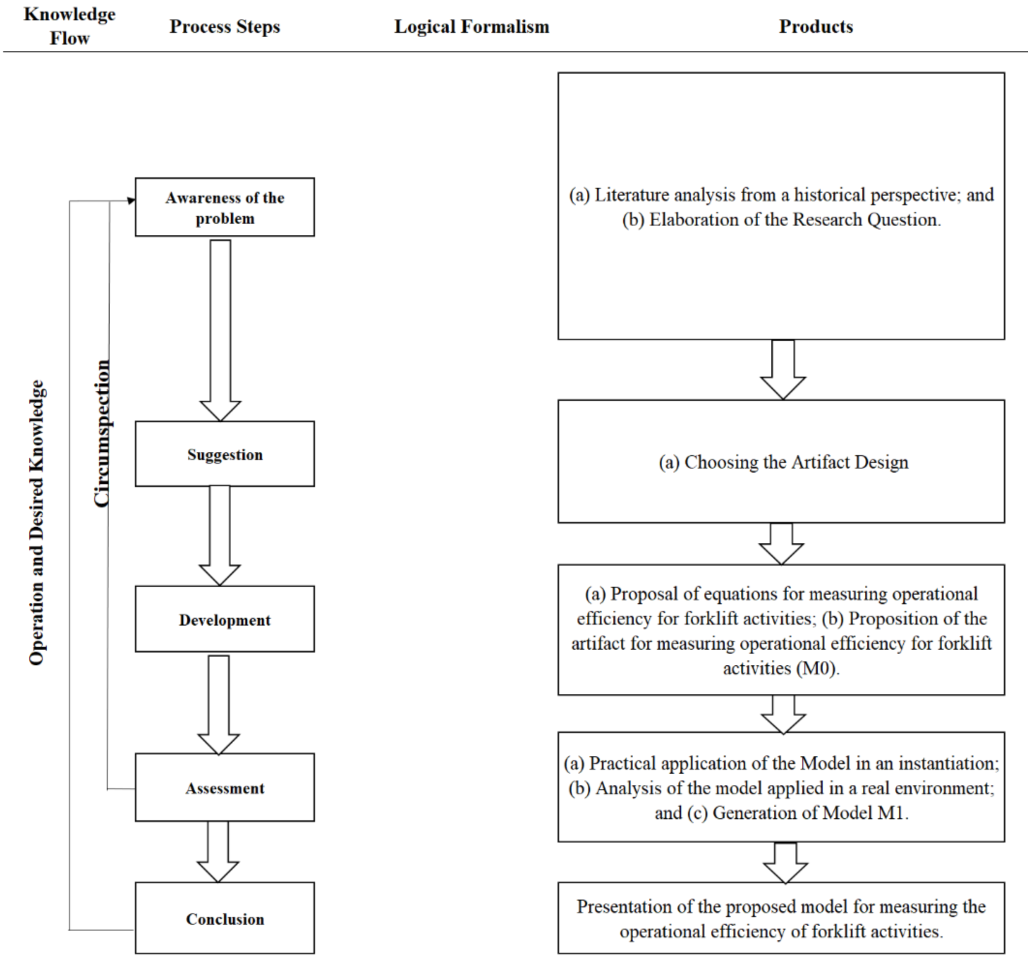

Figure 2 Working method applied in conducting this research.

3.2 Suggestion

Choosing the artifact design: Based on the SLR developed by Nunes (2024; in press), the several variations and adaptations of OEE and TEEP, developed by Nakajima (Anusha & Umasankar, 2020; Corrales *et al*., 2020; Kamali, 2019; Singh *et al*., 2018) for measuring operational efficiency in operations were observed. Thus, we defined this model as one that will be used to support the development of the conceptual model proposed in this research. This model has already been used in several variations of efficiency measures in healthcare environments (Müller *et al*., 2025; Souza *et al*., 2020), transportation (Benavides-Peña *et al*., 2017; Garza-Reyes *et al*., 2017), energy distribution (Barletta *et al*., 2015; Durga Prasad & Radhakrishna, 2019), costing (Novak & Vukasovic, 2016) and liquid bulk terminals (Nunes, in press, 2024b).

3.3 Development

Proposal of equations for measuring operational efficiency for forklift activities: Based on the analysis of this literature, the Nakajima model (Figure 1) was adapted to a model that encompasses scheduled and unscheduled stops included in the availability factor that meets the operations carried out in distribution centers.

The scheduled stops defined by the authors are as follows: (i) work shifts – it covers the work shifts in which the DC does not use forklifts in its operation; (ii) preventive maintenance – it involves the times in which forklifts are inoperative to execute the preventive maintenance plan; (iii) planned meetings – they cover the time in which the equipment is stopped for a previously scheduled meeting that is part of the management of the operational routine; (iv) meals – the time in which the equipment is out of operation so that the operator can have his meals and there is no replacement operator; (v) training – the time in which the forklift is not operating due to some training that the operator of this equipment needs to be trained in and there is no replacement operator; (vi) medical examinations – the time in which the equipment is out of operation so that the operator can undergo periodic medical examinations and there is no replacement operator; and (vii) transfer of operator to another function – the time the forklift is not operating due to the need to use the operator of this equipment and another operational activity and there is no substitute operator. Unscheduled stops were defined as follows: (i) corrective maintenance – the time the forklift is stopped due to failures in its systems that require maintenance; (ii) refueling – the time the forklift is not operating due to refueling; (iii) emergency meetings – the time the equipment is stopped for an unscheduled emergency meeting that is not part of the management of the operational routine; (iv) lack of fuel or battery power – the time the equipment is out of operation due to lack of power to operate; (v) lack of operator – the time the forklift is stopped due to the lack of a qualified operator; (vi) going to the toilet – the time the equipment is not in operation due to the operator being absent for physiological needs and there is no substitute operator; and (vii) lack of scheduled tasks – the time in which the forklift is out of operation due to the lack measurement is performed when the equipment is loaded and in motion. Thus, the losses in this factor are as follows: (i) unloaded movements – when the equipment moves without any material on its forks and (ii) movements in operations in material transfer tasks – when there is a WMS system to manage the activities of the material movement process. Regarding the quality factor, the losses defined are: (i) damage – it addresses the time wasted in movements where damage occurred in the material(s) moved due to operational error; (ii) collisions – the time in which the forklift is used to analyze damage caused by collisions with the equipment; and (iii) material falls – the time wasted for the operator to stop the equipment to collect and reassemble the load that fell during the forklift movement.

Proposal of an artifact to guide the measurement of operational efficiency in forklifts: Based on these definitions and equations, the model for measuring the productive efficiency of forklifts was proposed. The adaptation of the OEE equations to the reality of forklift operations was carried out and is presented below.

The authors named the measurement of TEEP (Antunes *et al*., 2008; Nakajima, 1988) for forklifts FTE (Forklift Total Efficiency) and OEE (Cheah *et al*., 2020; Nakajima, 1988) as OFE (Overall Forklift Effectiveness). Moreover, the equations were developed, also based on Nakajima's concepts and are as follows: for the availability factor in which forklifts operate 24 hours a day on all available days in the month (A_{FTE}) (Equation 6) (Kennedy, 2018; Nakajima, 1988).

$$\text{Availability } (A_{FTE}) = (OT / LT) \times 100 \quad (6)$$

When forklifts operate at times planned by companies, the availability factor is calculated using Equation 7 (Nakajima, 1988; Stamatis, 2010).

$$\text{Availability } (A_{OFE}) = (OT / POT) \times 100 \quad (7)$$

Regarding the performance factor, Equation 8 presents the applied variables related to the occupancy of the forks (O_C).

$$\text{Occupancy } (O_C) = (LOT / OT) \times 100 \quad (8)$$

The quality factor (Q) represents the quality rate of the activities performed by forklifts and is calculated using Equation 9 (Nakajima, 1988).

$$\text{Quality } (Q) = (VA / LOT) \times 100 \quad (9)$$

From this model, the forklift's production efficiency is calculated using Equation 10:

$$OFE^2 = (A \times O_C \times Q) \times 100 \quad (10)$$

From these equations, the relationships between the times to be applied in the measurement were developed, as well as the OFE equations, based on the OEE developed by Nakajima (1988). An initial conceptual model, called M0 (Model 0) was generated based on the concepts presented in the theoretical review of this research (Nakajima, 1988; Nunes; 2024b; Souza *et al*., 2020; Garza-Reyes *et al*., 2017), as shown in Figure 3.

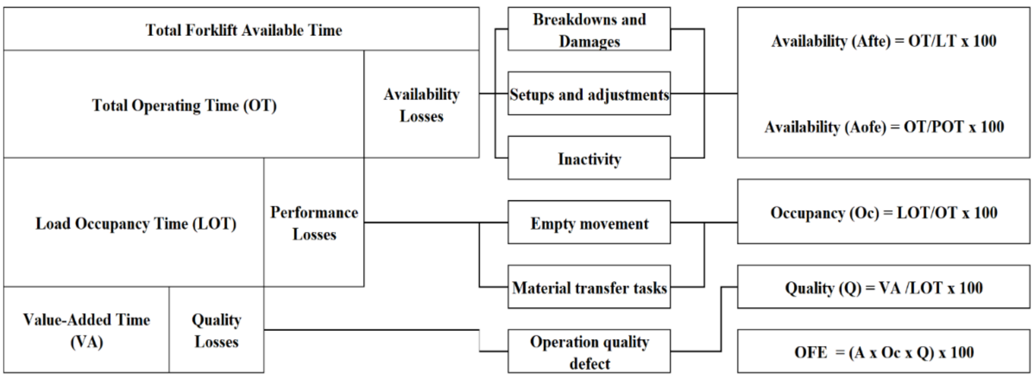

Figure 3 Conceptual Model (M0) developed to measure the operational efficiency of forklifts – OFE.

[2] When the forklift operates at Total Available Time for a forklift, consider 24 hours a day, seven days a week, to calculate Forklift Total Efficiency (FTE).

Table 2 presents the referential notation in the interpretation of the equations and figures of the proposed OFE Models

Table 2 Notation used in the OFE models.

Symbol	Definition
TAT	Total Available Time for forklift operation: 24h/day, 7 days/week
POT	Planned Operating Time: scheduled time for forklift operation, excluding planned downtime.
OT	Operating Time: time in which the forklift actually moved, excluding all stoppages.
LOT	Load Occupancy Time: time in which the forklift moves with a load on its forks, except in address transfer operations.
VA	Value-Added Value: time in which the forklift performs useful movements that add value to the customer:)
A	Availability factor: measures how much of the scheduled operating time a forklift was actually running.
O_C	Occupancy Rate: measures the operating time of a forklift with a load on its forks, excluding material transfer movements.
Q	Quality factor: considers movements with a load, excluding losses due to damage, collisions, dropped material, and load adjustments.
OFE	Overall Forklift Effectiveness (adaptation of OEE for forklifts)
FTE	Forklift Total Efficiency (adaptation of TEEP for forklifts)

After developing the model for measuring the operational efficiency of forklifts, this model was applied in a field test in a controlled environment to verify its applicability in relation to its qualities and opportunities for improvement (Strassburguer *et al*., 2023)

3.4 Assessment

The evaluation of the artifact was carried out through an instantiation (empirical application) – practical application of the model in a real environment. This instantiation was carried out in a Brazilian Logistics Distribution Center (LDC), defined through a convenience sample of the researchers. For reasons of confidentiality agreement, the name and location of this LDC will not be presented in this work. This LDC serves customers from all over South America, especially Brazil, Argentina, and Uruguay, which are responsible for 70%, 15%, and 7% of the demand for this operation. In 2023, this distribution center was responsible for revenue of approximately US$ 55 million. This LDC has, in its facilities, approximately 35,000m, with a ceiling height of 11m. It has a structure composed of fourteen docks, leveled by means of hydraulic levelers, with a storage structure using pallet racks, and with a capacity of 48,000 positions. In terms of human resources, this operation has 90 employees divided into an operations director, an operations manager, four operations coordinators, three operations analysts, and 83 operators (24 of whom are forklift operators), divided into two work shifts. This team works on the execution of receiving, storage, separation, shipping, and inventory tasks. The two work shifts are from 6 am to 00:50 am, with a 1-hour break for meals in each of these shifts, totaling 1,020 minutes of work. An analysis of the efficiency of the forklifts was agreed upon with the LDC management, and it was carried out within 10 business days of operation. At the end of the period, the results were presented to management, and due to the need to insert two new stops, a new model called M1 was generated to meet these insertions.

3.5 Conclusions

Based on the analysis of references on Operational Efficiency, the OEE model for measuring the operational efficiency of equipment proposed by Nakajima (1988) and the variation analysis developed in research analyzed in healthcare environments (Souza *et al*., 2020), transportation (Benavides-Peña *et al*., 2017; Garza-Reyes *et al*., 2017), energy distribution (Barletta *et al*., 2015; Durga Prasad & Radhakrishna, 2019), costing (Novak & Vukasovic, 2016) and liquid bulk terminals (Nunes, 2024b), a conceptual model, called M0, was developed to measure the operational efficiency of forklifts. The M0 model was presented in the Empirical Application and based on two suggestions from the operational team of the company in which the application was carried out, or authors inserted them and thus, the M1 model (new version of the proposed model) was generated and applied in the real environment of the instantiation of the proposed method. The final remarks presented the results found in the instantiation (empirical application) of the proposed model, the limitations of this research, and suggestions for future research on the topic of measuring operational efficiency in forklifts.

4. EMPIRICAL APPLICATION

Based on the development of the model M0 proposed to measure the operational efficiency of forklifts, built based on the DSR method proposed by Vaishnavi *et al*. (2015), the implementation of the OFE in a logistics distribution center (LDC) began. This instantiation aims to validate this model through the empirical application of the M1 Model. The implementation of the OFE was planned for March 11-15 and 18-22, 2024, totaling 10 business days in operation. To begin with the pilot, the implementation steps were developed and presented to the LCD Management, which validated them (Table 3). It was agreed with the management that steps 1 to 5 would be carried out on March 5 and 6.

The definition of the operational manager was carried out together with the LDC Manager and culminated in the indication of the operational supervisors (responsible for the operation) for each shift. This choice was made due to the need to monitor all the working hours of the forklift in which the OFE was implemented (in the two shifts in which the LDC operates). For data collection, the authors prepared a Logbook (LB) to be inserted with the forklift and filled out by the operators during each work shift. This form contains the identification of the work shift and the forklift that is measuring the OFE, and it is up to the operator to fill in the start and end times of each activity performed during the forklift operation. Figure 4 shows this Logbook (Nunes, 2024b). After this, it was necessary to provide training on the topics of efficiency, OEE, and OFE – proposed model, data analysis, and completion of the logbook for the operational supervisors and operators of the implemented forklift.

Table 3 Steps for implementing OFE in empirical application.

Steps	Activities	Target audience
1	Definition of implementation sponsors for the two operating shifts	LDC Manager
2	Preparation of a logbook to record activities and events	Authors and operational manager of each work shift
3	Training in efficiency and OEE concepts	Authors and operational manager of each work shift
4	Training in OFE concepts	Authors and operational manager of each work shift
5	Training in data recording (collection) using the logbook	2 Operators (1 from each work shift)
6	Implement the logbook for the forklift in which the OFE was implemented	Authors and operational manager of each work shift
7	Monitor the completion of logbooks throughout the shifts for ten working days	Authors and operational manager of each work shift

Shift:	Equipment	Start time (hh:mm)	End time (hh:mm)	Start time (hh:mm)	End time (hh:mm)	Start time (hh:mm)
AV	Equipment in operation with load	:	:	:	:	:
	Preventive maintenance	:	:	:	:	:
	Planned meetings	:	:	:	:	:
	Meals	:	:	:	:	:
	Trainings	:	:	:	:	:
	Medical examinations	:	:	:	:	:
	Operator transfer to another function	:	:	:	:	:
Unscheduled Stops	Corrective maintenance	:	:	:	:	:
	Supplies	:	:	:	:	:
	Emergency meetings	:	:	:	:	:
	Lack of fuel	:	:	:	:	:
	Lack of operator	:	:	:	:	:
	Going to the toilet	:	:	:	:	:
	Lack of task scheduling	:	:	:	:	:
Auxiliary transport	Unloaded displacements	:	:	:	:	:
	Displacements in material transfer operations	:	:	:	:	:
Quality	Damage during transport	:	:	:	:	:
	Collisions	:	:	:	:	:
	Load adjustments	:	:	:	:	:

Figure 4 Logbook (LB) for OFE data collection.

This training was carried out by one of the authors and lasted approximately two hours. It involved four operational supervisors and two operators (one from each shift). In this team, it was decided that the forklift in which the OFE measurement would be implemented would be a retractable forklift manufactured by Still, model FMX 20, with a 13 m lift and a load capacity of 2 tons.

In the presentation of the activities related to Figure 4, the operators suggested that two new activities be included: (i) battery replacement during unscheduled stops, which will measure the time that the forklift is not operating due to battery replacement (electrical equipment), since in addition to fuel-powered forklifts, electric forklifts are also used in the operation; (ii) load adjustments related to process quality, which deals with the time spent while the equipment is stopped to adjust the load on the forks that are in unsafe conditions for movement. These two suggestions were evaluated by the authors, who considered them relevant for measurement and were thus included in the model. By including two activities in the proposed model M0 – battery replacement and load adjustments – they were inserted into this proposition and are presented in the relationships between times and operational losses of the OFE – Model M1, as shown in Figure 5 (the equations presented for calculating OFE (Figure 3) were not changed).

Subsequently, the Logbook was modified, including two new activities (battery replacement and load adjustments) for presentation to the LDC operational team. During the LB presentation, the operators suggested that the suggested notes—written on a sheet of paper (LB)—be transferred to a digital solution, considering that this would cause more forklift downtime and could distract attention from equipment operation, in addition to the possibility of data being erroneously transcribed into a spreadsheet. Together, the authors and the operational team decided to make a mobile application available on a tablet for this measurement. Thus, an application using PowerApps™ for data collection, called AV 4.0 (Add Value 4.0), was developed using PowerApps™. This development included the features of the M1 version of the proposed model and took a week, which delayed the start of the measurement. Measurements were conducted on March 18-22 and 25-29, 2024. Figure 6 shows the AV 4.0 screens.

After developing the digital solution (Figure 6) for data collection for version M1 of the proposed model shown in Figure 5, operators were trained on AV 4.0, and data was collected. The application data was transferred daily, at the end of each shift, to a CSV file and then to an MS Excel spreadsheet, where the data was compiled. At the end of the.

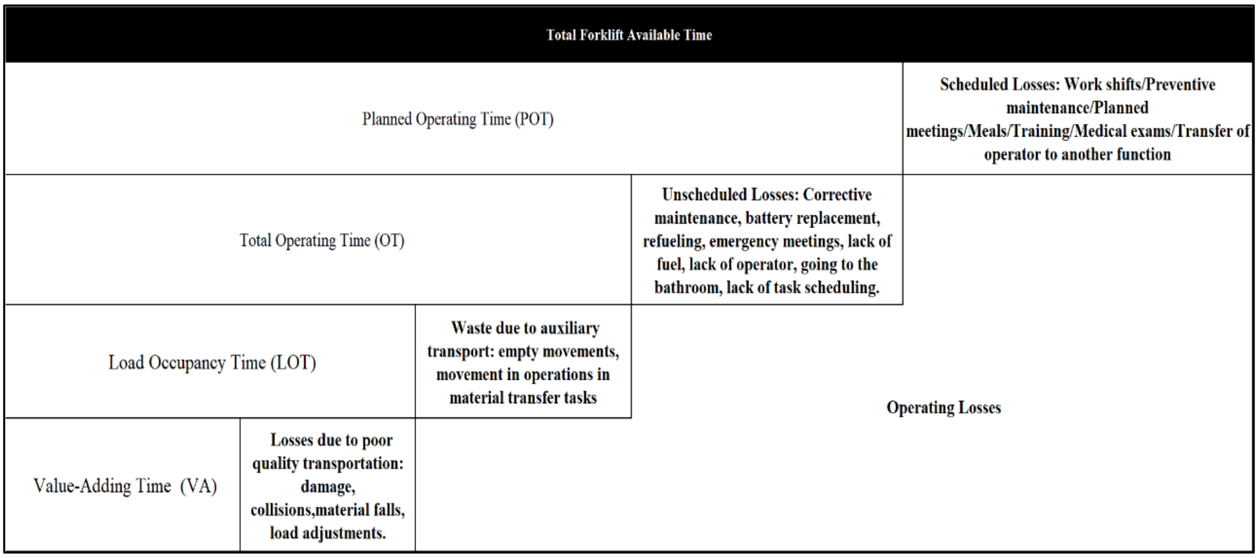

Figure 5 Relationships between times and operational losses of the OFE of model M1.

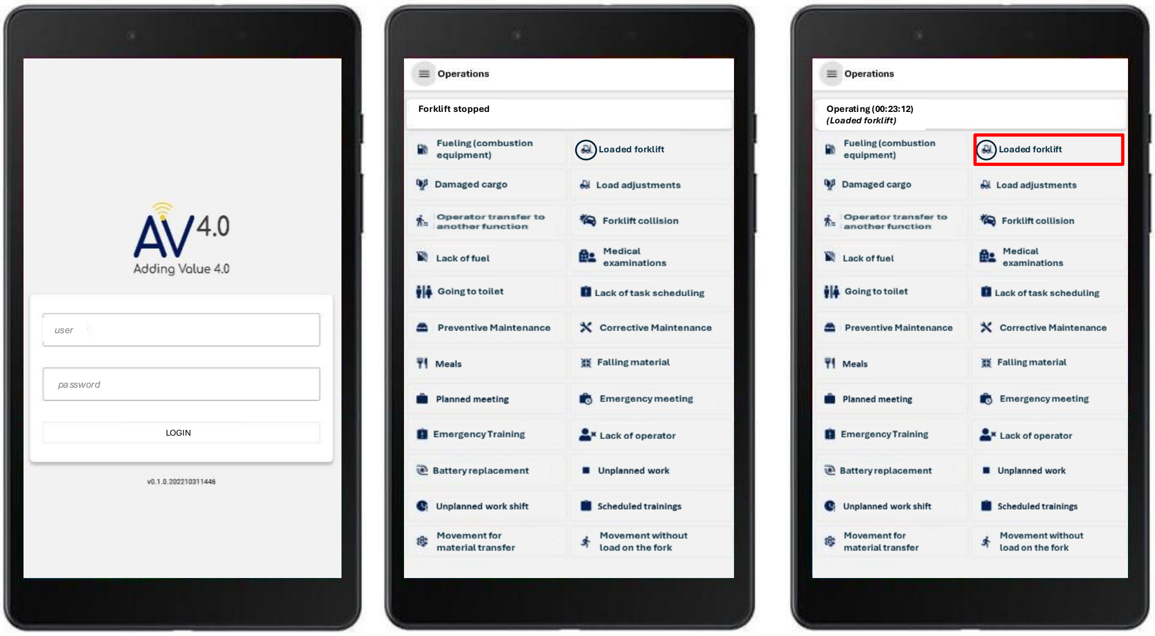

Figure 6 Mobile application developed for OFE data collection

Table 4 Results of the OFE- Model M1 measurement in the empirical application.

Day	POT (min)	OT (min)	LOT (min)	Q (min)	A_{OFE}	O_C	Q	OFE
1	1,020	360	69	69	35.2%	19.2%	100.0%	6.8%
2	1,020	420	18.6	18.6	41.1%	4.4%	100.0%	1.8%
3	1,020	180	159	159	17.6%	88.3%	100.0%	15.6%
4	1,020	180	193.8	193.8	17.6%	107.7%	100.0%	19.0%
5	1,020	240	223.8	223.8	23.5%	93.3%	100.0%	21.9%
Day	**POT (min)**	**OT (min)**	**LOT (min)**	**Q (min)**	**A_{OFE}**	**O_C**	**Q**	**OFE**
6	1,020	240	291.6	291.6	23.5%	121.5%	100.0%	28.6%
7	1,020	180	295.8	295.8	17.6%	164.3%	100.0%	29.0%
8	1,020	240	46.8	46.8	23.5%	19.5%	100.0%	4.6%
9	1,020	420	64.8	64.8	41.1%	15.4%	100.0%	6.4%
10	1,020	420	63.6	63.6	41.1%	15.1%	100.0%	6.2%
Total	**10,200**	**2,880**	**1,427**	**1,427**	**28.2%**	**49.5%**	**100.0%**	**14.0%**

Table 5 Scheduled losses.

Scheduled losses	Time (min)
Meals	1,200
Planned meetings	300
Preventive maintenance	220
Operator transfer to another function	120
Total	1,840

ten business days of measuring the OFE on the FMX 20 forklift, the results shown in Table 4 were obtained

Regarding the reduction of 7,320 minutes of availability of the FMX 20 forklift, during the OFE measurement, we observed that scheduled stops represented 1,840 minutes – approximately 25% of the time. The activities that caused them are those presented in Table 5.

During the 10 days of OFE measurement, there were 20 60-minute meal breaks (one per day for each operator on each shift). The planned meetings arise from the start-of-shift meetings, which last 15 minutes each and are held on both shifts to analyze the results of the previous shift and direct the activities of the next team. After these meetings, the forklift operators perform a start-of-shift checklist to verify the status of the essential functions of this equipment. The estimated time for this activity is 11 minutes for each check. This activity was included as preventive maintenance since it checks the signaling, horn, wheels, and drive controls of the forklifts. Regarding the transfer of an operator to another function, on days 3 and 4, the operator from the 1st shift was transferred to help load the delivery trucks for the customer for 60 minutes each day.

Unscheduled stops represented approximately 75% of the loss in the availability of the FMX 20 forklift, which is 5,490 minutes. The distribution of these losses is presented in Table 6.

Table 6 Unscheduled losses.

Unscheduled losses	Time (min)
Lack of task scheduling	3,600
Corrective maintenance	1,010
Battery replacement	675
Going to the toilet	125
Lack of operator	60
Lack of fuel	20
Total	**5,490**

The most significant loss from unscheduled downtime was the lack of task scheduling, which occurred entirely in the 2nd shift. In the last 6 hours of work of this shift, the FMX 20 forklift was out of operation, as there were no more tasks to be performed. Thus, it remained idle for this period. Regarding corrective maintenance, during the OFE analysis period, the hydraulic cylinder that moves the forklift's lifting tower failed and needed to be replaced. Since there was no spare for this part, the equipment was inoperative for 12 hours. In addition, the drive wheel also showed defects, which also resulted in its replacement. Battery changes, an activity that was included after the operators suggested it during the training of the initial model proposed for measuring OFE efficiency, accounted for 675 minutes. At the same time, the operators' toilet breaks, or hydration sessions accounted for 125 minutes. The lack of operators was due to the delay of the 1st shift operator on the 7th day of measurement, and the lack of fuel was the result of the battery running out of charge of the equipment in operation at a location in the LDC far from the battery charging center. A tugboat was called to transport a charged battery to the location where the FMX 20 was parked and thus perform the battery change.

From these data, it was possible to calculate the Operating Time (OT) of the FMX 20, which considered Equation 7 for the calculation and dealt with the time in which the forklift moved, disregarding these scheduled and unscheduled stops. Since the FMX 20 operates at times planned by the company, the availability factor must consider the shifts planned for this operation in relation to the equipment movement time (Nakajima, 1988; Nunes, 2024b) and the result is presented by equation 11.

$$\text{Availability } (A_{OFE}) = (2.880 / 10.200) \times 100 = 28.24\% \quad (11)$$

Regarding the performance factor, the recording of the AV 4.0 application considered the Operation activities – equipment operating with load and movements without load, since movements in material transfer operations were not recorded because the company did not have the WMS to manage the LDC operational tasks. Thus, 1,427 minutes of equipment operating with load and 1,453 in movements without load were recorded. By using Equation 8, it was possible to calculate the Occupancy Rate (O_C) of the FMX 20 - Equation 12.

$$\text{Occupancy } (O_C) = (1.427 / 2.880) \times 100 = 49.54\% \quad (12)$$

For the analysis of activities that impact process quality, no activity was recorded during the period in which the OFE was measured on the FMX 20. Therefore, the Quality (Q) was considered 100%. After measuring the three factors (Availability, Performance, and Quality), it was possible to

Table 7 Summary of the evolution of the OEE model to the proposed OFE.

Times used in the OEE and adapted for the OFE	OEE (Nakajima, 1988)	OFE – M0	OFE – M1
Planned Downtime (OEE) Planned Operating Time (OFE)	Regularly scheduled cleaning, lubrication, or inspections of machinery to ensure optimal performance and temporary pauses in production for holidays or other planned events.	Workshifts, preventive maintenance, planned meetings, meals, training, medical exams and transfer of operator to another function.	Workshifts, preventive maintenance, planned meetings, meals, training, medical exams and transfer of operator to another function.
Loading Time (OEE) Total Operating Time (OFE)	Equipment failure, material shortages, operator issues, emergency repairs, set-up and adjustments etc.	Corrective maintenance, refueling, emergency meetings, lack of fuel, lack of operator, going to the bathroom and lack of task scheduling.	Corrective maintenance, battery replacement, refueling, emergency meetings, lack of fuel, lack of operator, going to the bathroom, lack of task scheduling.
Net Operating Time (OEE) Load Occupancy Time (OFE)	Idling, minor stoppages and reduce speed	Empty movements and movement in operations in material transfer tasks.	Empty movements and movement in operations in material transfer tasks.
Valuable Operating Time (OEE) Value-Added Time (OFE)	Time in which the asset produces only good quality products at the maximum possible speed, without stops	Damage, collisions and material falls.	Damage, collisions, material falls and load adjustments.

calculate the OFE for the FMX 20 forklift that was monitored in the empirical application - Equation 13.

$$OFE = (0.2824 \times 0.4954 \times 1) \times 100 = 14.0\% \quad (13)$$

From the practical application of the proposed model for measuring forklift operational efficiency, it was possible to establish a synthesis of the model's evolution, based on OEE (Nakajima, 1988) and the two versions developed in this research: M0 - Conceptual model adapted from OEE; and model M1, refined during practical application in the field of forklift operations, as guided by the DSR method for creating artifacts (Hevner, 2022; Vaishnavi *et al*., 2015). Table 7 presents this synthesis.

Analyzing the summary presented in Table 7, we observe the adaptation of the OEE model, developed by Nakajima (1988), to measure operational efficiency in forklifts. This model is based on the M0 model, developed using the authors' OEE theoretical framework and based on the theoretical review of the research. After empirical application, with input from forklift operators at the company where the instantiation was performed, two new variables were introduced to be considered in this measurement, making the M1 model more robust than the conceptual M0. Thus, the final model proposed in this research—M1 model—can contribute to measuring the operational efficiency of forklifts based on its application in environments where this equipment is used. The final remarks of this research are presented below.

5. FINAL REMARKS

This research aimed to adapt the concept of Overall Equipment Efficiency (OEE) to analyze the productive efficiency of forklifts in the warehousing operations of a logistics distribution center in Brazil. First, a model based on Nakajima's OEE, called Overall Equipment Efficiency (OFE), was developed through Design Science Research. Then, for validation purposes, the research presented an attempted empirical application of the M0 model to measure the operational efficiency of forklifts in a Logistics Distribution Center (LDC).

After discussions with forklift operators, the researchers suggested and accepted the inclusion of two new variables to be considered in the presented model. Thus, in accordance with Design Science Research, a new artifact, the M1 model, was generated and applied in the field for 10 business days. The model was implemented on an FMX 20 forklift, using a mobile application called AV 4.0 for data collection.

Based on the analysis of the results, we found that the average operational efficiency of the forklift was 14.0%, with an occupancy rate of 49.5% and an availability factor of 28.24%. Scheduled downtime accounted for 25% of downtime, while unscheduled downtime accounted for 75% of operational losses. Based on the data obtained, it was possible to validate the applied method and improve the initial model. Two new activities were incorporated into the M1 model: battery replacement and load adjustments. These adjustments allowed for greater accuracy in assessing operational efficiency, ensuring a comprehensive analysis of losses and opportunities for improvement in forklifts, contributing to achieving the pillars of equipment availability, performance, and quality. Based on the 85% OEE benchmark (Nakajima, 1988; Antunes *et al*., 2008; Stamatis, 2010; Kennedy, 2018), it is believed that OFE should be around 40 to 45%, considering that forklifts are essentially equipment for lifting and lowering loads. Therefore, when lifting a load, it is most likely to be lowered empty.

Despite the contributions of this research, some limitations should be considered. Data collection was conducted in a single distribution center, which may limit the generalization of the results to other logistics contexts. Furthermore, a data collection application may have introduced biases due to the accuracy of the information entered by operators. Therefore, the OFE model presented in this research is not definitive, but it serves as a basis for measuring forklift operational efficiency and should be further developed.

For future research, we suggest applying the model to different types of distribution centers and warehouses to assess its robustness and adaptability. Furthermore, the integration of technologies such as IoT and machine learning can improve data collection and analysis, increase measurement accuracy and enable more detailed insights into forklift operational efficiency. Thus, the research contributes to the operational management of logistics centers by offering a structured model for monitoring equipment efficiency. The use of the DSR method in building the model reinforces its applicability and relevance for future studies and implementations in other logistics environments.

CONFLICTS OF INTEREST

Not applicable.

DATA AVAILABILITY STATEMENTS

Confidential data under NDA with the company participating in the instantiation.

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