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Overall Warehouse Effectiveness (OWE): A New Integrated Performance Indicator for Warehouse Operations

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Abstract: *Background:* Warehouses play a vital role in logistics systems, not only for storing goods but also for providing value-added services. To improve warehouse productivity and reduce costs, it is essential to measure their performance and identify inefficiencies. *Method*: This paper introduces a new aggregated key performance indicator (KPI), called Overall Warehouse Effectiveness (OWE), to evaluate the efficiency effectiveness of the physical structure of a warehouse. OWE utilizes the concepts of Availability, Performance and Quality, similar to the Overall Equipment Effectiveness (OEE) metric used in manufacturing. *Results:* The proposed indicator is then applied to a case study to demonstrate its use and provide theoretical and practical implications. *Conclusions*: In terms of theoretical implications, the proposed metric fills a gap in the literature by providing an aggregated indicator specifically designed for storage systems. For practitioners, OWE enables the identification of efficiency waste, customer service faults and adequacy of inventory management policies.

Keywords: OEE; warehouse performance; KPIs; performance measurement

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1. Introduction

The expansion globalization, the advancement of the world economy and the developing industrialism of consumer orders have prompted an increased demand for logistics services [1]. This environment is characterized by strong competition and increasingly demanding customer requirements in terms of punctuality and timeliness of deliveries, which leads to a reduction in margins for global logistics companies [2].

The role of warehouses for logistics services is crucial because they contribute significantly to the storage of goods from the time of production until the goods are supplied to consumers on demand. In the highly competitive business environment of today, a warehouse is a place not only to store inventory but also to manage and operate value-added services [3]. Warehouses are therefore one of the most relevant items for overall firm performance [4]. This scenario requires companies to continuously search for systems and methods to increase the productivity of their warehouses and thus contain costs, while using the same quantity of resources.

In order to improve any system, it is essential to measure the actual performance of the system and identify waste and inefficiencies [5]. Measurement is the initial and most basic step for achieving improvements in an organization and is also a vital component of continuous improvement [6,7]. The first step of a warehouse performance measurement process is identifying the right key performance indicators (KPIs) and prioritizing them based on industry-specific contexts [8]. Several warehouse KPIs have been put forward by scholars in recent years, such as productivity, space utilization, cycle time and cost (see [9] for a comprehensive literature review).

While individual metrics such as inventory accuracy, order fulfillment rates, on-time delivery and employee productivity are essential for evaluating specific aspects of warehouse performance, an aggregated performance indicator can provide a comprehensive view of the overall effectiveness of the warehouse. Several aggregated performance measurement indicators are available in the literature for manufacturing processes, among which the most used is OEE [10]. The indicator OEE is one of the most efficient indicators that can authentically measure the operational performance within production systems; it is used to benchmark, analyze and improve production processes in general [11]. Furthermore, OEE provides a quantitative metric for measuring the performance of not only individual equipment but also entire processes [12]. OEE has thus become a pillar for continuous improvement strategy of companies operating in completely different sectors such as the automotive industry [13], the semiconductor industry [14], the metal industry [15], railways [16], the provision of airbag safety devices to the automotive industry [17] and the food industry [18,19].

However, only a handful of aggregated indicators are available to study the performance of logistics assets, and they are mainly focused on material handling assets [20].

The objective of this paper is to define a new, aggregated, synthetic Overall Warehouse Effectiveness (OWE) KPI that makes it possible to analyze the effectiveness of the physical structure of the warehouse and thus identify wastes, faults in the customer service level, adequacy of the inventory management policy and, finally, areas for improvement. As a matter of fact, warehouse productivity is affected by several underlying factors such as the warehouse layout, information system, labor and equipment [21]. To this end, the OEE is used as a foundation to evaluate the overall performance of a specific resource of the warehouse that was previously overlooked, namely, the warehouse rack.

The paper is structured as follows. First, a review of the indicators used in the literature to measure warehouse performance as well as of previous applications of the OEE, in both the manufacturing and logistics sectors, is presented. Then, the research approach and the mathematical formulations underlying the OWE are proposed. Next, the new KPI is applied to a case study to discuss its use and identify theoretical and practical implications. Finally, conclusions are drawn.

2. Literature Review

2.1. Warehouse Performance Indicators

Ref. [9] propose a comprehensive review of warehouse productivity performance indicators for the measurement of the input of major warehouse resources (labor, equipment, space and information system) within the work area to represent the movement and storage output performance. Ref. [21] surveyed warehouse experts and found that Storage Space Utilization and Throughput are the most important KPIs for warehouse productivity. Ref. [22] analyzed the performance of warehouses using the 25 key performance indicators (KPIs) introduced by [23], grouped into five categories (productivity, financial, cycle time, quality and utilization), where each of these is applied to the main warehouse processes, namely, receiving, putaway, storage, order picking and shipping. In terms of productivity, KPIs such as total number of products shipped per time period are used [24]. In terms of "cycle time", the most important KPI for the receiving process is "Receipt processing time per receipt", that for the putaway process is "Putaway cycle time", that for the storage is "Inventory days on hand", that for order picking is "Order picking cycle time" and that for shipping is "Warehouse order cycle time". Quality KPIs take note of the existence of faults and failures in all warehouse processes, such as, for instance, receipts processed accurately [23]. Finally, KPIs for warehouse productivity investigate how efficiently is the warehouse space utilized. One example of such a KPI is inventory space utilization, namely the rate at which space is occupied for storage [25]. The overall capacity usage of the warehouse has also been explored [26].

2.2. Overall Equipment Effectiveness (OEE)

OEE, proposed by [10], represents the overall yield of a resource—or set of resources—assessed during the period in which these resources are available. OEE is a very synthetic index, consisting of a single output, which contains within it a great deal of information regarding the production plant, which is why it is effective in making visible where improvements can be made and the impact of lean tools aimed at improvement. It is a hierarchy of metrics that measure how effectively a manufacturing operation is realized [27].

The composition of the OEE index makes it possible to identify areas for improvement; in fact, it is a function of three performance indicators, all of which are key to monitoring the proper functioning of a plant [28]:

- Availability;
- Process performance;
- Quality rate.

Each component indicates an aspect of the process that can be improved.

The OEE indicator decomposes the performance of a production system into three measurable components: availability, performance and quality. Each component indicates an aspect of the process that can be improved. The OEE can be applied on multiple levels—to a single workstation, a single piece of machinery, an entire department or even the entire plant. The original formulations for the component indices of the OEE indicator are shown in Equations (1)–(4):

$$\text{Availability } A(T) = \frac{\text{Operating Time}}{\text{Scheduled time for production}} \tag{1}$$

$$\text{Performance } P(T) = \frac{\text{Net Operating Time}}{\text{Operating Time}} \tag{2}$$

$$\text{Quality } Q(T) = \frac{\text{Valuable Operating Time}}{\text{Net Operating Time}} \tag{3}$$

$$\text{OEE} = A(T) \times P(T) \times Q(T) \tag{4}$$

This is a standard definition of the Availability, Performance and Quality indices, corresponding to the classic formulation of OEE (Figure 1) with a time-based metric.

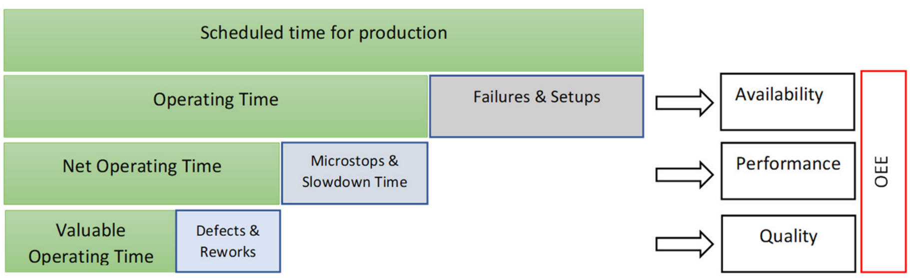

Figure 1. Representation of OEE in a time-based metric. Authors' own elaboration from [10].

The same formulas can be declined according to the production flow, defined in a reference period (T):

$$\text{Availability } A(T) = \frac{\text{Operating Output}}{\text{Planned Output for production}} \tag{5}$$

$$\text{Performance } P(T) = \frac{\text{Net Operating Output}}{\text{Operating Output}} \tag{6}$$

$$\text{Quality } Q(T) = \frac{\text{Valuable Output}}{\text{Net Operating Output}} \tag{7}$$

The OEE formulation supports the identification of losses in the effectiveness of the equipment, which can be classified into several categories ranging from equipment failure and idle times to material losses and rework.

Although OEE is traditionally used by practitioners as an operational measure for monitoring production performance, it can also be used as a metric for process improvement activities in other contexts. This has led to the broadening of OEE to overall factory effectiveness (OFE), overall asset effectiveness (OAE), overall environmental equipment effectiveness (OEEE), overall greenness performance (OGP) and overall labor effectiveness (OLE) (for a review of alternative uses of OEE, see [20]).

Ref. [29] pointed out that it is necessary to aim at increasing the performance of the whole factory rather than that of individual tools and therefore coined the term "overall factory effectiveness" (OFE), which focuses on combining activities and relationships between different machines and processes.

Overall Resources Effectiveness (ORE) is a manufacturing performance measurement system that has been developed by [30] with the objective of providing a more inclusive evaluation than OEE of a machine or process performance. The main difference between ORE and traditional OEE is that the first evaluates the overall performance of a machine or process not only based on its availability (A), performance (P) and quality (Q) but also in terms of three more elements: material efficiency (M), process cost and material cost variations. The integration of these three elements into the traditional overall effectiveness evaluation helps to expand the concept of this measure and, in this way, monitor other factors that can also have a considerable impact on the performance of a machine or process.

In their literature review, Ref. [31] highlighted that the main difference between the variations of the OEE lies in the types of production losses captured by the measurement tool. In this regard, Overall Asset Effectiveness (OAE), which has been more extensively applied in practice than in theory, can also accommodate productivity losses that are due to commercial, natural and environmental reasons.

Ref. [32] tested a new process-focused flow performance measure supporting a holistic approach to the manufacturing enterprise called Operations Flow Effectiveness (OFE). OFE highlights operations management design weaknesses and flow inhibitors that reduce cash flow. In this regard, the conventional OEE measure was extended by including the measurement of quality and delivery reliability of system inputs/outputs to enable the measurement of material flow through the whole system.

Ref. [33] proposed a novel methodology called Overall Material Usage Effectiveness (OME) that seizes upon OEE's straightforward and easy-to-use structure to address the problem of measuring the effective use of materials within a factory.

Finally, some scholars have added sustainability to the traditional OEE measures of performance. The Overall Environmental Equipment Effectiveness (OEEE), proposed in [34], adds the concept of sustainability based on the calculated environmental impact of the complete product life cycle to the OEE. Nevertheless, the aforementioned index shares the limitations of the original OEE, as it solely focuses on effectiveness at the equipment level, thereby disregarding the evaluation of the entire production system. Sustainability issues also come into play in Overall Greenness Performance (OGP), described in [35]. The Overall Greenness Performance (OGP) metric integrates the principles of lean manufacturing, specifically value-added processes, with the Overall Equipment Effectiveness (OEE) framework. This combination creates a hierarchy of metrics that assess the environmental effectiveness of a manufacturing operation based on the value-added processes that customers are willing to pay for.

According to the principles of lean manufacturing, the unnecessary movement of people, information or materials and the excessive storage of material in the logistics areas are considered wastes, with a consequent increase in costs. In order to reduce the wastes in a manufacturing context, any unnecessary transport of materials in the plant and any excessive storage should be reduced. To this end, Ref. [36] demonstrated the hypothesis that the OEE metric can also be used for transport facilities such as AGVs, and there is an interdependence between machine and transport effectiveness. In their simulations, they showed that the OEE metrics can be used for the modeling and productivity evaluation of manufacturing and logistics systems, with the generalization of Overall Factory Effectiveness (OFE) and Overall Transport Effectiveness (OTE).

Furthermore, Ref. [37] proved that the management of internal transporting activities within the production affects the effectiveness of the workstations. The proposed Transportation Measure made it possible to identify changes in the process of transporting materials, the reduction of the lead time and waiting time. At the same time, the frequency of transportation required to ensure material flow within the production system is minimized.

One study [38] highlighted the importance of judging the efficiency and effectiveness of a warehouse department, because this plays a vital role within the supply chain process. The purpose of this analysis was to evaluate the usability of the IoT in the warehouse through control of the Material Handling Equipment (MHE), using a forklift as the key MHE to analyze the efficiency of the IoT KPI in comparison with the existing OEE KPI.

Finally, Ref. [20] evaluated the effectiveness of an urban freight transportation system using the OEE metric. In this approach, the quality metric ensures that orders are delivered within the time windows (non-defective), the performance metric causes the speed of the operation to be optimized (i.e., transportation) and the availability metric reduces the non-transportation time (i.e., waiting time and unloading time).

In the literature, many works that analyze OEE in the production and logistics areas can be found, and several variations of the OEE concept have been proposed (see Table 1). However, few of these works have extended the application of a single KPI in the logistic process, and these are limited to transportation assets such as AGVs. Our research highlighted the lack of works capable of measuring the waste in the management of goods within the storage area. The present work aims to fill this gap.

Table 1. Variations of the OEE in manufacturing contexts.

Metric	Equation	Variation	Reference
Overall Factory Effectiveness (OFE)		Relationships among different machines and processes	[29]
Overall Asset Effectiveness (OAE)	$OAE = \frac{\text{Actual tonnage}}{\text{Theoretical maximum tonnage}}$	Losses due to business-related and other non-operation-related causes	[31]

Table 1. *Cont.*

Metric	Equation	Variation	Reference
Overall Resources Effectiveness (ORE)	$ORE = \frac{\text{Investment recovered}}{\text{Overall investment}}$	Manufacturing performance measurement system	[30]
Overall Environmental Equipment Effectiveness (OEEE)	$OEEE = OEE \times SUSTAINABILITY$	Concept of sustainability based on the calculated environmental impact	[34]
Operations Flow Effectiveness (OFE)		Holistic view of material flow through the input–process–output cycles of a firm	[32]
Overall Greenness Performance (OGP)		Environmental hierarchy of metrics according to Va (Value adding) processes	[35]
Overall Material Usage Effectiveness (OME)		Measure the effective material usage within manufacturing processes	[33]
Operations Labor Effectiveness (OLE)		Improvement in safety and fatigue management	[39]

3. OWE: A New, Encompassing Warehouse KPI

3.1. Research Approach

The purpose of this paper is to define a KPI suitable for logistics resources focusing on the "location storage" resource, similarly to what the OEE represents for manufacturing resources.

In other words, our goal is to build a synthetic KPI called Overall Warehouse Effectiveness (OWE), which evaluates the overall performance of a warehouse. This KPI allows to compare logistics activities carried out in similar field (i.e., *benchmarking*) and to identify waste and areas for improvement of a specific activity (i.e., *baseline analysis*).

Within a production process, bounded at the two extremes by the arrival of raw materials and the departure of finished products, it is possible to find many different types of material resources (henceforth referred to simply as resources), among which the most useful for the present discussion are the following:

1. Process resources: resources involved in the production cycle.
2. Logistics resources: resources that intervene during the storage and transportation of raw materials, semi-finished and finished products.

Just as OEE is used to measure the effectiveness of process resources, OWE is introduced here to provide a similar type of assessment for logistics processes.

Specifically, Table 2 compares the meanings of Availability, Process Performance and Quality for the OEE and OWE.

In a warehouse we can identify 3 types of logistics resource: space, equipment and labor [40,41]. Space, or static resources, contains goods and prevents goods damages. Equipment, or dynamic resources, consists of transportation units or material handling systems, move goods between machines and warehouse stations (i.e., space). Both equipment and space resources require labor resources to operate them. Labor, space and equipment resources are all necessary in order to create a complete production planning and control procedure [42]. Contrary to production resources, whose function is to transform and create added value, the main function of warehouse resources is to maintain the integrity of the goods stored in the warehouse and make those goods available to the final customer.

Table 2. Comparison of OEE vs. OWE indicators.

KPI	Availability	Process Performance	Quality Rate
OEE	Ability of the resource to be actually available to produce compared to the production schedule. (5)	Actual capacity that the resource can exert to generate value compared to the capacity that is assigned to it in the process design phase. (6)	Ability of the resource to produce compliant parts. (7)
OWE	Ability of the resource to be effectively available to maintain goods with respect to the actual planning of input and output flows.	Ability of the resource to maintain assets efficiently and taking into account the actual planning of input and output flows; this ability is expressed by comparison with ideal cases.	Ability of the resource to make intact products available to the customer with complete and timely deliveries.

In the literature, the efficiency and the effectiveness of internal handling systems, and therefore of the dynamic aspect of any logistic area, have been analyzed and estimated as a function of OEE [39], while the analysis of the efficiency and effectiveness of storage systems is lacking. Therefore, in this first dissertation on OWE, it has been decided to focus on warehouse racks and their saturation. To this end, we will treat the static (i.e., space) resource of the warehouse, namely, the storage location. Further research will aim at considering dynamic resources as well.

The parameters which constitute the OWE make it possible to identify several features of a storing area (Table 3). In particular, the "Availability" parameter analyzes and how the "space" resource of a warehouse is related to the stock to be kept within a certain time interval. This parameter is used to evaluate how far a logistical area deviates from complete saturation of the warehouse, i.e., from a state of total optimization of the "space" resource. This ideal state of the warehouse with respect to the "space" resource is related to a trade-off between two types of waste: space and overstocking. On the one hand, the warehouse may be oversized, especially in a fixed storage space allocation. On the other hand, the warehouse may be undersized and therefore not available to store a portion of the unit loads (ULs) within a certain time interval.

The "Performance" parameter focuses on the average saturation of the "space" resource. The average degree of saturation of storage locations depends on stock management policies and thus, indirectly, on the movements and flows of goods in a warehouse. However, the input and output flows of a warehouse are not always aligned because different items can have different "Inventory Turnover ratios" and may thus be handled with different frequencies. In this context, the "Performance" parameter evaluates how long a unit of stock is kept in storage, compared to an ideal, just-in-time case whereby a complete turnover of all ULs takes place every day.

Table 3. Objective of the OWE indicators referring to the compartment resource.

OWE Parameter	Objective
Availability	Warehouse planning allows undersized or oversized warehouses to be identified. It also takes into account the actual availability of compartments.
Performance	Effectiveness of stock management policies, taking into account the scheduling of Input and Output flows and stock levels. In addition, it enables to evaluate the different asset allocation criteria from a "static" warehouse point of view.
Quality	Congruity of Flow Output with Demand; allows the correct sizing of the operating and safety stock to be verified

The third parameter focuses on the quality and deliverability of the ULs handled in the warehouse. Some ULs may be damaged during handling and/or their stationing within the individual storage locations. Furthermore, ULs may also be delivered from the warehouse after the promised date. Therefore, the "Quality" parameter measures the degree of conformity of the Output flows with the Demand within the same time interval. This loss of quality due to the different warehouse resources can be overcome by having an additional stock in the storage area compared to the operational stock, thus affecting the definition of the safety stock.

3.2. Mathematical Formulations

Any warehouse static resource is characterized by three fundamental aspects, as shown in Figure 2:

- Input of goods (INPUT);
- Time of use of the resource (T);
- Output of the goods (OUTPUT).

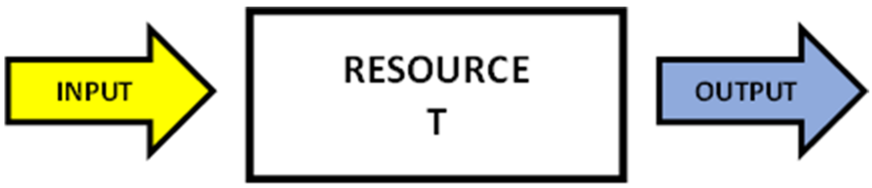

Figure 2. Characteristics of a warehouse static resource.

In the discussion of OWE, we choose to use the formulation referring to the output in other words the products leaving the warehouse in a reference time interval T. Thus, the parameters of Availability, Performance and Quality will be expressed as output ratios.

The main assumptions for the mathematical formulations are as follows:

- The analysis has a time bucket t equal to one day, meaning that each UL has a minimum theoretical stay in the warehouse equal to one day, but nothing prevents choosing time buckets of a shorter duration.
- $i(t)$ is the input function in time bucket t and is defined in the interval $1 \leq t \leq T$ with $t = 1, 2, \ldots, T$.

- $o(t)$ is the output function in time bucket t and is defined in the interval $1 \leq t \leq T$ with $t = 1, 2, \ldots, T$.
- There is an equivalence between ULs and storage locations, such that each storage location holds only one UL.

The main variables of the model are defined in Table 4.

Table 4. Variables for the mathematical formulations.

Variable	Definition
T	Reference time interval in which the analysis is carried out
Storage Capacity (SC)	Storage capacity of the warehouse under analysis, equaling the number of available storage locations.
I_{max} (T)	Maximum inventory occurring in the warehouse during the analysis interval T. This value is calculated at the end of T.
O (T)	Output or outflow from the warehouse at T, whose management within the warehouse gives rise to I_{max} (T). This value is taken at the end of T.
$O_{th,max}$ (T)	The maximum theoretical output or outflow that can be managed in the interval T in a warehouse considering different numbers of storage locations occupied.

The outflow from the warehouse at time T is defined as follows:

$$O(T) = \sum_{t=1}^{T} o(t) \tag{8}$$

Then we can define the components of the OWE using the previous assumptions and definitions.

The Availability indicator is the ability of the resource to be available to maintain goods with respect to the actual planning of input and output flows. Considering the characteristics of the warehouse, it can be expressed as the ratio between the maximum manageable theoretical output in the interval T in a warehouse of capacity equal to $I_{max}(T)$ locations and the maximum manageable theoretical output in the interval T in a warehouse of capacity equal to SC locations. This means that it only evaluates the physical structure of the warehouse.

$$A(T) = \frac{O_{th,max}(T, I_{max})}{O_{th,max}(T, SC)} = \frac{I_{max}(T) \times T}{SC \times T} = \frac{I_{max}(T)}{SC} \text{ with } A(T) = 1 \text{ if } I_{max}(T) > SC \tag{9}$$

where the variables are defined as follows:

- $O_{th.max}$ (T, I_{max}): maximum theoretical output needed to handle I_{max}, which is equal to $I_{max} \times T$.
- $O_{th.max}$ (T, SC): maximum theoretical output needed to handle the whole storage capacity, which is equal to $SC \times T$.

It is assumed that each UL has a minimum theoretical stay in the warehouse equal to 1 day and that all storage locations are occupied.

This indicator measures losses due to wasted space; therefore, when its value is lower than 1, the warehouse is oversized compared to the actual capacity requirements.

Considering a warehouse with respect to the “space” resource, it is possible to identify two types of waste: “space” and “overstocking”. In the first case, the warehouse turns out to be oversized, and a large proportion of the storage locations turn out to be unused, especially in a fixed storage space allocation. In the second case, the warehouse turns out to be undersized and therefore not available to maintain in an optimal condition a portion of the LUs in a certain time interval.

The formulation proposed above does not allow the evaluation of inefficiencies due to an undersized warehouse; the following alternative formulation is proposed to fill the gap:

$$A(T) = 1 - \frac{\left|O_{th,max}(T, SC) - O_{th,max}(T, I_{max})\right|}{O_{th,max}(T, SC)} \tag{10}$$

It allows wastes due to both surpluses and deficits in capacity to be evaluated in the same way.

Availability, measured over a sufficiently long time T, in both cases signals a structural discrepancy between the nominal Storage Capacity (SC) and the storage capacity required to contain $I_{max}(T)$.

The Performance indicator measures the effectiveness of the service compared to optimal cases of stock management. This indicator is expressed as the ratio between the output from the warehouse in T and the theoretical maximum manageable output in the interval T in a warehouse with a storage capacity equal to $I_{max}(T)$ locations.

$$P(T) = \frac{O(T)}{O_{th,max}(T, I_{max})} = \frac{O(T)}{I_{max}(T) \times T} = \frac{\overline{o(t)} \times T}{I_{max}(T) \times T} = \frac{\overline{o(t)}}{I_{max}(T)} \tag{11}$$

where $\overline{o(t)}$ is the mean value of $o(t)$ calculated over the interval T.

The parameter $P(T)$ instead measures effectiveness losses due to non-optimized stock and location flow management. The evaluation is made by comparison with a theoretical minimum dwell time as defined above.

The Quality indicator is the ability of the resource to keep intact products available to the customer with complete and timely deliveries. This capability is expressed as the ratio of conforming output to total output, considering only those goods delivered intact and on time and recording any returns as unfinished.

$$Q(T) = \frac{O_q(T)}{O(T)} = \frac{\overline{o_q(t)} \times T}{\overline{o(t)} \times T} = \frac{\overline{o_q(t)}}{\overline{o(t)}} \tag{12}$$

where $O_q(T)$ is referred as a valuable output or valuable flow delivered to the customer, i.e., undamaged and on time, from which any returns, etc., have been excluded. This value is recorded at the end of T.

It measures losses due to deviations in quality and punctuality from what the customer requires.

Substituting the different terms into the OWE expression yields the following:

$$OWE = A(T) \times P(T) \times Q(T) \tag{13}$$

$$OWE = \frac{O_q(T)}{O_{th,max}(T, SC)} = \frac{\overline{o_q(t)} \times T}{SC \times T} = \frac{\overline{o_q(t)}}{SC} \tag{14}$$

Ultimately, this expression tells us that OWE is the ratio of how much “we have delivered” net of various losses to the maximum we potentially “could have delivered” with a warehouse of a given capacity (*SC*). In Figure 3, the OEE has been adapted to the OWE formula.

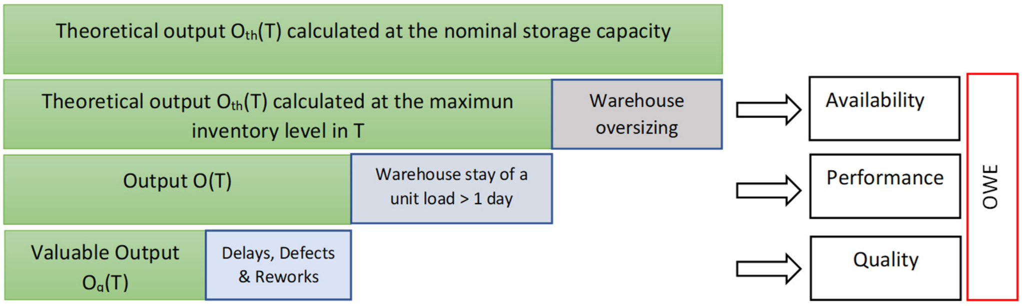

Figure 3. Representation of OWE in a metric based on output from the warehouse.

4. Case Study Application

The proposed calculation example concerns a finished goods warehouse handling two products, for each of which a filling function i(*t*) (INPUT) and a demand function o(*t*) (OUTPUT) were assumed in a period *T* equal to 24 elementary units of time. Based on these data and the assumptions that are given below, the indices of Availability, Service Performance and Quality needed to calculate the Overall Warehouse Effectiveness value were calculated.

For all demand scenarios the following assumptions are made:

- The warehouse has a Storage Capacity of 1400 locations.
- The input is considered concentrated at the beginning of the elementary unit of time and is realized in LUs.
- The output is considered concentrated at the end of the elementary time unit and is realized in LUs.
- The handling capacity is such that the input and output are realized.
- For product 1 (cod 001), the output (1) is equal to 2150 LUs in *T*.
- For product 2 (cod 002) the output (2) is equal to 1700 LUs in *T*.
- The total output *O(T)* is 3850 LUs in *T*.

The presented case study is a simulation, but it was conducted using some basic data from an existing company. The company in question operates in the tissue paper market and has a large finished goods warehouse located in northern Tuscany, where finished products processed in various production facilities within the same region are stored. The warehouse operates with a load unit allocation system characterized by having dedicated positions for different types of products. The finished products are stored in palletized load units (Europallet 2) with an average height of 1800 mm. The shelving is of the drive-through type, serviced by shuttles in the various levels of the lanes. Each lane in the shelves has an average of five levels, and each lane has an average of eight locations, according to the actual dimensions of the load units. The inbound and outbound flows were modified from their actual trend to amplify the effects on the calculations of the factors of the proposed parameter.

4.1. Demand Scenario 1

The next graph (Figure 4) shows the trend of input for the two products in *T*.

The next graph (Figure 5) shows the trends of output for the two products in *T*.

The next graph (Figure 6) shows the comparison between the output and the valuable output.

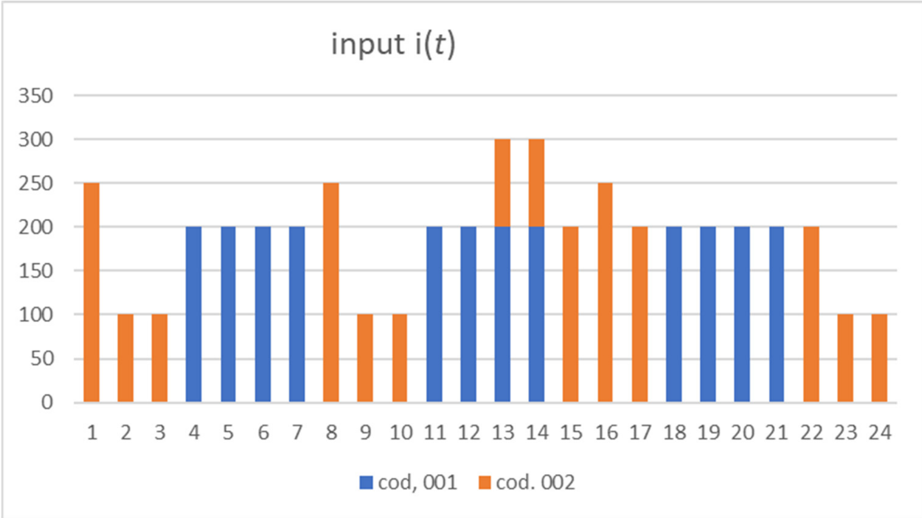

Figure 4. Input i(*t*).

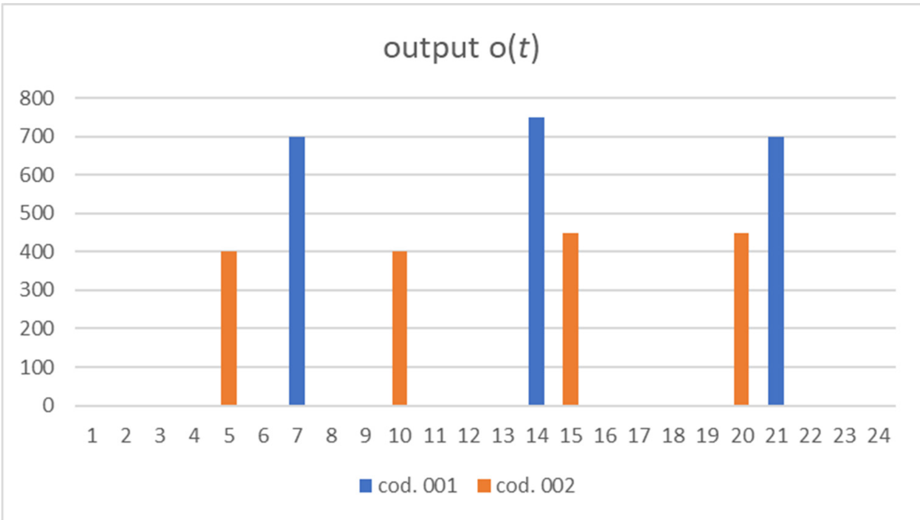

Figure 5. Output *o(t)* for demand scenario 1.

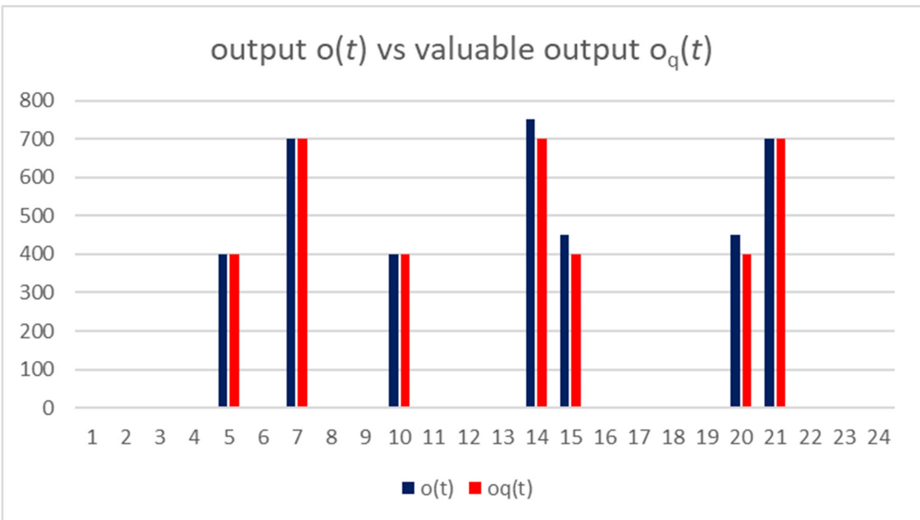

Figure 6. Output vs. valuable output for demand scenario 1.

Examination of the graph shows that the following:

- For product 1, in period 14, there were unfulfilled orders equal to 50 ULs.
- For product 2, in periods 15 and 20, there were unfulfilled orders equal to 50 ULs for a total of 100 undelivered products.

Assuming that, for both products, the stock at time t_0 is equal to zero, the inventory level at the beginning of each time step throughout the whole period T is shown in the following graph (Figure 7).

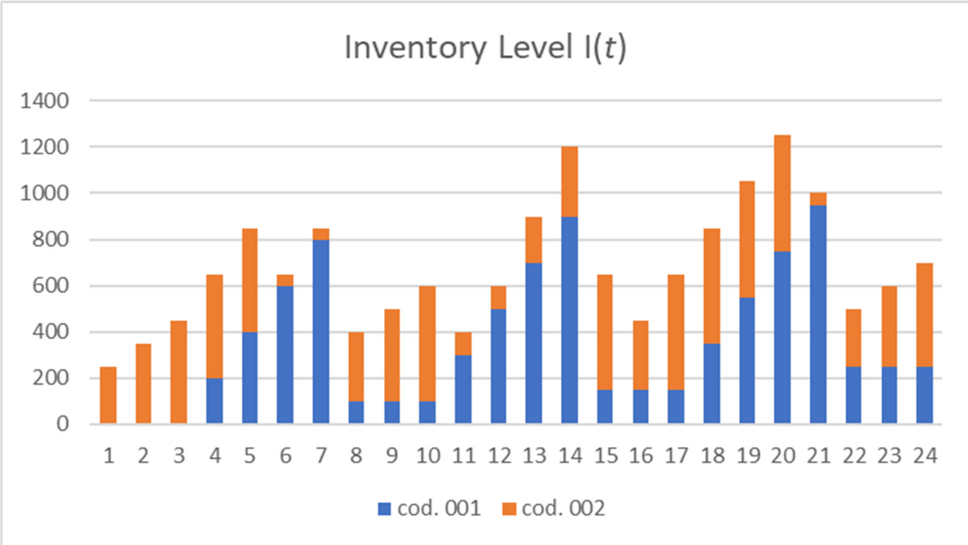

Figure 7. Inventory level for demand scenario 1.

It can be noted from the graph that the Total Maximum Inventory I_{max} is 1250 ULs.

According to these data, the values of the Availability, Service Performance and Quality indices are derived.

Recalling that the actual Storage Capacity (SC) is 1400 locations, from (24) we obtain that the maximum theoretical output or flow that can be handled in the interval of 24 days in a warehouse with a storage capacity of 1400 locations is given by the following:

$$O_{th,max}(T, SC) = O_{th,max}(24, 1400) = (24/1) \times 1400 = 33{,}600 \text{ Lus.}$$

If, during time T, an $I_{max}(T)$ of 1250 LUs is achieved, then the maximum theoretical output or flow that can be handled in a warehouse of storage capacity equal to the $I_{max}(T)$ is given by the following:

$$O_{th,max}(T, I_{max}) = O_{th,max}(24, 1250) = (24/1) \times 1250 = 30{,}000 \text{ LUs}$$

Hence, Equation (9) is applied as follows:

$$A(T) = \frac{O_{th,max}(T, I_{max})}{O_{th,max}(T, SC)} = \frac{30,000}{33,600} = 0.893$$

Recalling the formula for calculating the service performance, we obtain Equation (11):

$$P(T) = \frac{O(T)}{O_{th,max}(T, I_{max})} = \frac{3850}{30,000} = 0.128$$

The Quality index is given by Equation (12):

$$Q(T) = \frac{O_q(T)}{O(T)}$$

It can be deduced from the graph in Figure 5 that the total output *O(T)* is 3850 LUs, while the undelivered products (see Figure 6) amount to 50 Lus for cod 001 and 100 LUs for cod 002, for a total of 150 LUs. From this we can derive the valuable output $O_q(T)$ to 3700 LUs.

From this, the Quality index can be calculated:

$$Q(T) = \frac{O_q(T)}{O(T)} = \frac{3700}{3850} = 0.961$$

Once all the parameters have been determined, the OWE for the different combinations analyzed can be calculated (Equation (13)).

$$WE = A(T) \times P(T) \times Q(T) = 0.893 \times 0.128 \times 0.961 = 0.1098$$

In order to better understand how the different components of the OWE contribute to the reduction of warehouse effectiveness, we define three contributions (Figure 8):

$$OWE|A = Imax\ (T) = A(T) = 0.893$$

$$OWE|A, P = O(T) = A(T) \times P(T) = 0.893 \times 0.128 = 0.114$$

$$OWE|A, P, Q = Oq(T) = A(T) \times P(T) \times Q(T) = 0.893 \times 0.128 \times 0.961 = 0.1098$$

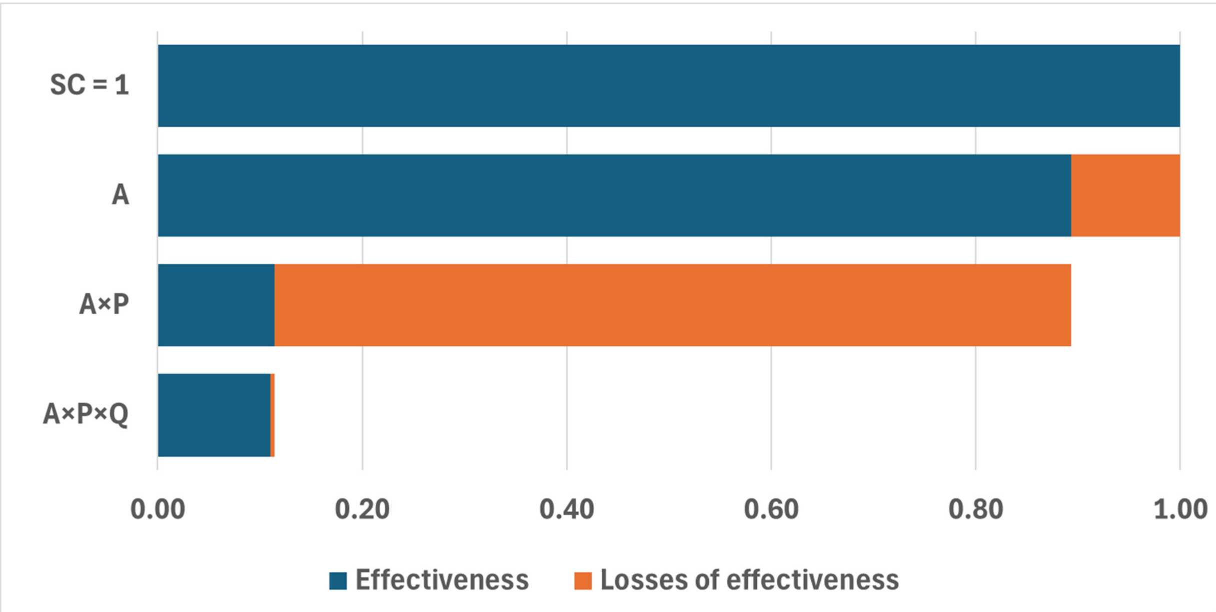

Figure 8. Standard OWE over a 24-day period.

Based on the results obtained, the following graph highlights the different types of ineffectiveness:

The first ineffectiveness is due exclusively to factor A, which takes into account the oversizing of the warehouse compared to the maximum stock held in the reference time interval *T*. Therefore, this ineffectiveness generates the non-use of some storage locations.

The second ineffectiveness adds the contribution of the P factor to the first ineffectiveness; A × P takes into account the incomplete movement of the ULs in the reference time interval *T*, compared to the number of potentially moveable ULs of the *SC*. Referring to the application case, this ineffectiveness is defined as the 3850 ULs moved in the 24-day time interval compared to the 33,600 LUs, potentially moveable in the warehouse, always in the same reference interval.

The last ineffectiveness also considers the contribution of the Q factor, which takes into account the lack of quality in delivery management. In the application case, it is defined as the 3700 ULs delivered compliantly in the 24-day time interval, compared to the 33,600 ULs potentially manageable in the delivery phase, always in the same reference interval.

The diagram analysis highlights that the OWE, which value is about 11%, is strongly affected by the performance index.

4.2. Demand Scenario 2

To show how for the same storage capacity *SC*, output flow *O(T)* and valuable output flow $O_q(T)$, a different time management of output flows *O(T)* results in:

- the modification of the parameters *A(T)* and *P(T)*
- the same value of the OWE

As shown in Figure 9, consider the same case as above, but the output flow is treated with a different demand timing.

The graph shown in Figure 10 highlights the following:

- For product 1, in period 12, there were unfulfilled orders equal to 50 LUs.
- For product 2, in periods 15 and 20 there were unfulfilled orders equal to 50 LUs for a total of 100 undelivered products.

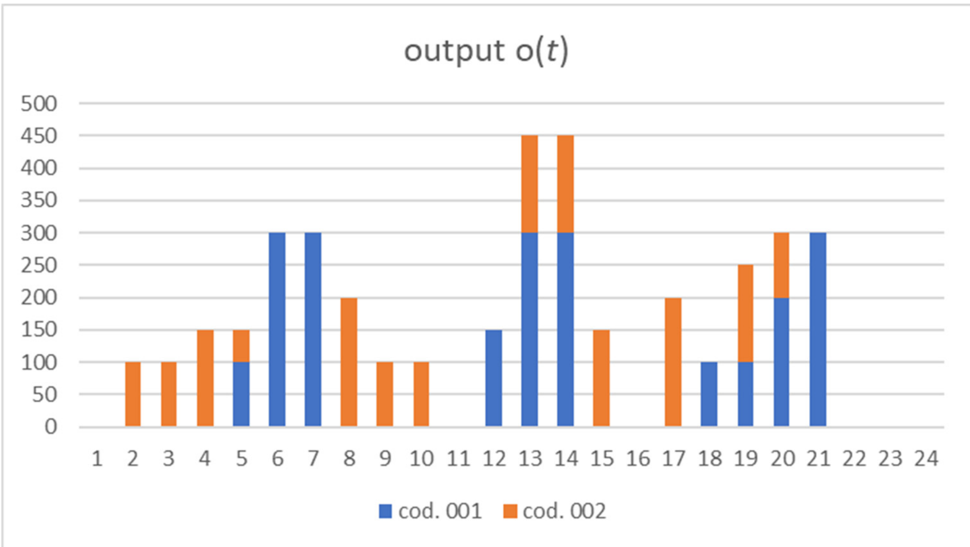

Figure 9. Output *o(t)* for demand scenario 2.

The next graph (Figure 10) shows the comparison between the output and the valuable output.

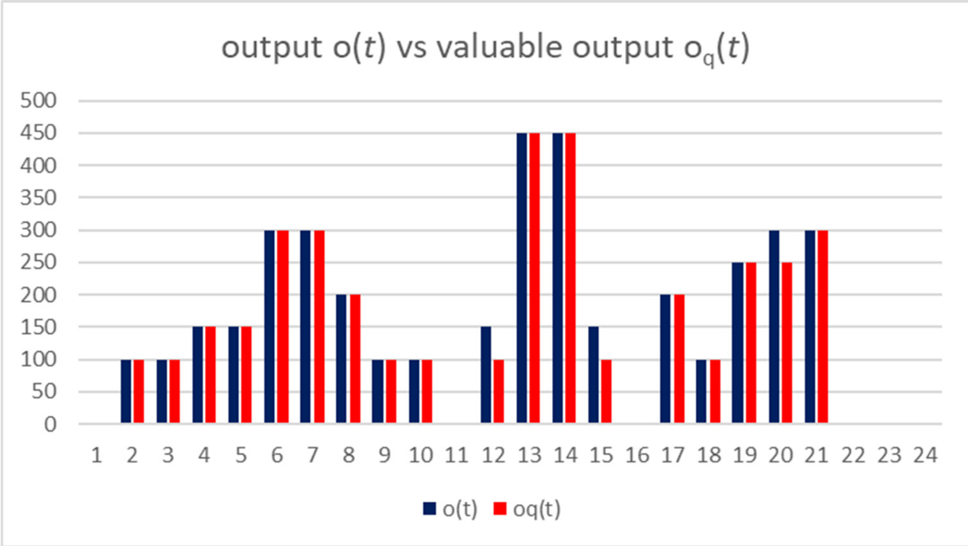

Figure 10. Output vs. valuable output for demand scenario 2.

Assuming that, for both products, the stock at time t_0 is equal to zero, the inventory level at the beginning of each time step throughout the whole period *T* is shown in the following graph (Figure 11).

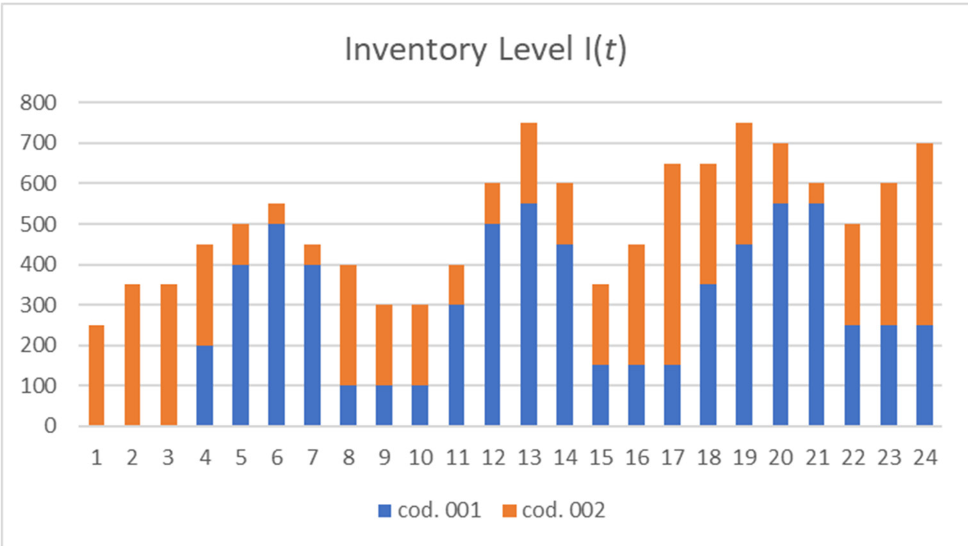

Figure 11. Inventory level for demand scenario 2.

According to these data, the values of the Availability, Service Performance and Quality indices are derived.

The maximum theoretical output or flow that can be handled in the interval of 24 days in a warehouse with a storage capacity of 1400 locations is equal to 33,600 LUs, as calculated for demand scenario 1.

If, during time T, an $I_{max}(T)$ of 750 LUs is achieved, then the maximum theoretical output or flow that can be handled in a warehouse of storage capacity equal to the $I_{max}(T)$ is given by the following:

$$O_{th,max}(T, I_{max}) = O_{th,max}(24, 750) = (24/1) \times 750 = 18{,}000 \text{ LUs}.$$

Hence, applying Equation (9):

$$A(T) = \frac{O_{th,max}(T, I_{max})}{O_{th,max}(T, SC)} = \frac{18,000}{33,600} = 0.536$$

Recalling the formula for calculating the service performance, we obtain Equation (11):

$$P(T) = \frac{O(T)}{O_{th,max}(T, I_{max})} = \frac{3850}{18,000} = 0.214$$

The Quality index is given by Equation (12):

$$Q(T) = \frac{O_q(T)}{O(T)}$$

The quality index in this scenario is equal to the quality index of scenario 1.

Once all the parameters have been determined, the OWE for the different combinations analyzed can be calculated (Equation (13)):

$$OWE = A(T) \times P(T) \times Q(T) = 0.536 \times 0.214 \times 0.961 = 0.1102$$

4.3. Analysis of Results

Firstly, it is important to note that the *OWE* calculated in the first and second scenarios are almost identical. The reason for this seemingly counterintuitive result is that the difference between the first and second scenarios is only due to how the outflow was distributed over the reference time, while the *OWE* represents the ratio between how much it has been delivered by the warehouse net of various losses and the maximum that could potentially be delivered with an *SC* capacity warehouse.

Analyzing the three parameters *A(T)*, *P(T)* and $Q(T)$ in both scenarios, it is evident that the $Q(T)$ parameter does not change while $A(T)$ and $P(T)$ widely vary.

First, let us point out the key difference between the two cases: In the first case, I_{max} is set at 1250, while in the second case, it is only 750. However, the storage capacity (*SC*) remains the same at 1400 locations in both cases.

This difference in I_{max} has important implications. *A(T)* measures the potential delivery capacity compared to what is theoretically possible with the Imax capacity warehouse and the *SC* capacity warehouse. In the second case, with the lower I_{max}, $A(T)$ is lower, indicating that some storage locations in the warehouse remain unused at the reference time T, leading to reduced Availability.

Similarly, $P(T)$ measures the actual delivery compared to the maximum achievable delivery with an Imax capacity warehouse. In the second case, $P(T)$ is higher because the lower I_{max} allows for more efficient management. This reduces the gap between the actual flow (*O(T)*) and the maximum flow achievable with I_{max} ($O_{th,max}(T, I_{max})$), making warehouse management more efficient.

Lastly, the OWE remains the same in both cases. However, in the first case, it indicates ineffectiveness in managing outflows, while in the second case, it points to ineffectiveness in managing the storage space.

5. Discussion

5.1. Practical Implications

This work engenders several implications for using the OWE in a real environment. To this end, by calculating the OWE one can obtain a suitable indicator for answering to the following questions:

1. Is the service level rendered to the customer sufficient?
2. Is the stock and inventory management policy efficient?
3. Is the physical warehouse being used introducing “waste” into the logistics process?

The lowest value of *A(T)*, *P(T)* and *Q(T)* has the greatest impact on the cause of underperformance since it relates to the following aspects:

- The number of units that you are unable to deliver to customers;
- The low performance of inventory management policies;
- Inadequate or excessive warehouse size and, in the case of automated warehouses, an excessive number of system failures.

A single indicator, considering only A or P or Q, can effectively evaluate different and separated aspects of warehouse performance. OWE, on the other hand, comprises three integral components, each closely associated with specific types of indicators commonly used to characterize logistics processes.

For instance, the concept of availability (*A(T)*) provides insights into the utilization of storage space in relation to the maximum capacity (Imax) and how this space evolves over time. Availability becomes intricately linked with indicators such as receptivity, warehouse utilization and the distribution of inventory within the warehouse.

Conversely, the Performance metric enables the assessment of the outflow magnitude over time relative to Imax. In an ideal scenario, where P = 1, all LUs present in a warehouse during a specific time interval should be simultaneously dispatched, resembling a Transit Point’s management approach. Based on this analysis, it becomes evident that the metric P is closely tied to dynamic indicators of a warehouse, including outflow rate and the number of LUs moved within a time interval.

The management of materials within a warehouse exerts a significant influence on cycle times, thereby affecting the level of Performance. This is particularly relevant in logistics areas characterized by a Selectivity Index of 1 [43] and/or an allocation strategy involving dedicated places or areas, as these measures can optimize cycle times and, consequently, enhance Performance.

The Quality index is intertwined with indicators that provide insights into the service quality offered by a logistics area to its customers. These indicators encompass factors such as the percentage of damaged items per unit load (LU), the accuracy of receipts processed and error rates. Additionally, they are contingent on internal order management planning, considering metrics such as the percentage of order lines processed per order and the percentage of pieces processed per order line.

In the realm of system design, achieving perfect optimization of all individual elements is often challenging. Instead, a judicious trade-off between the various components becomes necessary. This principle also extends to the definition of OWE. For example, the “Service Level” exerts a dual impact: it negatively affects Warehouse Performance, as an increase in Service Level corresponds to an increase in Imax, and it positively impacts Warehouse Quality, as a higher Service Level results in a lower percentage of Back Orders (thus increasing Fill Rate).

Interestingly, the presence of a safety stock has a pejorative effect on Service Performance, as it increases the value of I_{max} compared to the case without safety stock, and a positive effect on Quality, as it reduces non-deliveries.

Furthermore, when we consider equivalent total inflows and outflows of products within a warehouse during a specific time period (*T*), a “dedicated” storage policy, which implies a greater storage capacity (*SC*) compared to “shared or random” storage, results in a higher value of $O_{th,max}(T, SC)$, as this metric is a function of *SC*. In contrast, in the “shared or random” storage policy, the storage capacity *SC* is lower, leading to reduced unutilized storage space. Consequently, the increased storage capacity in the “dedicated” storage mode corresponds to lower utilization of storage locations, which in turn worsens the *A(t)* index when compared to the "shared or random" storage mode.

Moreover, when the total inflows and outflows within the warehouse during time *T* remain constant, a higher frequency of shipments from a finished goods warehouse or the receipt of raw materials in a warehouse result in a lower Imax, thereby increasing Performance. Conversely, a higher frequency of arrivals or shipments of materials from an existing warehouse indicates greater ineffectiveness in resource utilization (i.e., storage locations) since the resulting I_{max} is lower, subsequently reducing availability. In summary, a higher frequency leads to a reduction in Availability and an increase in Performance, with these two aspects being directly related through the term $O_{th,max}(T, I_{max})$.

Thus, OWE can be used by practitioners in several activities related to warehouse design or redesign. For instance, it can be used to find a benchmark during the warehouse design phase. Furthermore, it can be used to provide a baseline to assess how changes in flow and stock management policies or damage reduction initiatives may affect the warehouse performance.

However, the real weakness of the storage can be hidden by the definition of only one indicator, due to possible offsets of its constituent components, in this case A, P and Q as shown in the alternative case presented above.

Therefore, similarly to other aggregated metrics (i.e., OEE, Risk), before applying the OWE it is necessary to explicitly state its main components, in order to implement the most suitable responses in a process of improvement of a logistics area, declined in detail as solutions regarding storage capacity and inventory management policy.

5.2. Theoretical Implications

The utilization of a unified indicator for assessing warehouse performance yields several notable theoretical implications. Firstly, the introduction of a singular warehouse indicator capable of consolidating various commonly used metrics, simplifies the comparison of different logistics areas. Our findings contribute to performance evaluation by offering a composite index that integrates storage, movement efficiency and quality, addressing gaps identified in traditional approaches of warehouse performance measurement such as [44]. Furthermore, decomposition of OWE into the three indicators of availability, performance and quality aligns with research on optimizing storage utilization and order fulfillment efficiency [45]. Moreover, this proposed indicator can be readily adopted by warehouse operations managers pursuing broad performance improvement initiatives. As such, the OWE metric connects operational elements (availability and performance) with service quality, aligning with the broader goals of logistics efficiency in line with findings from who state that monitoring warehouse utilization is key for improving logistics efficiency [46].

Another significant implication lies in the extension of the OWE analysis to dynamic processes, referred to as "dynamic OWE." This expansion encompasses resources engaged in the handling LUs to and from storage locations, such as labor and transport equipment. It broadens the assessment of warehouse effectiveness to include activities affecting the determinants of A, P and Q. For instance, a greater emphasis on automated warehousing or the adoption of logistics 4.0 principles underscores the increased integration of labor and equipment resources, inevitably impacting A, P, Q and OWE.

Furthermore, the extension of OWE's definition to the dynamic dimension forms the foundation for a more comprehensive analysis, which also encompasses production areas. The development of a dynamic OWE index may involve the integration of OWE within a holistic framework alongside Overall Equipment Effectiveness (OEE) and other integrated indicators. These implications align with the context of a Holonic Manufacturing System [47], where each resource holon comprises communication, cooperation and functional components. In this context, a framework presented by [48] incorporates four distinct resource holon types: machines, warehouse stations, transport units and employees, each potentially associated with a specific indicator, such as OEE for machines and OWE for warehouses. In a holistic perspective, it may also prove beneficial to consider a unified indicator for transport, addressing the dynamic aspects of both production and internal logistics processes.

6. Conclusions

This paper introduces a new, encompassing warehouse key performance indicator (KPI) called Overall Warehouse Effectiveness (OWE), based on the OEE concept and focusing specifically on the effectiveness of the warehouse rack, which is often overlooked in performance evaluations. The paper presents a research approach and mathematical formulations for calculating the OWE, followed by a case study to demonstrate its application and discuss theoretical and practical implications. The proposed OWE provides a valuable tool for evaluating warehouse performance, ultimately contributing to improved effectiveness of warehouse operations.

Nevertheless, this study has certain limitations. Specifically, the proposed new OWE indicator only considers the static aspects of the warehouse, without any reference to the effectiveness of the handling systems of the logistics area. Furthermore, the application of the new OWE indicator is limited to a simulated case study, rather than a real-life implementation. Therefore, additional research is necessary to validate its effectiveness. This can be achieved by conducting interviews with practitioners, implementing proposed improvements and analyzing their outcomes to further establish the validity and reliability of the indicator. Several other avenues for research are engendered by this work. First, the OWE could be extended within the context of warehouse performance measurement to more dynamic resources including labor and material handling equipment (e.g., forklifts, conveyor belts, etc.). This would also support the evaluation of warehouses in the realm of Industry 5.0, which advocates for a collaborative environment between human resources and robotic equipment. OWE may also be integrated with further performance indicators belonging to production areas, aiming to comprehensively analyze a production and logistics system. Finally, OWE's potential for integration into real-time decision-making systems, such as digital twins, can further enhance this line of research.

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