Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 00 (2023) 000–000

Procedia
Computer Science

www.elsevier.com/locate/procedia

5th International Conference on Industry 4.0 and Smart Manufacturing

Design of KPIs for evaluating the environmental impact of warehouse operations: a case study

Antonio Cosma[a*], Romina Conte[a], Vittorio Solina[a], Giuseppina Ambrogio[a]

[a]University of Calabria, via P. Bucci 45C , 87036, Arcavacata di Rende (Italy)

Abstract

The aim of this work is to introduce a system for environmental monitoring within a 4.0 automated warehouse. In the era of globalization, the emphasis on meeting customer needs and establishing a sustainable supply chain has become essential for companies striving to maintain competitiveness in the market. Logistics, in this context, has emerged as a pivotal factor in gaining a competitive advantage. The challenge for companies lies in assessing the impact of ongoing changes and developing a robust logistics strategy to optimize operational efficiency, reduce costs, and mitigate environmental impact.

The automation of warehouses is often the solution adopted by companies to meet these new market demands. Through a meticulous analysis of costs and benefits, many companies have recognized the advantages offered by automated solutions in designing their warehouses. However, it is crucial to evaluate not only the economic aspects but also those related to sustainability. European regulations and growing environmental concerns necessitate companies to adopt sustainable practices, reducing environmental impact, energy resource usage, and promoting social well-being.

In this context, performance monitoring using specific key performance indicators (KPIs) becomes crucial. They allow for the assessment and monitoring of operational efficiency, resource utilization, and the environmental impact of the automated warehouse. This enables the identification of areas for improvement and the implementation of strategies for sustainable warehouse management. The availability of data that automated warehouses can provide through horizontal integration with Enterprise Resource Planning (ERP) systems further facilitates this process. These systems generate important logistics-related data, such as management control, budget, or production data.

Peer-review under responsibility of the scientific committee of the 5th International Conference on Industry 4.0 and Smart Manufacturing

Keywords: warehouse management; KPI; enterprise resource planning; sustainability.

1. Introduction

The aim of this work can be justified in the broader context of Green Warehousing [1], a paradigm used to denote a management concept of operational efficiency. It integrates and implements sustainability principles with the aim of minimizing energy consumption, energy costs, and greenhouse gas emissions in a warehouse. Therefore, it can be defined as a set of technological and organizational solutions designed to increase the productivity of storage and handling processes while simultaneously minimizing environmental impact and ensuring positive economic and social

1877-0509 © 2023 The Authors. Published by ELSEVIER B.V. This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0)
Peer-review under responsibility of the scientific committee of the 5th International Conference on Industry 4.0 and Smart Manufacturing

outcomes. To achieve the goal of an eco-friendly and efficient warehouse, various measures are needed that can make a difference in terms of energy savings and environmental impact reduction [2,3]. One of these solutions is the implementation of a Warehouse Management System (WMS), which allows for the optimization of storage, handling, and distribution operations, reducing waste and improving overall efficiency.

In traditional literature the warehouse automation has been defined as "the direct control and management by software of handling systems for the transportation and storage of goods without the need for operators or drivers". Warehouse automation is a term that encompasses automatic retrieval and storage systems (AS/RS), automated guided vehicles (AGV), and conveyor sorting systems. In particular, AS/RS systems can be connected to Warehouse Management Systems (WMS) to provide real-time information on item locations, retrieval times, and inventory availability, supplying valuable data for calculating Key Performance Indicators (KPIs). Additionally, AS/RS systems can be equipped with sensors and automation devices to collect real-time data on system performance, item availability, and environmental conditions such as temperature and humidity.

KPIs are defined as quantitative and strategic measures that reflect the critical success factors of businesses [4]. KPIs are an efficient and effective way to enhance company performance in all operational areas, including production, engineering, logistics, marketing, and sales. Through these indicators, management can not only measure business phenomena over time and space (across various business units and markets) but also plan and schedule business activities (defining measurable short and medium-term goals), measure deviations (between expected objectives and actual results), and take necessary actions to correct gaps.

In today's competitive environment, the performance measurement system should encompass a wide range of business process metrics, which is why KPIs are primarily focused on processes. The more critically a KPI is chosen, the better it can control improvements and adjust goals. The generation of specific key performance indicators depends on whether the issue is operational or strategic in nature. In the case of warehouse management, operational key performance indicators are primarily used to monitor efficient logistics processes, while strategic key performance indicators are used to develop and design efficient goods flows [5]. Key performance indicators are often based on average and approximate values and do not provide precise information but rather a quick overview.

This work aims to develop a set of KPIs and apply them to the specific context of an automated warehouse to assess sustainability and provide a foundation for continuous improvement, especially from an energy perspective. The work begins with an initial survey conducted at a general level but adaptable to other contexts [6], including the case study of this work.

2. Proposed method

In this work, a subset of Key Performance Indicators (KPIs) is introduced. It includes conventional metrics (KPI#1) and those specifically tailored to the objectives of this study (KPI#2-7). These indicators are derived based on the data provided by the Warehouse Management System (WMS) and its exportable data. Table 1 outlines the calculation method for each KPI.

Table 1 . KPIs for warehouse monitoring by sustainability perspective

#KPI	Definition	Calculus
1	Temporal efficiency of the receiving operation	$\frac{\text{Production time} - \text{Goods receipt time}}{\text{Average time taken}}$
2	Percentage of pallets in error	$\frac{\text{Number of pallets in error}}{\text{Total number of pallets moved}}$
3	Optimization of handling, with constraints on storage balance	$\frac{\text{Number of storage operations performed by a stacker crane}}{\text{Total number of storage operations performed}}$
4	Optimization of handling, with constraints on withdrawal balance	$\frac{\text{Number of picking operations performed by a stacker crane}}{\text{Total number of picking operations performed}}$
5	Withdrawal tasks canceled due to machine errors	$\frac{\text{Number of canceled tasks}}{\text{Total number of tasks executed}}$

6	Idle times of the stacker crane	$\frac{\text{Number of times the lift goes on standby}}{\text{Total number of movements}}$
7	Call/dock to door time vs. good issue time	$\frac{\text{Number of activities with long duration}}{\text{Total number of activities}}$

Using the highlighted KPIs, it is feasible to construct a comprehensive dashboard that monitors the energy consumption impact of all utilities and operations in a storage location. To create the KPI dashboard, assigning weights to each indicator is essential to derive a unified index normalized for the sustainability performance of the 4.0 automated warehouse. In this specific scenario, the Analytic Hierarchy Process procedure can be employed to determine their relative importance [7].

2.1. KPIs description

KPI #1 is an indicator that should be minimized because a low value signifies spending less time on the receiving operation. A high value indicates increased consumption of resources like energy and fuel. Optimal resource utilization leads to reduced usage times and energy consumption.

KPI #2 calculates the percentage of pallets with errors (damaged, misplaced, non-compliant with safety standards, etc.). Fewer mishandled pallets indicate efficient management, reducing resource wastage, including energy, and contributing to greater sustainability.

KPIs #3 and #4 are based on the idea that optimizing pallet storage (or retrieval) in the rack can enhance sustainability by lowering warehouse management costs and improving energy efficiency. Balancing storage (or retrieval) reduces congestion, minimizing additional movements and maneuvers. This boosts operational efficiency, reduces resource usage like fuel or electrical energy.

KPI #5 assesses retrieval tasks canceled due to machine errors. Errors lead to higher consumption, and improving efficiency by reducing cancellations minimizes resource wastage, including time and energy.

KPI #6 evaluates instances of stacker crane standby, which increases energy consumption due to machine downtime. Minimizing standby conditions enhances system operation and sustainability.

KPI #7 tracks the time from a truck's arrival at the loading bay to cargo delivery. The truck's active cooling system during this time impacts sustainability.

3. Case study

The case study in this work focuses on a multinational company in the food industry that utilizes the SAP Extended Warehouse Management system to manage its distribution warehouse. This system streamlines the oversight of daily warehouse activities, including goods receipt, storage locations, handling, inventory management, order processing, product shipment, and courier tracking. Furthermore, the company operates a 4.0 automated pallet warehouse, featuring double-sided racks served by an AS/RS system with five stacker cranes navigating along warehouse aisles with double-depth locations. Pallet allocation within the rack is automated and overseen by the SAP Extended Warehouse Management system, which optimizes process variables, supervises warehouse operations, and organizes handling based on predefined logics.

The integration of the Warehouse Management System (WMS) into the ERP system has enabled the company to collect a dataset for the analysis and improvement of business processes at various levels.

The observation period for handling operations spans the first 14 weeks of 2023. Utilizing the available data, directly measurable through the indirect job done, all eight KPIs can be displayed and monitored. The subsequent section presents and discusses the trend of each KPI.

Fig. 1 illustrates the outcomes of KPI#1 recorded over the fourteen weeks. The results indicate significant inefficiencies in warehouse operations throughout the observation period. The inefficiencies in the automated activity times are attributed to an improper load balance among the stacker cranes. With five stacker cranes in operation, there is a potential for load imbalances, causing one stacker crane to become overloaded. Only after detecting the overload the load is redistributed among multiple vehicles, leading to a general delay in work assignments. This challenge becomes more evident in the subsequent KPI (KPI#3).

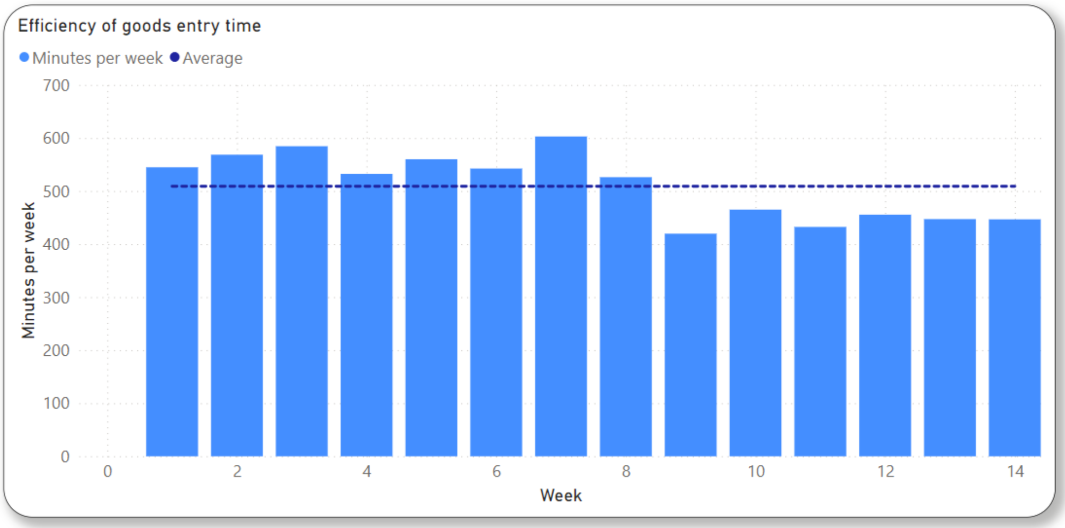

Fig. 1. KPI#1: Temporal efficiency of the receiving operation

Examining KPI#2 necessitates a more in-depth analysis to understand the reasons for errors. Figure 2 depicts the distribution of the index, indicating that weeks 2 to 6 are particularly challenging with the highest values of pallets in error. However, the situation is intricate, as weeks 1, 7, and 9 also surpass the threshold value of 120 pallets in error per week, a limit that the company can tolerate without an overall increase in costs. Naturally, the reference to the threshold is a compromise, and from a sustainable standpoint, only week 14 is considered environmentally friendly. Due to the high error values, it is essential to delve into these figures and verify their origin. In this regard, not only is a graph necessary for a comprehensive understanding of the KPI (Fig. 2), but also a detailed examination of Table 2.

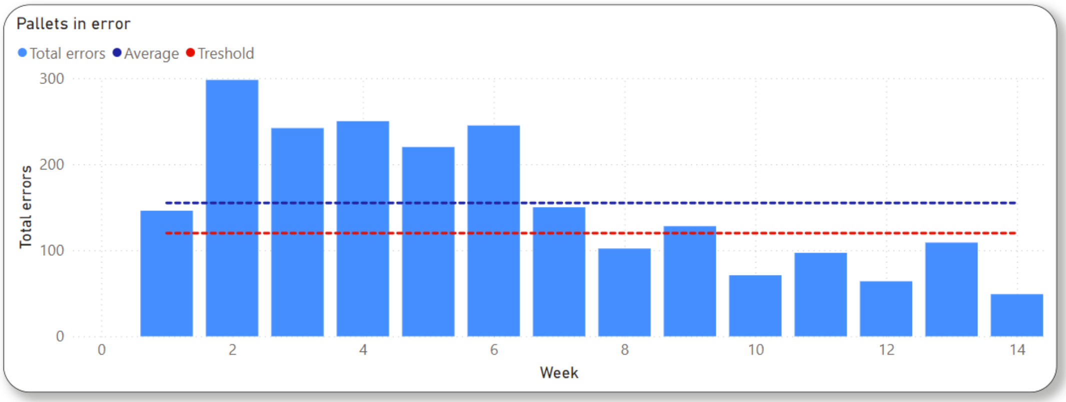

Fig. 2. KPI#2: Pallets in error

Table 2. Analytical data measured by the EWM system of errors during operations

Week	Wrong movements	Bare code Error	Tot Err	Tot Movements	KPI
1	129	17	146	516	0,283
2	278	20	298	892	0,334
3	229	13	242	858	0,282

4	222	28	250	855	0,292
5	210	10	220	754	0,292
6	229	16	245	597	0,410
7	135	15	150	404	0,371
8	96	6	102	297	0,343
9	119	9	128	409	0,313
10	63	8	71	290	0,245
11	81	16	97	351	0,276
12	59	5	64	329	0,195
13	91	18	109	438	0,249
14	43	6	49	227	0,216

As evident from Table 2, the primary causes of these errors mainly arise from incorrect handling, specifically in the improper placement of pallets in their designated positions within the system or in failing to retrieve them, leading to the repetition of operations. This can be attributed to both less attentive work management, indicating the need for more meticulous and precise tracking of warehouse personnel's tasks, and uncontrollable errors related to hardware and software malfunctions in the automated system (e.g., stacker cranes going offline, power outages, etc.). A second source of error is related to labels that prevent optical systems from reading them. In this specific case, the error can be traced back to the label itself or its type. In this regard, the problem can be resolved by modifying the label type.
However, the detailed analysis of the table allows to observe that the worst week is not the second (as might be inferred from Figure 1) but the sixth week, since the absolute number of errors is too high when compared to the total number of movements. To better highlight this aspect, an additional visualization icon should be added to the dashboard displaying the actual KPI with respect to the threshold.

Moving on to the next index, in the case study, KPI#3 relates to the optimization of handling, considering the balance of pallet storage in the rack as a percentage relative to the target of 20% per aisle per stacker crane (given that there are 5 aisles in total, constituting 100%). As indicated by the percentage values reported in Table 3, the first three stacker cranes frequently exceed the 20% limit, resulting in delays and inefficiencies that could be easily addressed with different allocations to T4 and T5. This inefficiency underscores the need for reengineering the solution by employing a more efficient job allocation algorithm.

Table 3. KPI#3: Optimization of handling, with constraints on storage balance

Week	Tot Movements	KPI x T1	KPI x T2	KPI x T3	KPI x T4	KPI x T5
1	3571	21,93%	20,27%	18,96%	20,53%	18,31%
2	5484	24,18%	20,11%	10,96%	22,72%	22,03%
3	5302	20,88%	19,54%	22,27%	19,29%	18,01%
4	5332	21,57%	19,82%	19,00%	20,16%	19,45%
5	3852	20,33%	21,16%	18,28%	20,35%	19,89%
6	3922	20,45%	20,93%	19,25%	19,30%	20,07%
7	3212	23,69%	21,86%	24,84%	23,07%	6,54%
8	3278	19,34%	16,96%	18,21%	12,23%	33,25%
9	6569	13,78%	9,24%	26,52%	26,72%	23,75%
10	5021	5,24%	29,93%	24,06%	20,25%	20,51%
11	5487	24,73%	21,23%	18,92%	17,93%	17,19%
12	6145	23,17%	22,54%	19,35%	18,84%	16,09%
13	5596	23,34%	20,93%	19,41%	17,96%	18,37%
14	3799	23,56%	22,37%	20,56%	16,71%	16,79%

In accordance with the last index, in the case study, KPI#4 measures the optimization of handling, considering the balance of pallet retrievals in the rack as a percentage relative to the target of 20% per aisle (given that there are 5 aisles in total, constituting 100%).

Table 4. KPI#4: Optimization of handling, with constraints on withdrawal balance

Week	Tot Movements	KPI x T1	KPI x T2	KPI x T3	KPI x T4	KPI x T5
1	5163	21,94%	17,99%	19,85%	20,09%	20,12%
2	3732	23,31%	17,31%	20,50%	19,00%	19,88%
3	5807	21,63%	19,37%	19,10%	20,82%	19,08%
4	4835	23,10%	20,41%	15,16%	20,87%	20,46%
5	4790	20,88%	20,31%	19,60%	20,13%	19,08%
6	5207	19,65%	20,13%	19,93%	19,97%	20,32%
7	5758	18,18%	16,64%	18,46%	16,83%	30,06%
8	4444	19,04%	18,14%	28,38%	30,56%	3,89%
9	4454	18,68%	38,33%	14,95%	9,95%	18,10%
10	6150	20,26%	5,56%	26,33%	23,50%	24,36%
11	4745	8,45%	25,10%	23,56%	22,11%	20,78%
12	3966	23,40%	21,53%	19,97%	18,33%	16,77%
13	6604	22,82%	21,11%	19,84%	17,82%	18,41%
14	6680	22,98%	21,60%	19,70%	18,50%	17,22%

The next KPI#5 measures the efficiency of the stacker crane during auxiliary handling, which includes pre and post-retrieval and storage operations (hence, during free movement within the warehouse area). It is quantified as the ratio between erroneous movements and the total number of movements. However, as evident, the KPI is quite low, indicating a high machine efficiency in work routing.

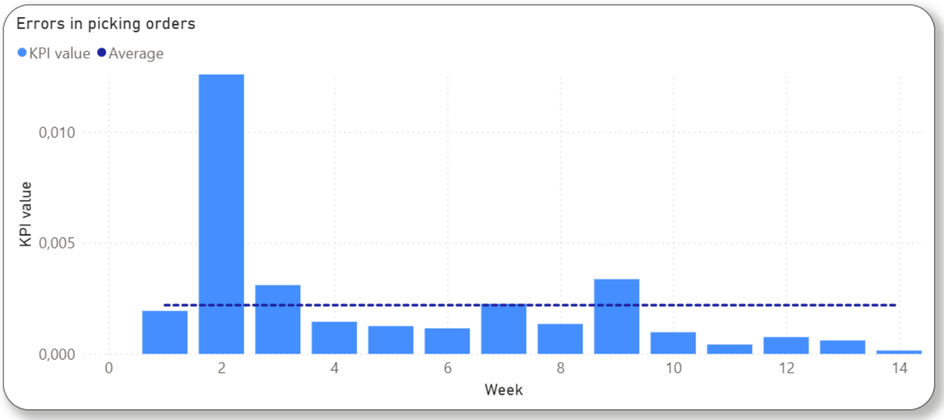

Fig. 3. KPI#5: Withdrawal tasks canceled due to machine errors

Stacker cranes are automated devices that, when not actively in use, go into standby (idle), still consuming a portion of energy that should be minimized. KPI#6 considers the incidence of idle times on the total number of movements and provides information about how often individual stacker cranes go into standby during retrieval or storage operations. Identifying the worst-performing KPIs allows for the analysis of logistics processes affected by inefficiency and, subsequently, making the necessary corrective decisions. Assuming a threshold value for KPI#6 equal to 15%, it is evident from the trends reported in Fig. 4 that only three stacker cranes in three different weeks spent energy in idle mode.

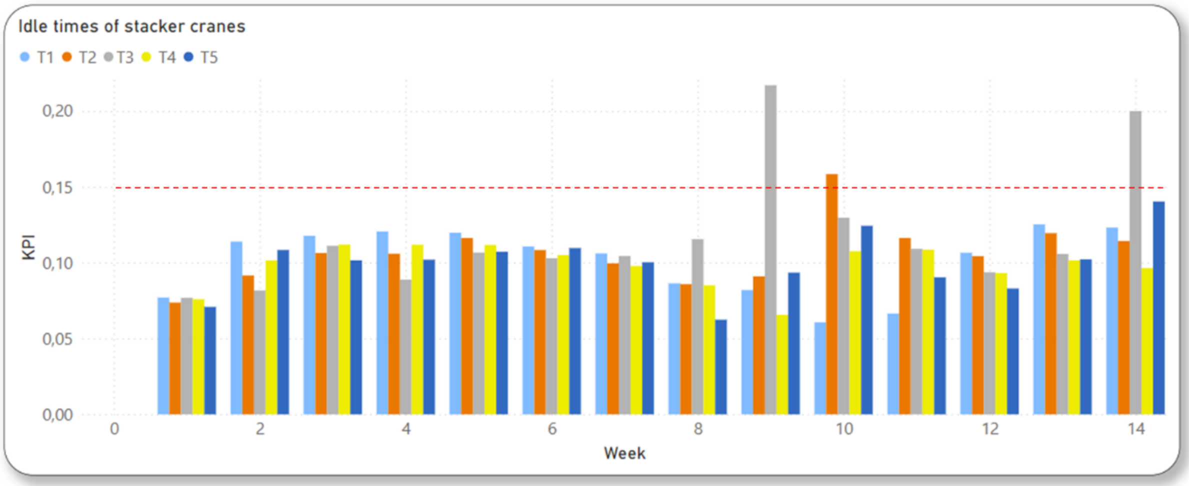

Fig. 4. KPI#6: Idle time of stacker cranes

The last KPI (KPI#7) describes the incidence of the duration of long-lasting activities (those exceeding 01:30:00 hours, according to the specific case study) on the total activities. These activities represent the period from the arrival of a truck at the loading bay to the completion of loading. Optimizing the efficiency of this operation is crucial because trucks at the loading bays need to keep their engines running to maintain the appropriate temperature for the food products being loaded. Identifying the slowest loadings allows for taking the necessary precautions. Table 5 reports the value of KPI#7. According to this KPI, the worst weeks are number 1 and number 10, with an incidence of very long operations of about 50%. This observation allows the company to identify the weeks that are less environmentally friendly compared to others but does not suggest a different strategy for reducing the value. A reduction of these values could be pursued only by changing the way loading operations are performed or the facilities that the operators can use during the loading phase.

Table 5. KPI#7: Call/dock to door time vs. good issue time

Week	Number of tasks with long duration	Number of total amount of tasks	KPI
1	92	159	0,579
2	60	123	0,488
3	69	174	0,397
4	46	145	0,317
5	53	146	0,363
6	69	162	0,426
7	58	156	0,372
8	33	90	0,367
9	31	91	0,341
10	90	174	0,517
11	50	141	0,355
12	28	122	0,230
13	40	199	0,201
14	51	212	0,241

4. Conclusions

In this work, a preliminary attempt to create a dashboard of indexes capable of measuring the performance of a storage location, both from a general efficiency and environmental standpoint, has been undertaken. Some KPIs are easily presented graphically (KPI 1, 2, and 5), while others require a deeper analytical analysis but can be made more readable by the addition of light indicators. Finally, the seven indexes can be sorted by priority by applying the AHP method. This allows each company that aims to address sustainability issues to choose the easiest way to evaluate its efforts.

Acknowledgements

This work is partly funded by the Department of Mechanical, Energy and Management Engineering (DIMEG), University of Calabria (UNICAL), through the call "Progetti di Rilevante Interesse Dipartimentale” (2022).

References

[1] M. Bartolini, E. Bottani, E.H. Grosse, Green warehousing: Systematic literature review and bibliometric analysis, J. Clean. Prod. 226 (2019) 242–258. https://doi.org/10.1016/j.jclepro.2019.04.055.

[2] J.M. Ries, E.H. Grosse, J. Fichtinger, Environmental impact of warehousing: a scenario analysis for the United States, Int. J. Prod. Res. 55 (2017) 6485–6499. https://doi.org/10.1080/00207543.2016.1211342.

[3] Z. He, P. Chen, H. Liu, Z. Guo, Performance measurement system and strategies for developing low-carbon logistics: A case study in China, J. Clean. Prod. 156 (2017) 395–405. https://doi.org/10.1016/j.jclepro.2017.04.071.

[4] I.B.S. Institution, Automation systems and integration - Key performance indicators (KPIs) for manufacturing operations management - Part 1: overview, concepts and terminology, 2014.

[5] P.-S. Chen, C.-Y. Huang, C.-C. Yu, C.-C. Hung, The examination of key performance indicators of warehouse operation systems based on detailed case studies, J. Inf. Optim. Sci. 38 (2017) 367–389. https://doi.org/10.1080/02522667.2016.1224465.

[6] M. Torabizadeh, N.M. Yusof, A. Ma’aram, A.M. Shaharoun, Identifying sustainable warehouse management system indicators and proposing new weighting method, J. Clean. Prod. 248 (2020) 119190. https://doi.org/10.1016/j.jclepro.2019.119190.

[7] R.W. Saaty, The analytic hierarchy process—what it is and how it is used, Math. Model. 9 (1987) 161–176. https://doi.org/10.1016/0270-0255(87)90473-8.