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IFAC PapersOnLine 54-1 (2021) 116–121

Development of a key performance indicator framework for automated warehouse systems

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Abstract: A Warehouse Management System (WMS) is a fundamental part of the entire supply chain's management system. Considering the importance of storing and retrieving goods, the current tendency is moving towards the complete automation of WMS and the application of new technologies. So far, many studies have been conducted on this topic, and all of them use a key performance indicator (KPI) system to evaluate the performance of the analyzed WMS. However, each study uses only a subset of KPIs, and no previous work addressed the issue of defining a formal framework for the comprehensive evaluation of automated warehouses. The aim of this paper is the definition of a formal KPI evaluation framework for WMS. The framework definition is designed following three steps: (i) the identification of available KPIs based on a systemic literature review, (ii) the ranking of KPIs based on the frequency of use in scientific research, and (iii) the classification of KPIs based both on their impact domain (economic, social or environmental) and on the company hierarchical level in which they are used.

Keywords: Warehouse Management Systems, Performance Evaluation, Capacity and Performance Evaluation, Factory and Industrial Automation, Manufacturing System Engineering

1. INTRODUCTION

The storage and retrieval of products are fundamental in manufacturing, logistics, and service delivery. This industry is currently exhibiting constant growth. According to the latest report by IMARC Group, the global warehousing and storage market reached a value of US$ 415.2 Billion in 2019 (IMARC Group, 2020). Warehouses enable the organization to continue its production throughout the year and to sell its goods whenever there is sufficient demand. The key application sectors of warehousing, such as manufacturing, retail, healthcare, construction, automotive, and technology, are expected to exhibit continuous growth in the coming years. Also, an increase in demand from the e-commerce sector is expected (Statista Research Department, 2020). The advent of online shopping has created a massive demand for warehouse space for both leading companies and new businesses. Besides, recent progress in the IT and transportation sector is also developing a positive impact on the storage and warehousing market. The increasing use of IT solutions is also making the storage and transportation of goods more efficient.

Given the importance of the sector, many efforts have been made to optimize warehouse systems. The evaluation of such systems is usually done by analyzing several key performance indicators (KPIs). KPIs are not only a performance control tool but also a planning tool that helps to plan future activities with a view to continuous improvement: deviations between expected objectives and obtained results are what management aims to minimize. The ISO 22400 standard defines the KPIs used in the production sector. This standard specifies and classifies a set of KPIs in current practice. However, ISO 22400 does not investigate the automated warehouse field (*ISO 22400-1/2*, 2014). The article aims to use the same approach defined by ISO 22400 to define a set of KPIs to evaluate the performance of an automated warehouse.

This article is structured as follows. Section 2 presents the state of the art of automated warehouse systems and the formal definition of performance indicators. Section 3 describes the methodology to define the set of KPIs, the paper selection procedure we adopted to analyze the available literature, and the weight system used to sort the KPIs based on their importance. The main indicators we found through the proposed methodology are summarized and described in Section 4. Finally, Section 5 draws conclusions and presents future works.

2. STATE OF THE ART

Warehouses are the main resources used for material handling, defined as the movement of materials to, through, and from productive processes and in receiving and shipping areas (Van den Berg & Zijm, 1999). Warehouses are divided into three types: (1) distribution warehouses, where products are collected from different suppliers and distributed to different customers; (2) production warehouses, used to store raw materials, semi-finished products, and finished products; (3) contract warehouses, i.e., a facility that performs warehousing operations on behalf of one or more customers (Van den Berg & Zijm, 1999).

Another classification is based on the automation level, and it is based on three classes: (1) manual warehouse systems, which include all the system where an operator walks or rides a vehicle along with pick locations; (2) automated warehousing systems, in which the picker occupies a fixed position, and the warehouse automatically transports the

10.1016/j.ifacol.2021.08.013

product in this area; finally, (3) automatic warehouse systems, are complete automated warehouses in which also the picking operations are performed by machines (Van den Berg & Zijm, 1999). In this paper, we focus on automatic and automated warehouses. However, the majority of this work findings can also be applied to manual warehouses.

All the warehouse systems need a constant examination of the performances. Orders could be shipped out to customers quicker and more efficiently, but if the warehouse's performances are not tracked, it is difficult to know-how. Therefore, it is fundamental to design a set of indicators that allow an overall warehouse representation (Tangen, 2004). KPIs enable the companies to establish a point of reference for the periodic improvements and help identify the areas that can directly affect the total business costs and the customer's satisfaction. For this reason, this work wants to focus on the definition and analysis of such KPIs.

A performance indicator is a numeric value that represents a complex empirical phenomenon. For adequate support to decision-making processes, it is necessary to evaluate performances to give insights to the management office. The elementary data gathered by sensors or operators must be aggregate into useful tools that are representative of system performance (Neely et al., 2005).

According to the Theory of Constraints (TOC), every activity is strictly bounded to the others in a complex system. It could be possible to estimate system performances by analyzing a few factors that should have a waterfall effect on the whole system (Goldratt, 1990). Moreover, focusing on a defined set of critical indicators allows for avoiding information overflow (Tangen, 2004). A performance evaluation system should be layered in different levels linked with the hierarchical organization levels (Cross & Lynch, 1988) in order to align the objectives of different business functions, stimulate concurrent activities, and ensure a link between the strategic vision and operations (Cross & Lynch, 1988), (Tangen, 2004).

3. CONCEPTUAL FRAMEWORK

This article aims to examine how it could be possible to evaluate an automated warehouse system by formalizing a performance framework. According to the aforementioned Theory of Constraints, we systematically reviewed literature in order to extract the most used indicators. Then we arranged those indicators in a framework focused on three points of view (social, environmental, and economic) and three hierarchical levels (strategical, tactical, and operational). These steps are described in the following paragraphs.

3.1 Methodology

Balance Scorecard (BSC), developed from the idea in (Kaplan & Norton, 1996), is one of the first models proposed to represent the efficiency and effectiveness of activities inside a complex organization. The logic behind BSC is that a single type of indicator cannot represent a company's economic results. Therefore it is necessary to provide intermediate indicators in addition to the economic ones. The BSC method aims to analyze results balancing different perspectives: financial focus, customer focus, internal business process focus, and learning/growth focus. The main aim of this paper to discover which are the main performance indicators for an automated warehouse.

According to (Neely et al., 2005) and (Ante et al., 2018), it is always possible to map and represent a complex system from a different perspective. Our methodology consists of applying this method on performance indicators obtained from a literature review process and organized according to two different perspectives: Triple Bottom Line (TBL) accounting framework and Anthony's Pyramid structure.

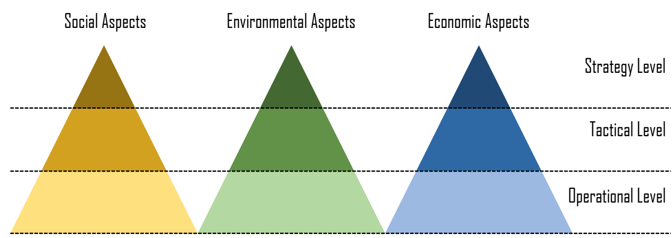

Fig 1. Indicator point of view and granularity

The TBL is a framework that evaluates a process from three distinct points of view of sustainability: social aspects, environmental aspects, and economic aspects. According to this theory, an organization should be able to perpetuate its activities over time with respect to the environment and society and by generating profit (Torabizadeh et al., 2020). Anthony's pyramid defines three different granularity levels: strategic, tactical, and operational (Gorry & Scott Morton, 1971). The strategy level is the highest and refers to aggregate information used for long-term decision-making processes. The tactical level is a middle management level that controls if the goals set by the higher level are attained in an efficient and effective manner. Finally, the operational level is at the bottom of the pyramid and refers to very detailed information that is mainly used for frequent and not very incisive decisions. Combining these two perspectives gives origin to our proposal to classify KPIs for automatic warehouses, as represented in Figure 1.

3.2 Paper Selection Procedure

The identification of the most critical KPIs for automatic warehouses starts with a systematic literature review from the database Scopus. In order to extract the most comprehensive number of documents without including off-topic articles, we define the following query: "TITLE (autom* AND warehouse)." This query allowed us to find papers with a focus on automated and automatic warehouses. Searching the same keywords inside the whole abstract would extract too many documents without a clear focus. Therefore we limited the query on the title. In June 2020, the aforementioned query retrieved 499 different articles.

To obtain and analyze the KPIs used in the extracted articles, we performed a sampling method based on two criteria: (a) quality papers selection and (b) random papers selection. An article, in order to be considered of high quality, i.e., to be classified in the category (a), must satisfy at least one of the following three conditions: (I) the paper is published in a journal classified as Q1 or Q2, (II) the paper is published in a journal with a Scimago Journal Ranking (SJR) greater than 0.5, or (III) the paper has at least 14 citations. The documents that satisfy this condition are 113 out of 499, representing 22.6% of the total volume. The documents belonging to the second group (b) are selected by a random sampling performing on the remaining 386 papers. The random group is composed of 124 documents that are 25% of the initial quantity (499).

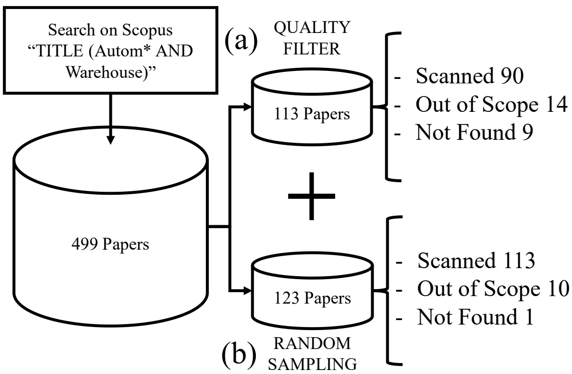

Fig 2. Methodology Scheme

After selection, the papers to be analyzed are 237, but some of them are not possible to get or read (i.g., without English translation), while some others are considered "out of scope" because they are not referring to an automatic or automated warehouse, but to topics like a data warehouse. From the high-quality group (a), we excluded 14 papers out of topic and 9 whose full text was not available. From the randomly sampled group (b), we excluded 10 papers out of topic and 1 whose full text was not available. In conclusion, we analyzed 40% of the papers obtained by the query on Scopus. These papers are 203, of which 90 from the high-quality group (a) and 113 from the randomly sampled group (b). The scheme of the analysis we conduct is summarized in Figure 2.

3.3 Weight system definition

From the 203 papers examined, a total of 70 unique indicators were extracted. In the examined sample, the average number of indicators used to evaluate a warehouse is 5.5, the maximum number is 19, while there are papers that consider only one indicator. To assess any indicator's impact, we define three metrics: the relative frequency (1), the weighted frequency (2), and the global frequency (3).

To calculate the relative frequency, we divide the indicator occurrences by total outcomes. The relative frequency f_θ^r of a generic indicator θ can be calculated as follows:

$$f_\theta^r = \frac{f_\theta^a}{K}, \quad (1)$$

where f_θ^a is the absolute frequency of the generic indicator θ, and K represents the total number of examined papers (203).

In order to take account of the paper citations in which the indicator is present, we define a weighted frequency. The weighted frequency f_θ^w of a generic indicator θ is calculated as follow:

$$f_\theta^w = \frac{\sum_{k=1}^{K} C_k B_k^\theta}{\sum_{k=1}^{K} C_k}, \quad (2)$$

where C_k is the number of citations for the k-th paper and B_k^i is a Boolean variable equal to 1 if the i-th indicator is present in the k-th paper; otherwise, it is equal to 0.

Finally, a global frequency index is calculated as a mean between the previous frequencies. In order to compare the two different values, normalization is applied, obtaining two normalized frequencies $\hat{f}_\theta^r$ and $\hat{f}_\theta^w$ on which the global index is calculated. To normalize value, we divided by the maximum value: $\hat{x}_{ij} = x_{ij}/\max(x_{ij})$, according to (Yu et al., 2009), this method satisfies all requirements for a correct normalization of positive indices. Therefore, the global frequency index G_θ of a generic indicator θ is calculated as follows:

$$G_\theta = (\hat{f}_\theta^r + \hat{f}_\theta^w)/2. \quad (3)$$

4. KPI IDENTIFICATION

The 70 selected indicators are categorized into three clusters following the TBL structure: economic, environmental, and social. Inside the three clusters, other subcategorizations were made depending on the nature of KPIs. As we expected, the economic cluster is the biggest one with 57 different indicators (almost 80% of the total). Environmental and Social Cluster have similar dimensions, 5 indicators are clustered as environment-related, and 8 indicators are clustered as Social related.

The following paragraphs describe for each cluster the list of retrieved KPIs. For each KPI, the unite measure, the relative frequency, the weighted frequency, the global index, and the hierarchy level are reported; the hierarchy level is expressed through a letter: O stands for operational, T stands for tactical, and S stands for strategic. In each table, the KPIs are arranged in descending order based on the global frequency index.

3.1 Economic KPIs

The indicators of this cluster refer to the economic value created by the organization. In particular, they evaluate the warehouse's performances that directly influence the company's costs and profits. Inside this group, we subcategorized the indicators into 5 separated subclusters:

- Generic Performances;
- Time Related Performances;
- Cost Performances;
- Information System Performances;
- Warehouse Measure.

In Table 1, the generic performance KPIs are reported. The receptivity index consists of the total number of load units that can be stored in the warehouse, i.e., its storage capacity. The selectivity index represents the picking simplicity of a load unit stored in a warehouse: the higher the index value, the better the picking condition will be. Such an index is defined as the number of directly reachable load units divided for the receptivity. The area occupation is the area occupied to stock items and needed for the storing and retrieving activities: in the case of a completely manual warehouse system, this indicator represents the stock area, while for an automatic system, it measures the entire infrastructure. According to Alp and Tan (2008), capacity flexibility refers to the ability to adjust the total production capacity in any period with the option of utilizing contingent resources in addition to permanent resources. The capacity decisions can be made in all decision-making hierarchies: strategic, tactical, and operational. The shelf occupation is like selectivity, but it refers exclusively to the percentage of space occupied on the shelves and not in the free storage areas. The object misplacement is the percentage of tasks performed in wrong positions: load unit stock in the wrong location or items retrieved from the wrong cell. Object misplacement can cause phantom stockouts, and for that reason, this KPI should be constantly monitored. The peak utilization is the system utilization when the number of items managed by the system is more than the critical value, i.e., they are enough to make the system work at its bottleneck rate. The stock balance is an index that represents the overall balance of stock volume inside the warehouse. It is calculated as a weighted sum of difference; the index grows with an increase of system ill-balance. An application of the stock balance index could be found in (Nakayama et al., 1980). Finally, the Warehouse/Exposition index is a ratio that represents how a company is using its space: it is based on the principle that space allocated for exposition (i.e., walkable by customers) generates revenue, and space allocated for storage is a cost.

Table 1. Generic Performance

	unit	f_θ^r(%)	f_θ^w(%)	G_θ(%)	
Throughput	LU/min	24.14	32.64	91.15	T
Area occupation	m^2	14.29	39.66	79.59	S
Receptivity	LU	20.20	20.49	67.67	T
Capacity Flexibility	-	20.20	16.79	63.01	S
Travel Distance	m	17.24	17.54	57.83	O
Resource Utilization	%	12.32	19.55	50.15	O
Shelf Occupation	%	5.91	5.08	18.64	O
Critical WIP	LU	7.39	2.01	17.83	T
Machine Collision	1/hour	5.42	1.69	13.36	O
Unoccupied Space	%	4.43	2.13	11.87	O
Vehicle Capacity	LU	3.45	2.76	10.62	O
Inventory Turnover	days	3.45	2.01	9.67	S
Object Misplacement	%	3.45	1.88	9.51	T
Selectivity	%	3.94	0.94	9.35	T
Positioning Accuracy	%	1.97	1.25	5.66	O
Number of Failures	1/year	1.48	1.13	4.48	T
Bottleneck Rate	LU/min	1.97	0.19	4.32	T
Peak Utilization	%	0.99	0.81	3.07	T
Unprocessed Order	%	0.99	0.63	2.83	T
Picking Accuracy	%	0.99	0.13	2.20	O
Stock Balance	-	0.49	0.19	1.26	T
Warehouse/Exposition	%	0.49	0.00	1.02	S

Table 2 reports the KPIs representing the time required by all subprocesses involved in the warehousing activities. Most of these are common and well known in the literature. For instance, task time is the time needed by the system to execute a storage or retrieval task. The service time is considered on a par with the lead time, i.e., the time that elapses from the customer's commercial request to the requested order's supply. Finally, the inventory time, usually expressed in days, measures how much time the average inventory will last. A graphical definition of the focal time indicators is represented in Figure 3.

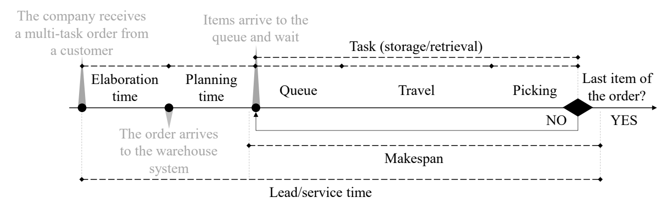

Fig 3. Graphical Definitions of Time Indicators

Table 2. Time Related Performances

	unit	f_θ^r(%)	f_θ^w(%)	G_θ(%)	
Cycle Time	min	19.70	36.09	86.31	T
Picking Time	min	14.29	35.03	73.75	O
Order Elabor.Time	min	14.29	33.33	71.61	O
Travel Time	min	19.70	17.92	63.41	O
Queue Waiting Time	hours	10.84	11.84	37.38	T
Task Time	min	10.84	10.40	35.56	O
Planning Time	hours	2.46	21.80	32.59	T
Storage Time	min	6.90	8.65	25.19	O
Retrieval Time	min	5.91	6.77	20.78	O
Inventory Time	days	6.40	4.32	18.72	T
Lead Time	days	7.39	5.89	22.73	T
Makespan	hours	2.46	6.02	12.68	T
Charging Platform Av.	%	2.46	1.44	6.92	O
Packing Time	min	1.97	1.57	6.06	T
Warehouse Av.	%	0.99	1.69	4.17	T
Charging Time	hours	1.48	0.69	3.93	O

Table 3 displays the KPIs that express the cost of different warehouse operations. The daily cost to maintain units stocked is calculated in the holding cost (i.e., energy consumptions, refrigeration, depreciation, insurance, etc.). Labor is the cost of paying employees, and it includes all employee-related expenses. Direct labor cost is the cost of activities directly involved in the production of the finished products. Indirect labor cost is not direct labor cost but is the cost of ancillary operations that makes the business possible. For instance, costs such as administrative staff, facility rental, and office supplies are needed to manage the business properly, but they are only indirectly related to the production process and are considered an indirect cost (i.e., cost overhead). Finally, space's cost includes all the costs sustained for maintaining the area in which the warehouse system's infrastructure is built.

Table 3. Cost Performances

	unit	f_θ^r(%)	f_θ^w(%)	G_θ(%)	
Management Cost	€/year	11.82	14.10	42.26	S
Storage Cost	€/task	8.37	6.14	25.09	T
Retrieval Cost	€/task	6.40	3.95	18.24	T
Inventory Cost	€	3.45	8.08	17.33	S
Holding Cost	€/day	4.93	2.57	13.44	T
Direct Labor Cost	€	3.45	2.01	9.67	S
Indirect Labor Cost	€	1.97	2.26	6.93	S
Maintenance Cost	€/year	1.48	0.13	3.22	S
Space Cost	€/m^2	0.49	0.00	1.02	S

In Table 4, the information system KPIs are reported, i.e., the measures that describe how well the ICT resources are working for the entire system to function. The use of ICT has become a robust tool driving the success of any organization's supply chains. Similarly, as explained in (Gyawu et al., 2015), inventory and warehouse management can realize many benefits if proper ICT tools are identified and used well. For this reason, monitoring information system operations through correct KPIs is fundamental.

Table 4. Information System Performances

	unit	$f_\theta^r(\%)$	$f_\theta^w(\%)$	$G_\theta(\%)$	
Image Rec. Speed	*s*	5.91	3.45	16.59	T
Algorithm Reliability	*%*	3.45	5.08	13.54	T
Response Latency	*ms*	2.46	5.33	11.82	O
Solver Iterations	-	0.99	0.25	2.36	O
QR Code Reliability	*%*	0.49	0.00	1.02	T

4.2 Environmental KPIs

Activities, products, and services of an organization that interacts with the environment are called "environmental aspects," which can have a negative or positive impact on the environment. Typically, aspects can include emissions to air, discharges to water, and waste generation, which can generate environmental and health consequences such as global warming, water pollution, or contaminated land.

Table 5 reports the KPIs that describe the warehouse system's measures, i.e., the condition under it works, like temperature or humidity and barometric pressure. These measures can directly or indirectly impact the environment.

Table 5. Warehouse Measures

	unit	$f_\theta^r(\%)$	$f_\theta^w(\%)$	$G_\theta(\%)$	
Temperature	*°C*	1.48	0.11	3.03	O
Barometric Pressure	*mmHg*	1.48	0.08	2.79	O
Humidity	*g/m^3*	0.99	0.10	1.91	O
Roof Temperature	*°C*	0.99	0.01	1.12	T
Pollutant/Dirty Conc.	*$\mu g/m^3$*	0.49	0.06	0.55	T

Finally, the environmental aspects cannot miss the indicators that measure the direct impact that this system has on the environment: energy consumption, emissions, and any type of pollution. The percentage of energy recovery represents the percentage of energy generated by the warehouse divided by the total energy consumed. Finally, passive consumption is the average power consumption when the system is on but inactive. The described indicators are presented in Table 6. The analysis of the energy consumption of automated warehouses is increasing interest in the research. One application of similar KPIs can be found in (D'Antonio et al., 2019).

Table 6. Emission. Waste and Environmental Commitment Indicators

	unit	$f_\theta^r(\%)$	$f_\theta^w(\%)$	$G_\theta(\%)$	
Energy Consumption	*kWh*	14.78	10.03	43.25	T
Energy Recovery	*%*	7.39	7.14	24.31	T
Pollutant Emission	*g/hour*	3.45	4.07	12.28	S
Passive Consumption	*kWh*	3.94	1.07	9.51	T
Vehicle Autonomy	*hours*	1.48	0.25	3.38	T

4.4 Social KPIs

Companies interact with different social entities, such as their employees, customers, supply chain partners, communities, and the general public (Benoît et al., 2013). Based on activities concerning social sustainability and the ISO 26000 (Hemphill, 2013), companies are responsible for considering their impact on their human resources and the human society in which they are immersed.

As we expected, not many indices have been found in the literature for this category. The ones we found mainly measure the operator's safety and how much the warehouse system is based on human work or automation. Future work will be carried out to have several indices comparable to the economic one. Social KPIs are reported in Table 7.

Table 7. Labour Practice. Decent Work and Social Responsibility Indicators

	unit	$f_\theta^r(\%)$	$f_\theta^w(\%)$	$G_\theta(\%)$	
Human Utilization	*%*	5.42	1.88	13.59	O
Human Error	*1/year*	2.96	4.89	12.28	O
Work Safety	-	2.46	1.19	6.60	S
Human Activity Time	*FTE*	2.46	1.13	6.52	T
Machine Safety	-	2.46	0.69	5.97	T
Noise	*dB*	0.99	0.44	2.59	O
Activity Automation	*%*	0.49	0.00	1.02	S
Operators per Area	*$1/m^2$*	0.49	0.00	1.02	T

5. CONCLUSIONS

This paper shows the results obtained by analyzing KPIs for automatic warehouse systems. Differently from previous works, this is a systematic and quantitative search of KPIs used in this sector to supply to the experts of the field a complete and ranked list of all the usable indicators to optimize a warehouse system for manufacture and logistics. These results have been obtained by reading a significant sample of articles that we have considered inherent to the topic. However, this sample represents less than half of the total amount of published papers on this subject. This limit brings directly to two future improvements: analyzing all the accessible articles and using information not limited to the scientific literature.

Regarding the second point, the authors think it will be necessary to identify additional KPIs based on industrial companies' knowledge operating in the logistics and manufacturing sectors. For this reason, a survey is under development to collect the suggestions of the workers in different hierarchy levels of the industrial organizations. The result of this survey will be used as a validation tool for the analysis carried out.

Another additional work consists of choosing the most suitable derived indicator to rank the KPIs under analysis. Many experts consider the maximum function the best aggregator for measures like the relative frequency and the weighted frequency in the literature. This means that a more profound reflection and more detailed analysis must be done in this direction. Once chosen the best, the ranking methodology will be inserted in the tools used to aggregate the warehouse indexes. Such integration will require elevated efforts and most probably will not lead to a single indicator but to the creation of a set of indices that derive from measures classified based on the groups identified in this article and the strategic, tactical, and operational levels.

Finally, another possible future improvement is the use of purely quantitative methods to analyze the results. For example, through data processing techniques, it is possible to cluster the indexes based on their citations in the research work and identify the main applications in different types of work, such as optimization, simulation, or machine learning models.

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