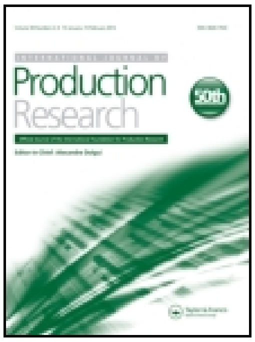

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Warehouse performance measurement: a literature review

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As the supply chains get more complex, the variety of indicators and tools to measure warehouse performance has also increased. Furthermore, the metrics that are used for performance evaluation are assessed in different manners and hence there is not clear definition for some of these metrics. To address these issues, this literature review focuses on operational warehouse performance measurement, for which the warehouse managers need to carry out periodic analysis. Using the content analysis method, performance indicators are acquired from selected papers and are classified according to time, cost, quality and productivity dimensions. The contributions of this literature review are as follows: we present a synthesis of the literature on operational warehouse performance, we provide the definitions for the performance indicators and a framework to demonstrate their boundaries and, finally, based on the literature analysis, we also provide some discussions on current trends in warehouses and propose future research directions on warehouse performance evaluation.

Keywords: warehouse performance; indicators; logistics performance; warehouse management; review

1. Introduction

The strategic role of warehouses is well recognised in a supply chain (see Dolgui and Proth 2010). Due to the increasing complexity of logistics networks, the warehouse performance analysis has become an important issue (Wu and Dong 2007). The performance analysis has the objective of helping managers to evaluate the performance of the enterprise and to make decisions in consequence. As for any manager, the warehouse manager also uses performance analysis tools and techniques to assess the performance of his warehouse.

Warehouse performance evaluation has been explored in different ways by researchers. These works differ from one another with respect to the objectives (long- or short-term decisions), the way to measure these objectives (variety of performance indicators), the type of warehouse systems (distribution centre, cross-dock platforms, etc.), the focus area inside the warehouse (storage, picking, etc.) and the tools used for measurement (statistical tools, mathematical programming, etc.). Regarding all this diversity, there is not a consensus of a group of measures used to assess warehouse performance (Keebler and Plank 2009). Therefore, it is not very easy for the managers to choose the most appropriate indicators to supervise the warehouse.

In this context, this work presents a structured analysis of the literature on warehouse performance evaluation. The aim is to synthesise the indicators utilised in warehouse performance analysis, providing clear definitions and delimitations of them. We will focus only on operational warehouse performance, i.e. the periodic performance evaluation of warehouse operations.

Many state-of-the-art articles are already available in the literature on various aspects of the warehouse management. For example, the general concepts and technologies can be found in Dolgui and Proth (2010). Methodologies and optimisation tools on specific warehouse problems, such as throughput and storage optimisation, warehouse design, routing and order picking problems, are already discussed in previous state-of-the art articles (Cormier and Gunn 1992; De Koster, Le-Duc, and Roodbergen 2007; Gu, Goetschalckx, and McGinnis 2007, 2010). These review articles address warehouse performance on strategical and tactical decision-making and we observe that the concepts, methodologies, technologies and tools are well documented in the literature. In order to design management tools and optimisation methods, we need to identify the performance metrics of interest to take into account in these models and our work helps in addressing this issue. To the best of our knowledge, no review papers focusing specifically on performance measurement for short-term warehouse management is found in the literature and this article aims to fill this gap.

This paper differs from the prior literature reviews: by using a structured research process including content analysis, which is a systematic way to extract information from papers, transforming it in summarised results; and by focusing particularly

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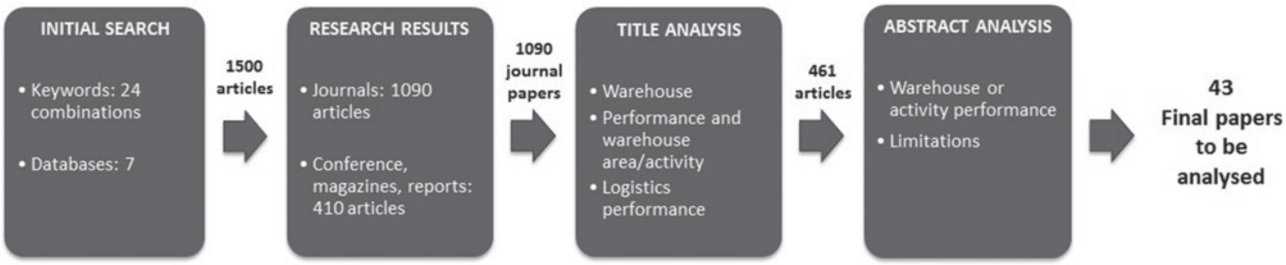

Figure 1. Bibliography research scheme.

on operational warehouse performance evaluation. To make clear the interpretation of warehouse performance management, we refer to the performance analysis as ‘the periodic measurement and comparison of actual levels of achievement with specific objectives, measuring the efficiency and the outcome of corporation’ (Lu and Yang 2010). Also, in the following discussion, the terms ‘metric’, ‘performance measure’ and ‘performance indicator’ are used as synonyms, as commonly done in the literature (Franceschini et al. 2006).

The organisation of the paper is as follows: Section 2 details the research methodology and Section 3 demonstrates the content analysis results. Section 4 classifies the performance indicators found in the papers as direct and indirect indicators. The direct performance indicators are synthesised in Section 4.1 with their definitions; the indirect indicators are presented in Section 4.2. In order to clarify the boundaries of direct indicators, Section 5 presents a framework positioning the measures according to their activity and dimension classification. The future research directions are given in Section 6 and Section 7 shows the conclusions of the work.

2. Research methodology and delimitations

The process of collecting and selecting the papers, which determines the bibliographical portfolio (or paper database, as used in this work), is based on ProKnow-C (Knowledge Development Process-Constructivist) methodology. Examples of papers using this technique are Silva da Rosa et al. (2012) and Ensslin et al. (2014). Figure 1 describes the steps performed in this work to define paper database. In Figure 1, the ‘Initial Search’ phase, we define a list of relevant keywords used for the database search (see Table 1). The subtable on the upper left corner of Table 1 demonstrates the databases searched and the subtable on the upper right corner shows the main keywords utilised. The lower half of Table 1 presents all 24 possibilities of ‘Keywords Combinations’ tested in all databases. The initial search did not limit publication year and document type; the only limitation was the results published in English language. This initial search resulted in 1500 articles, where 1090 were from journals and 410 from conferences, magazines and reports. Documents from conferences, magazines and reports not always report all informations about the research due to the space limitation. Therefore, to maintain consistency, only journal publications are used in our analysis.

Analysing the article’s publication year, we found that the first publication about warehouse performance appears in 1970s with the work of Lynagh (1971). But the number of relevant papers for this literature review available in databases up to 1990 are really rare. We can cite just the works of Khan (1984) and Svoronos and Zipkin (1988) as examples. Thus, we restricted our study on publications from 1991 up to 2012, in accordance with their representativeness. This range of years offers sufficient support to make conclusions from the results of content analysis.

Following the steps presented in Figure 1, in the third phase, the journals articles are filtered by considering that their titles contain the keywords: (i) warehouse or similar (Distribution Center, Facility Logistics, Logistics Platforms and Cross Docking); (ii) the words ‘performance’ or ‘management’ or ‘evaluation’ and the warehouse area/activity and (iii) logistics management and logistics performance measurement. The review papers treating different warehouse issues are also retained since they could give some contribution for the warehouse management. At this stage, the number of articles are narrowed down to 461 papers.

Finally, the abstract of these articles were analysed. In this phase, the papers were filtered according to their relationship to warehouse performance. In case of doubt on the paper’s content, the full text was also verified. Note that the final database (43 articles) does not include the works that are directly related to:

- Economical analysis about warehouse construction and/or investment;
- WMS evaluation (technical features) and implementation;

Table 1. Databases and keywords used for papers research.

Databases	Keywords
Scopus (scopus.com)	Warehouse/distribution centre
Emerald (emeraldinsight.com)	Facility logistics/logistics platforms
EBSCO (ebscohost.com)	Performance/efficiency
Wiley (onlinelibrary.wiley.com)	Evaluation/measurement/assessment
Science direct (sciencedirect.com)	Logistics
Web of science (webofknowledge.com)	Operation management
Compendex (engineeringvillage2.com)	Metrics/index/KPI
Keyword combinations	Combinations
(Performance measur[a]/assessment) AND (warehouse/distribution centre/logistics platform)	6
(Performance measur[a]/assessment) AND (warehous[a]/DC) AND (logist[a])	4
(Performance evaluation) AND (distribution centre/logistics platform)	2
(Warehouse/distribution center / logistics platforms) AND (performance)	3
Warehouse operations management	1
(Warehouse/distribution centre) AND (logistics) AND (index)	2
(Warehouse efficiency) AND (measur[a])	1
(Performance) AND (metric) AND (warehouse)	1
warehouse overall performance	1
(Warehouse management) AND (logistics)	1
(Warehouse) AND (logistics) AND (KPI)	1
(Logistics) AND (performance)	1

[a]Words trunked for database search.

- Warehouse design;
- Warehouse location;
- SC optimisation (two or three echelons);
- Policy choice for storage and picking activities;
- Distribution network optimisation.

The justification of not including the subjects cited above is that they treat strategical and tactical decision-making (e.g. warehouse location, design) and not the operational performance management which is the main focus of our literature review (e.g. unloading time, labour productivity).

Only the works using decision-making for periodic warehouse management are taken into account. As the decision support tools are considered as means to manage the performance, the articles presenting decision support systems (DSS) to help warehouse manager's decisions (Lam, Choy, and Chung 2011; Lao et al. 2011, 2012) and the articles treating the system influence on enterprise performance (Autry et al. 2005; Karagiannaki, Papakiriakopoulos, and Bardaki 2011) were included in this review as well.

The final database is used to make two different analysis as shown in Figure 2: first, we provide a descriptive analysis of all 43 papers in Section 3. That is, a quantitative evaluation of the general characteristics of the articles. The second analysis, presented in Section 4, focuses on the performance indicators used in warehouses. In the final database, only 35 articles present performance indicators. Thirty two among these thirty-five papers discuss the performance indicators which can be expressed by some simple equations, being 'measured directly'. We qualify them as 'direct indicators'. We address this kind of papers in Section 4.1. Sixteen articles among thrity five assess performance indicators in an 'indirect way'. It means that these indicators represent more complex concepts which are difficult to measure by simple expressions like ratios. Therefore, more sophisticated statistical tools (e.g. regression analysis) are used to assess them. These performance indicators are named as 'indirect indicators' and an analysis of them is provided in Section 4.2.

The papers of the final database are explored based on content analysis research method. Content analysis is an observational research method that is used to systematically evaluate the literature in terms of various categories, transforming original texts into analysable representations (Krippendorff 2004; Pokharel and Mutha 2009). Content analysis can be carried out in two steps: definition of variables analysed and the unitisation of them. The definition of the variables depends on research objectives. In this article, the variables extracted from papers are: work methodology, mathematical tools utilised, warehouse activities and indicators used to assess performance. The second step to be performed is the unitisation. Krippendorff (2004)

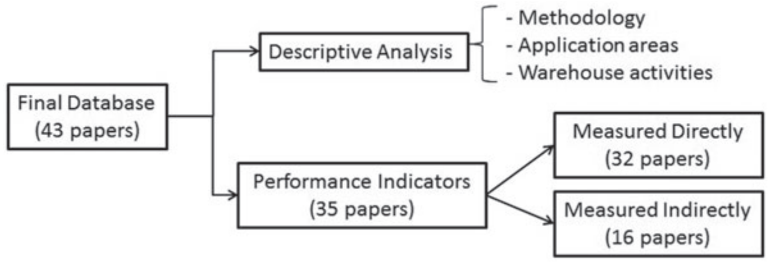

Figure 2. Analysis realised in this paper.

defines unitising as 'the systematic distinguishing of segments of text that are of interest to an analysis'. That is, in the final paper database, we look for the variables and when they are not explicit in the text some predefined rules are used to classify the information acquired from the text. In order to maintain consistency in this procedure and to avoid biases, this step is conducted by only one of the authors of this paper (this procedure is usually adopted when performing content analysis Krippendorff 2004). This principal reader has filled the variables as presented in each study on a spreadsheet. This master listing of findings is then analysed by all authors.

The results of the spreadsheet analysis are given in the next sections.

3. Results of content analysis

This section shows the content analysis by using tables which present some quantitative outcomes resulted from paper's classification. They present patterns identified from the data, allowing to categorise the warehouse performance literature. More specifically, Section 3.1 introduces paper methodologies and Section 3.2 presents the warehouse activities most studied in the works.

3.1 *Work methodology*

The articles are classified based on five research methodologies (see Seuring and Muller 2008): review, case study, survey, conceptual and mathematical papers. A paper is classified as quantitative/mathematical work if simple tools (e.g. mean, percentage and standard deviation, etc.) as well as more sophisticated tools (e.g. linear regression, analytical model, simulation) are used. A conceptual work develop or discuss theories; there is no practical applications or results implemented in practice. The case study is a work that develops a theory and verifies the results in practice; or it is a paper solving some specific problem verified in practice. Survey is a research paper that usually carries out a questionnaire with a lot of companies/persons to make conclusions about a subject. Each paper could be classified in more than one methodology, depending on its characteristics. The review papers are studied separately to complete the discussions about specific issues. The results of this classification are given in Table 2.

The quantitative works represent 74.4% of the total papers (i.e. survey/mathematical (39.5%), case study/mathematical (30.2%) and conceptual/mathematical (4.7%)). Due to their significance, we detailed the quantitative works according to the type of method used (see Table 3). The basic statistics are further detailed as ANOVA and F test; p value and σ; and Others. We note that some papers use more than one mathematical tool. In such papers, most of the time, the basic statistics are combined with other tools. For example, factor analysis or regression analysis is combined with the basic statistics to describe relations among warehouse activities (10 out of 32 papers). Another example is the use of statistics to compare the simulation results. The next subsections present which kind of industries and warehouse activities were most representatives according to the database.

3.2 *Warehouse activities*

Warehouses could have different activities according to product specification, customer requirements and service levels offered. For De Koster and Warffemius (2005), the complexity of the warehouse activities depends mainly on: (i) the number and variety of items to be handled; (ii) the amount of daily workload to be done; and (iii) the number, nature and variety of processes necessary to fulfill the needs and demands of the customers and suppliers. Even though differences may exist among the warehouse activities, they were defined as: receiving, storage, order picking, shipping (van den Berg and Zijm 1999). In what follows, we will use this generic classification. Some studies related to warehouse performance also mention

Table 2. Work methodology – total 43 articles.

Review	Case study	Survey	Conceptual	Mathematical	NP[a]	%	Articles
		✓		✓	17	39.5	Kiefer and Novack (1999), Ellinger, Ellinger, and Keller (2003), Autry et al. (2005), De Koster and Warffemius (2005), Voss, Calantone, and Keller (2005), Sohn, Han, and Jeon (2007), De Koster and Balk (2008), Park (2008), O'Neill, Scavarda, and Zhenhua (2008), Menachof, Bourlakis, and Makios (2009), Forslund and Jonsson (2010), Lu and Yang (2010), De Marco and Giulio (2011), Johnson and McGinnis (2011), Markovits-Somogyi, Gecse, and Bokor (2011), Banaszewska et al. (2012), Yang and Chen (2012)
	✓			✓	13	30.2	Wu and Hou (2009), Manikas and Terry (2010), Matopoulos and Bourlakis (2010), Wang, Chen, and Xie (2010), Johnson, Chen, and McGinnis (2010), Cagliano et al. (2011), Lam, Choy, and Chung (2011), Goomas, Smith, and Ludwig (2011), Karagiannaki, Papakiriakopoulos, and Bardaki (2011), Lao et al. (2011), Sellitto et al. (2011), Lao et al. (2012), Ramaa, Subramanya, and Rangaswamy (2012)
✓					5	11.6	Cormier and Gunn (1992), van den Berg and Zijm (1999), De Koster, Le-Duc, and Roodbergen (2007), Gu, Goetschalckx, and McGinnis (2007), Gu, Goetschalckx, and McGinnis (2010)
	✓				3	7.0	Spencer (1993), Gunasekaran, Marri, and Menci (1999), Gallmann and Belvedere (2011)
			✓		3	7.0	Mentzer and Konrad (1991), Rimiene (2008), Bisenieks and Ozols (2010)
			✓	✓	2	4.7	Yang (2000), Saetta et al. (2012)
			Total		43	100.0	

[a]Number of publications.

Table 3. Mathematical tools.

Math tool	NP[a]	%
(1) Basic statistics	20	40
(1.1) ANOVA and/or F test	8	16
(1.2) σ[b], *p value*	7	14
(1.3) Others	5	10
(2) Regression analysis	6	12
(3) Factor analysis	5	10
(4) DEA[c]	5	10
(5) Analytical model	4	8
(6) Simulation	4	8
(7) Others	6	12
Total	50	100

[a]Number of publications.
[b]Standard deviation.
[c]Data envelopment analysis.

the delivery process (5 articles are identified). In some cases, the delivery could be considered as a warehouse responsibility in the metrics sense. This is why, the delivery is also considered as a warehouse activity in our analysis. However, we did not include other warehouse activities such as replenishment (transfer of products from the reserve storage to the picking

Table 4. Warehouse activities studied.

Receiving	Storage	Picking	Shipping	Delivery	NP	%	Articles
✓	✓	✓	✓		12	27.9	Cormier and Gunn (1992), van den Berg and Zijm (1999), Gunasekaran, Marri, and Menci (1999), Kiefer and Novack (1999), Gu, Goetschalckx, and McGinnis (2007), Rimiene (2008), Karagiannaki, Papakiriakopoulos, and Bardaki (2011), Cagliano et al. (2011), Gallmann and Belvedere (2011), Lao et al. (2012), Yang and Chen (2012), Ramaa, Subramanya, and Rangaswamy (2012)
✓	✓	✓	✓	✓	5	11.6	Mentzer and Konrad (1991), Ellinger, Ellinger, and Keller (2003), Wu and Hou (2009), Lu and Yang (2010), Sellitto et al. (2011)
		✓	✓		5	11.6	Spencer (1993), Autry et al. (2005), De Koster and Balk (2008), Johnson, Chen, and McGinnis (2010), Johnson and McGinnis (2011)
	✓	✓	✓		3	7.0	De Koster and Warffemius (2005), O'Neill, Scavarda, and Zhenhua (2008), Saetta et al. (2012)
		✓			3	7.0	De Koster, Le-Duc, and Roodbergen (2007), Lam, Choy, and Chung (2011), Goomas, Smith, and Ludwig (2011)
	✓	✓			2	4.7	Bisenieks and Ozols (2010), Gu, Goetschalckx, and McGinnis (2010)
✓	✓	✓			2	4.7	Manikas and Terry (2010), Wang, Chen, and Xie (2010)
✓		✓	✓		2	4.7	Menachof, Bourlakis, and Makios (2009), De Marco and Giulio (2011)
	✓				2	4.7	Sohn, Han, and Jeon (2007), Park (2008)
✓			✓	✓	1	2.3	Matopoulos and Bourlakis (2010)
✓		✓			1	2.3	Voss, Calantone, and Keller (2005)
				✓	1	2.3	Forslund and Jonsson (2010)
			✓		1	2.3	Markovits-Somogyi, Gecse, and Bokor (2011)
		✓	✓	✓	1	2.3	Banaszewska et al. (2012)
	✓			✓	1	2.3	Yang (2000)
✓	✓				1	2.3	Lao et al. (2011)
				Total	43	100.0	

area) and sorting (if the picking is performed in batches, the products could be sorted before packing), because the database papers do not present performance indicators for these activities. As each of these five activities can be divided into several sub-activities, we consider the following definitions and boundaries to be used in our analysis:

- Receiving: operations that involve the assignment of trucks to docks and the scheduling and execution of unloading activities (Gu, Goetschalckx, and McGinnis 2007);
- Storage: materials movement from unloading area to its designated place (Mentzer and Konrad 1991; Yang and Chen 2012);
- Order Picking: the main and labour-intensive activity of warehouses (Dotoli et al. 2009), consisting in order preparation;
- Shipping: involves scheduling and assignment of trucks to docks (Gu, Goetschalckx, and McGinnis 2007), the orders packing after picking and the loading of trucks;
- Delivery: transit from the warehouse to the customer.

Based on the above warehouse activities, the selected articles are analysed and classified as in Table 4. This table helps identifying the major research areas by warehouse activities.

A major observation we make out of Table 4 is that almost 40% of the articles consider all major activities of the warehouse at the same time (rows 1 and 2 of Table 4). The articles mentioned in the second row, except Mentzer and Konrad

(1991), are on the employee performances. According to van den Berg and Zijm (1999) and Mentzer and Konrad (1991), the labour tasks impact all warehouse activities. Therefore, we choose to classify these papers as impacting all activities.

Another interesting insight is the fact that the majority of the articles include the picking activity in their studies. This is quite relevant with industrial observations and shows a certain maturity in the works undertaken. The order picking process is the most costly among all warehouse activities, because it tends to be either very labour-intensive (manual picking) or very capital intensive (automatic picking). More than 60% of all operating costs in a typical warehouse can be attributed to order picking (van den Berg and Zijm 1999; Gu, Goetschalckx, and McGinnis 2007; Manikas and Terry 2010).

In the next section, we present further analysis on the selected articles. But this time, the analysis is focused specifically on the indicators used to asses the warehouse performance.

4. Warehouses performance indicators

The traditional logistics performance measures include 'hard' and 'soft' metrics. The first one treats quantitative measures such as order cycle time, fill rates and costs; the second deals with qualitative measures like manager's perceptions of customer satisfaction and loyalty (Chow, Heaver, and Henriksson 1994; Fugate, Mentzer, and Stank 2010). The 'hard' metrics are easily computable with some simple mathematical expressions while the soft metrics require more sophisticated tools of measurement (e.g. Regression analysis, fuzzy logic, Data Envelopment Analysis, etc.). In this paper, we will refer to the 'hard' metrics as *direct* indicators and the soft ones as *indirect* indicators.

4.1 *Direct warehouse performance indicators*

All direct indicators extracted from papers are classified according to four performance evaluation dimensions, commonly used in industries. Each indicator can be only assigned to a single dimension at time. These are: *time* (Chan and Qi 2003; Frazelle 2001; Gallmann and Belvedere 2011; Gunasekaran and Kobu 2007; Mentzer and Konrad 1991; Neely, Gregory, and Platts 1995; Spencer 1993), *quality* (Frazelle 2001; Gallmann and Belvedere 2011; Neely, Gregory, and Platts 1995; Stainer 1997), *cost* (Beamon 1999; Cai et al. 2009; Chan and Qi 2003; Keebler and Plank 2009; Mentzer and Konrad 1991; Neely, Gregory, and Platts 1995) and *productivity* (Chan and Qi 2003; Frazelle 2001; Gallmann and Belvedere 2011; Keebler and Plank 2009; Stainer 1997). We note that some works prefer to use *flexibility* instead of *productivity* as the fourth dimension (Beamon 1999; Gunasekaran and Kobu 2007; Neely, Gregory, and Platts 1995; Stainer 1997), defining it as the 'ability to respond to a changing environment' (Beamon 1999). However, flexibility may be intangible and difficult to measure (Gunasekaran and Kobu 2007) in some cases. We present in Section 4.2 that flexibility is preferably measured indirectly rather than directly. Consequently, in this section, productivity will be used as a dimension for direct warehouse performance indicators.

The following procedure is used for the classification. Initially, all the direct indicators found in the selected papers are listed. Once the list is completed, two types of aggregations are made: (i) similar indicators are regrouped; (ii) very specific metrics are included in more generic ones. One example of this second group is the work by Manikas and Terry (2010) mentioning the indicator 'time of quality control in receiving'. This can be considered as a portion of the 'receiving operation time'. Therefore, we include this indicator together with the class of indicators called the 'receiving time'. Finally, the indicators are organised according to what they measure (time, quality, cost or productivity). We note that, for the sake of uniformity throughout this literature review, the classifications presented in this article are based on our interpretation, instead of the original category proposed by the selected papers. For example, Banaszewska et al. (2012) consider the 'number of consignment processed per warehouse employee' as a productivity indicator. Indeed, the measure is a productivity indicator. In this review, we propose a sub-category, called the *labour productivity* and Banaszewska et al. (2012) appears in this category (see Table A2). Another example is the article by Saetta et al. (2012), where the authors measure the customer satisfaction as 'the percentage of orders on time' and we classify the article under a broader indicator which is the 'on time delivery' (see Table A2). The results from this analysis are given in Table 5, which demonstrates all performance indicators comprised in a dimension. The third column of Table 5 shows the number of publications containing each specific indicator. The discussions about the results of Table 5 are presented in the next sections.

Throughout the classification process, we have observed several problems: it is neither easy to draw straightforward frontiers for the indicators, nor the measurements are clearly defined. For example, we found two indicators with different names but measured the same way. Conversely, some metrics have the same name but they are measured differently. Moreover, whereas in some papers, the measurements are explicit; in some others, only the indicator's names are given.

To address these issues, the next sections present indicator definitions in Tables 6–9. The definitions come initially from paper database. In the case where several definitions are found for a given indicator, we show both in the table (e.g. order lead time in Table 6). In the case where no definitions are given, we look for these definitions in Warehouse Education and Research Council (WERC 2008) database (available at www.werc.org) (e.g. picking accuracy in Table 7). Finally, when the

Table 5. Direct warehouse indicators found in literature.

Dimensions	Indicator name	NP[a]
Time	Order lead time	9
	Receiving time	5
	Order picking time	4
	Delivery Lead Time	3
	Queuing time	2
	Putaway time	2
	Shipping time	2
	Dock-to-stock time	2
	Equipment downtime	1
Quality	On-time delivery	10
	Customer satisfaction	8
	Order fill rate	5
	Physical inventory accuracy	5
	Stock-out rate	4
	Storage accuracy	4
	Picking accuracy	3
	Shipping accuracy	2
	Delivery accuracy	2
	Perfect orders	2
	Scrap rate	2
	Orders shipped on time	1
	Cargo damage rate	1
Cost	Inventory cost	7
	Order processing cost	3
	Cost as a % of sales	3
	Labour cost	2
	Distribution cost	2
	Maintenance cost	2
Productivity	Labour productivity	11
	Throughput	10
	Shipping productivity	7
	Transport utilisation	5
	Warehouse utilisation	4
	Picking productivity	3
	Inventory space utilisation	3
	Outbound space utilisation	3
	Receiving productivity	2
	Turnover	2

[a]Number of publications.

definition is neither in the papers nor in WERC database, we defined the indicators based on the best common sense that we could infer from the literature and we refer to the authors that have used these measures in their papers. For example, in Table 7, cargo damage rate is used by Lu and Yang (2010) but the indicator is not explicitly defined by the authors. Thus, for the purpose of this work, we provide an indicator definition according to the described procedure, identified by * symbol in the tables.

4.1.1 *Time related performance indicators*

The first part of Table 5 shows the time metrics which have been used in papers and their frequency. Surprisingly, order picking time is in the third position, even though (Gu, Goetschalckx, and McGinnis 2007) state that past research has focused strongly on order picking since this activity has the largest impact on the warehouse performance. One reason could be that

Table 6. Warehouse time indicators definition.

Indicator	Definition	Authors
Order lead time	Lead time from customer order to customer acceptance	Mentzer and Konrad (1991), Kiefer and Novack (1999), Rimiene (2008), Menachof, Bourlakis, and Makios (2009), Yang and Chen (2012)
	Lead time from order placement to shipment	Yang (2000), Ramaa, Subramanya, and Rangaswamy (2012)
Receiving time	Unloading time	Gu, Goetschalckx, and McGinnis (2007), Matopoulos and Bourlakis (2010)
Putaway time	Lead time since a product(s) has been unloaded to when it is stored in its designated place	Mentzer and Konrad (1991), De Koster, Le-Duc, and Roodbergen (2007), Yang and Chen (2012)
Order picking time	Lead time to pick an order line	Mentzer and Konrad (1991)
Delivery lead time	Lead times from the warehouse to customers	De Koster and Warffemius (2005)
Queuing time	Time that products wait on hold to be handled	Karagiannaki, Papakiriakopoulos, and Bardaki (2011)
Shipping time[a]	Lead time to load a truck per total orders loaded	Gu, Goetschalckx, and McGinnis (2007), Wang, Chen, and Xie (2010)
Dock to stock time	Lead time from supply arrival until product is available for order picking	Ramaa, Subramanya, and Rangaswamy (2012)
	The amount of time it takes to get shipments from the dock to inventory floor without inspection	Yang and Chen (2012)
Equipment downtime	Period in which an equipment is not functional, downtime incurred for repairs	Mentzer and Konrad (1991)

[a]This indicator is not explicitly defined in these references and we consider the definition presented in this table for the purpose of this work.

in the literature, the order picking time is more specifically treated in optimisation works, which are not considered in this review.

Table 6 presents time indicator definitions. Both order lead time and dock to stock time have two different definitions. For the order lead time, the difference between these two definitions is related to the point at which the final time is measured. In the first definition (customer perspective), it is the customer acceptance and in the second definition (warehouse perspective) is the shipment time. For dock-to-stock time, the only difference between the two definitions is that Yang and Chen (2012) do not consider inspection inside the total time from dock up to stock. It is important to note that Ramaa, Subramanya, and Rangaswamy (2012)'s definition should not be interpreted as if the indicator comprehends the inventory and replenishment times (time from the storage up to the product is picked). The authors consider that the product is available for order picking at the moment of storage. Thus, dock to stock is the time from supply arrival up to the storage in the inventory floor.

Some insights come from the analysis of Tables 5 and 6. Firstly, almost all warehouse activities are covered by at least one indicator. The only exception is the inventory time: there is no paper using an indicator to measure it (e.g. inventory coverage). Also, no author has measured the entire time spent by a product in the warehouse using one or several indicators. Mentzer and Konrad (1991) presents indicators covering most of the activities (as shown in Table A2, in Appendices) in a descriptive way; however, no measurement is done. Regarding the warehouse activities covered by indicators, for the inbound processes there are receiving and putaway times and for outbound processes picking, shipping and delivery times. Interestingly, these five indicators could be represented by just two: dock-to-stock time (for inbound process) and order lead time (for outbound process). In the case of order lead time, this indicator comprehends also administrative time beyond the ones presented (picking, shipping and delivery times) since its definition express that order lead time starts to be measured at the time the customer makes an order (see Table 6).

4.1.2 *Quality related performance indicators*

The second part of Table 5 illustrates the quality indicators used in the selected papers. We observe that the emphasis are on the 'on-time delivery' and the 'customer satisfaction'. The result corroborate with the statement of Forslund and Jonsson

(2010), that 'perfect order reflects delivery performance in a more comprehensive way, but seems not to be as widely applied as on-time delivery'.

In Table 7, the indicators are classified in five distinct groups according to A – Punctuality, B – Completeness, C – Correctness, D – Breakage and E – Customer Satisfaction. While groups C and D are related to internal operations and group E to customer-oriented results, the groups A and B can be linked to both, i.e. internal operations that are closely related to customer satisfaction. We can see that even if internal measures of correctness and breakage are the majority of indicators (with 8 indicators, see Table 5), the customer-oriented measures still remain the most used in the literature (see Table 7).

The distinction between the on-time delivery and orders shipped on time (see Table 7) resides in what is considered as the final monitoring point. If the warehouse monitors the delivery activity, it will use the on-time delivery indicator, which covers up to the time of product reception by the customer. The orders shipped on time does not include the delivery activity and stops at the moment when the products leave the warehouse.

4.1.3 *Cost related performance indicators*

For cost indicators, it is interesting to note that fewer works are recorded using this kind of measure compared to the other three dimensions (see Table A2). This could be explained by the affirmation of Gunasekaran and Kobu (2007) that the operational-level performance evaluation is mostly based on non-financial indicators, but depends always on company's characteristics and choices. Despite the strategic importance in the supply chain, warehouses have most of their activities in the operational level.

Table 5 shows that the majority of the papers mentioning cost metrics use inventory costs indicator. From this data, it is apparent that what really interests managers regarding the warehouse management costs is the inventory cost. The inventory is a 'cost generator' by nature: according to Kassali and Idowu (2007), inventory is a business activity that involves costs and risks. The risks may come from probable product losses (e.g. quality deterioration) or price uncertainty. Analysing the way that inventory costs are measured in the papers, we observe that inventory level assessed monetarily is the most employed metric (see Table 8 for inventory cost definitions). However, this is an incomplete way of measurement for inventory costs. Other expenses like holding cost and stock out penalty should also be considered (see, for instance Li, Sava, and Xie 2009; Rimiene 2008). Likewise, some other expenses like depreciation and insurance (sometimes considered in total warehouse costs) might also be included in inventory cost calculations.

Some indicators may lead to misleading interpretations. For example, the indicator cost as a % of sales could improve with an increase in sales price or a decrease in warehouse costs. The focus, in this case, should be on total warehousing costs changes.

4.1.4 *Productivity related performance indicators*

Another important dimension for the warehouse management is the productivity. Productivity can be defined as the level of asset utilisation (Frazelle 2001), or how well resources are combined and used to accomplish specific, desirable results (Neely, Gregory, and Platts 1995). It is interesting to note that some productivity indicators allow impartial comparison of different situations. For example, it is possible to compare various countries using labour productivity indicator (as defined in Table 9). Even if the average annual worked hours are different in each country, for example, Mexico 2,237 hours per year (h/y), USA 1,788 h/y and France 1,489 h/y (2013 data available at http://stats.oecd.org/), the labour productivities are still comparable.

It can be seen from Table 5 that throughput and labour productivity are the most employed metrics in warehouses. We note that the throughput is defined in two different manners in Table 9. The majority of papers define throughput relating it to time. Nevertheless, the definition by De Marco and Giulio (2011) is interesting as well because it provides a valuable way to analyse the warehouse productivity in terms of available space.

4.2 *Indirect warehouse performance indicators*

In the past, the distribution centres (DC) primarily served as warehouses with distribution functions. Nowadays, the DCs have International headquarters, call-centres, service centres or even manufacturing facilities as well (De Koster and Warffemius 2005). This evolution is the outcome of a need to provide tailored services for the customers and to gain competitive advantage. These new services require additional indicators to measure the related performance. Oftentimes, the indicators

Table 7. Warehouse quality indicators definition.

Group	Indicator	Definition	Authors
A	On-time delivery	Number of orders received by customer on or before committed date	Voss, Calantone, and Keller (2005), Forslund and Jonsson (2010), Lu and Yang (2010), Yang and Chen (2012)
	Orders shipped on time	Number of orders shipped on time per total orders shipped	Kiefer and Novack (1999)
B	Order fill rate	Orders filled completely on the first shipment	Ramaa, Subramanya, and Rangaswamy (2012)
C	Physical inventory accuracy[b]	Measures the accuracy (by location and units) of the physical inventory compared to the reported inventory	Kiefer and Novack (1999), Rimiene (2008), Wang, Chen, and Xie (2010), Yang and Chen (2012), Ramaa, Subramanya, and Rangaswamy (2012)
	Picking accuracy[b]	Accuracy of the orders picking process where errors may be caught prior to shipment such as during packaging	Rimiene (2008), Saetta et al. (2012), Yang and Chen (2012)
	Storage accuracy	Storing products in proper locations	Voss, Calantone, and Keller (2005), Rimiene (2008)
	Shipping accuracy	Number of errors free orders shipped	De Koster and Warffemius (2005), De Koster and Balk (2008)
	Delivery accuracy[a]	Number of orders distributed without incidents	Voss, Calantone, and Keller (2005), Gallmann and Belvedere (2011)
D	Stock-out rate	Number of stock products out of order	Lao et al. (2011), Yang and Chen (2012), Lao et al. (2012)
	Scrap rate	Rate of product loss and damage	Voss, Calantone, and Keller (2005)
	Cargo damage rate[a]	Number of orders damaged during delivery activity	Kiefer and Novack (1999), Lu and Yang (2010)
E	Perfect orders	Orders delivered on time, without damage and with accurate documentation	Kiefer and Novack (1999)
	Customer satisfaction	Number of customer complaints/number of orders delivered	Lao et al. (2011), Voss, Calantone, and Keller (2005), De Marco and Giulio (2011), Lao et al. (2012)

[a]This indicator is not explicitly defined in these references and we consider the definition presented in this table for the purpose of this work.
[b]Indicator definition taken from Warehousing Education and Research Council (WERC 2008). Group Definition: A – Punctuality; B – Completeness; C – Correctness; D – Breakage; E – Customer Satisfaction.

are complex; either the equations are not available or they are too difficult to calculate. The warehouse capability (Sohn, Han, and Jeon 2007), the supervisory coaching behaviour (Ellinger, Ellinger, and Keller 2003), the customer perception (De Koster and Balk 2008), etc. are some examples of these indicators. In this article, we call such indicators, the *indirect* indicators. Instead of simple and straightforward equations, some structured mathematical tools are needed to calculate the value of these indicators. Normally, these mathematical tools evaluate different kinds of information and extract correlations and/or performances from databases. Some examples of such tools used in the literature are: SEM (structured equations model), DEA (data envelopment analysis), regression analysis and canonical matrix.

The number of publications assessing each indirect indicator found in papers is listed in Table 10. The indirect indicators are evaluated differently depending on paper's objective. For example, flexibility is usually measured in association with other performance components such as time, volume and delivery. The three papers treat flexibility in the following way: De Koster and Balk (2008) ask respondents about order flexibility comparing to competitors, Lu and Yang (2010) estimate respondent perceptions of 'service flexibility to meet customers' need' as part of logistics capability and Yang and Chen (2012) evaluate flexibility by the number of emergent order handling. Due to these differences, we present next some details on the other indicator themes without giving definitions as made for the direct indicators.

Table 8. Warehouse cost indicators definition.

Indicator	Definition	Authors
Inventory cost	Total storage costs/unit Inventory level (measured monetarily)	Rimiene (2008) Cagliano et al. (2011), Gallmann and Belvedere (2011)
Order processing cost[a]	Total processing cost of all orders per number of orders	Kiefer and Novack (1999), Rimiene (2008), Ramaa, Subramanya, and Rangaswamy (2012)
Labour cost	Cost of personnel involved in warehouse operations	Cagliano et al. (2011)
Distribution cost	The mean number of vehicles and total travel distance per day provide measures of distribution costs.	Yang (2000)
Cost as a % of sales	Total warehousing cost as a percent of total company sales	Ramaa, Subramanya, and Rangaswamy (2012)
Maintenance cost	Costs of building maintenance Equipment maintenance	De Marco and Giulio (2011) Johnson, Chen, and McGinnis (2010)

[a]This indicator is not explicitly defined in these references and we consider the definition presented in this table for the purpose of this work.

- *Labour:* the results in Table 10 demonstrate the importance of employee performance in warehouses with numerous articles in the area. One reason for the importance of this subject is reported by Park (2008) who highlights that the front-line distribution centre personnel could be responsible for any task in moving products inside the distribution centre. Any service failure or inefficient performance directly increases customer-order cycle time and negatively impacts the level of service as perceived by the customers. Ellinger, Ellinger, and Keller (2003) integrate the perception of supervisors to examine the employee performance (seen by the supervisors). Voss, Calantone, and Keller (2005) show that the front-line employee performance and interdepartmental customer orientation have a positive effect on DC services. In their study, the authors consider the following variables to measure the employee performance: proper data recording, efficient trailer loading, storing products in proper locations, effective distribution operations, minimal product loss, minimal product damage, high productivity and high performance. Wu and Hou (2009) propose a model for the analysis of employee performance trends. This model is intended to determine the employees to reward or to train. Goomas, Smith, and Ludwig (2011) evaluate the order selectors' performance after the implementation of an overhead scoreboard that informs the number of completed tasks, the number of tasks in queue and the team performance against the engineered labour standards. Park (2008) study the relationship between the store-level performance and the composition of the workforce. Workforce composition is expressed as the full-time and the part-time employees.
- *Value Adding Logistic (VAL) Activities:* can be measured by the number of VAL activities offered by the company and performed in warehouses. De Koster and Balk (2008) divide VAL activities in low and high levels. The activities adding low value to the product include labeling, putting manuals, kitting; whereas high VAL activities consist of sterilisation, final product assembly, product installation, etc.

  For Gu, Goetschalckx, and McGinnis (2007), the roles of VAL activities also include: buffering the material flow along the supply chain to accommodate variability caused by factors such as product seasonality and/or batching in production and transportation; consolidation of products from various suppliers for combined delivery to customers. The survey of O'Neill, Scavarda, and Zhenhua (2008) confirm that VAL activities have become common activities in warehouses. However, on the average, only five per cent of floor area is dedicated to these activities, indicating that VAL activities are minor in nature.
- *Inventory Management:* is an area where the automation support for activities have increased. The relations between inventory management and warehouse automation are getting closer to each other. Wang, Chen, and Xie (2010) propose a digital warehouse management system (DWMS) based on RFID to help managers to achieve better inventory control. Yang and Chen (2012) examine the impact of information systems on DC's performance. Among the results, we find a positive correlation between *warehousing and inventory management* and *emergent order*

Table 9. Warehouse productivity indicators definition.

Indicator	Definition	Authors
Labour productivity	Ratio of the total number of items managed to the amount of item-handling working hours	De Marco and Giulio (2011)
Throughput	Items/hour leaving the warehouse	Mentzer and Konrad (1991), Kiefer and Novack (1999), De Koster and Warffemius (2005), Voss, Calantone, and Keller (2005), Gunasekaran and Kobu (2007), Gu, Goetschalckx, and McGinnis (2007)
	items/m^2 per day	De Marco and Giulio (2011)
Shipping productivity	Total number of products shipped per time period	Mentzer and Konrad (1991), Kiefer and Novack (1999), De Koster and Warffemius (2005)
Transport utilisation	Vehicle fill rate	O'Neill, Scavarda, and Zhenhua (2008), Matopoulos and Bourlakis (2010)
Warehouse utilisation[a]	The average amount of warehouse capacity used over a specific amount of time	Rimiene (2008), Matopoulos and Bourlakis (2010), Wang, Chen, and Xie (2010), Johnson and McGinnis (2011)
Inventory space utilisation	Rate of space occupied by storage	Ramaa, Subramanya, and Rangaswamy (2012)
Outbound space utilisation	Utilisation of the area inside the warehouse used for retrieving, order picking, packing and shipping	Johnson, Chen, and McGinnis (2010)
Picking productivity	Total number of products picked per labour hours in picking activity	Kiefer and Novack (1999), Manikas and Terry (2010), Yang and Chen (2012)
Receiving productivity	Number of vehicles unloaded per labour hour	Mentzer and Konrad (1991)
Turnover	Ration between the cost of goods sold and the average inventory	Johnson and McGinnis (2011), Yang and Chen (2012)

[a]Indicator definition taken from Warehousing Education and Research Council (WERC 2008).

handling. In Sohn, Han, and Jeon (2007), the issues related to the inventory management and the accuracy of logistics information (considered in Table 10 as warehouse automation) are also discussed.

- *Warehouse Automation:* De Koster and Balk (2008) measure the degree of warehouse automation according to the level of technology used (use of a computer or WMS are low levels; RFID and barcoding or robots are high levels). Banaszewska et al. (2012) assess information technology in warehouses by the number of available information systems.
  The impact of the use of warehouse automation on its performance has also been addressed. Yang and Chen (2012) conclude that high levels of information systems utilisation in the order selection activity should have positive influences on delivery.
- *Customer Perception:* customer relationship and customer satisfaction are considered as the most satisfactory performance variables by managers (Lu and Yang 2010). Accordingly, Kiefer and Novack (1999) state that understand the influence of some measures in customer's reaction is far more important than any internal measure alone.
  De Koster and Balk (2008) measure customer perception by using DEA. The authors verify the contribution of some activities (like cross-docking, cycle counting and return handling) to the increase of customer perception.
  Lu and Yang (2010) consider customer response as attributes of logistics service capabilities. Customer response encompasses pre-sale customer service, post-sale customer service and responsiveness to customer. As a result, the companies that are customer-response-oriented have the best performance among DCs in Taiwan.
- *Maintenance:* Sohn, Han, and Jeon (2007) have performed a survey based on warehouse characteristics in order to assess the capability of each warehouse taking part in the study. The facility management is determined by the authors as: (i) maintenance and repair of warehouse facilities, (ii) cooperation with facilities-related departments, (iii) new

Table 10. Indirect warehouse indicators found in literature.

Indicator theme	NP[a]
Labour	7
Value-added logistics activities	4
Inventory management	4
Warehouse automation	4
Customer perception	3
Flexibility	3
Maintenance	1

[a]Number of publications.

construction of modern warehouses and (iv) full equipment for protecting facilities against fire. As a result of the study, Sohn, Han, and Jeon (2007) conclude that facility management is the second highest impact on warehouse capability, after manpower management.

5. Analysis of the direct performance indicators

In order to provide well-defined boundaries for the warehouse indicators, the result of indicators in Table 5 and their respective definitions (Tables 6 up to 9) are further analysed using an activity-based framework. Consequently, the indicators that are classified in Section 4.1, according to quality, cost, time and productivity dimensions, are now also classified in terms of warehouse activities described in Section 3.2. The result of this new classification is illustrated by Table 11.

In order to classify the direct indicators with respect to the warehouse activities, we defined three types of direct indicators:

- Specific Indicators: are defined specifically for an activity.
- Transversal Indicators: are defined for a process rather than a unique activity. Therefore, their boundaries are also defined for a group of activities.
- Resource related Indicators: Some direct indicators are related to the resources used in the warehouses. We divide them into two distinct categories: Labour and Equipment/Building.

5.1 *Specific and transversal indicators*

In Table 11, we propose a mapping for both the specific (on the upper half of the table) and transversal indicators (on the lower half) on the warehouse activities. The activities are given on the columns. Although inventory is not a warehouse activity, we choose to include inventory as an activity in Table 11 due to its importance in warehouse management. Gallmann and Belvedere (2011) state that companies consider inventory management as a key to achieve excellent service levels. We also observe numerous metrics treating the subject (see Section 4.1). On the rows of Table 11, the reader can observe the previous dimensions of classification (time, quality, cost and productivity). Each direct indicator is then placed in the related cell in the table. For example, ‘order picking time’ is a time indicator which is specific to the picking activity.

In the lower half of Table 11, we illustrate the direct transversal indicators. Chan and Qi (2003) have defined that the inbound logistics concern both the materials transportation and the storage; while outbound logistics involve the outbound warehousing tasks, transportation and distribution. Based on this idea, the inbound process covers both receiving and storage activities, and are named as ‘Inbound Processes’ in Table 11 while picking, shipping and delivery activities are regrouped under ‘Outbound Processes’. Inventory is considered as an internal process in this case linking inbound to outbound processes. The indicators are then placed according to the extent of their boundaries. For example, the transversal indicator ‘Dock to stock time’ is classified as an inbound indicator encompassing receiving and storage activities. ‘Order lead time’ is an outbound indicator, covering picking, shipping and delivery activities. Here, we classify the ‘queuing time’ as global to all warehouse activities since it can be measured either for any type of activity or for all activities.

We note that the boundaries of indicators as described in Table 11 depend on warehouse production processes. Table 11 is created following a make-to-stock environment. A warehouse which operates on a no storage strategy (e.g. crossdocking) could define the boundaries of the indicators differently. The operating strategies impact mainly the transversal indicators. One example is the order lead time. If a make-to-order system is considered, the customer order would start upstream (in the supply process) and not at the picking activity.

Table 11 shows that the number of outbound indicators are much higher than the number of indicators for the inbound processes/activities. This reveals that the outbound processes/activities are considered more critical than the inbound ones

Table 11. Direct indicators classified according to dimensions and activities boundaries.

<table>
<tr><th rowspan="2">Dimensions</th><th colspan="6">Activity - Specific Indicators</th></tr>
<tr><th>Receiving</th><th>Storage</th><th>Inventory</th><th>Picking</th><th>Shipping</th><th>Delivery</th></tr>
<tr><td>Time</td><td>receiving time</td><td>putaway time</td><td></td><td>order picking time</td><td>shipping time</td><td>delivery lead time</td></tr>
<tr><td>Quality</td><td></td><td>storage accuracy</td><td>physical inventory accuracy; stock-out rate</td><td>picking accuracy</td><td>shipping accuracy; orders shipped on time</td><td>delivery accuracy; on-time delivery; cargo damage rate</td></tr>
<tr><td>Cost</td><td></td><td></td><td>inventory cost</td><td></td><td></td><td>distribution cost</td></tr>
<tr><td>Productivity</td><td>receiving productivity</td><td></td><td>inventory space utilization; turnover</td><td>picking productivity</td><td>shipping productivity</td><td>transport utilization</td></tr>
<tr><th rowspan="2">Dimensions</th><th colspan="6">Process - Transversal Indicators</th></tr>
<tr><th colspan="2">Inbound Processes</th><th></th><th colspan="3">Outbound Processes</th></tr>
<tr><td rowspan="2">Time</td><td colspan="2">Dock to stock time</td><td></td><td colspan="3">Order lead time</td></tr>
<tr><td colspan="5">Global= Queuing time</td><td></td></tr>
<tr><td rowspan="2">Quality</td><td colspan="2"></td><td></td><td colspan="3">Order fill rate, Perfect orders</td></tr>
<tr><td colspan="6">Global= Customer satisfaction, Scrap rate</td></tr>
<tr><td rowspan="2">Cost</td><td colspan="2"></td><td></td><td colspan="2">Order processing cost</td><td></td></tr>
<tr><td colspan="5">Global= Cost as a % of sales</td><td></td></tr>
<tr><td rowspan="2">Productivity</td><td colspan="2"></td><td></td><td colspan="2">Outbound space utilization</td><td></td></tr>
<tr><td colspan="5">Global= Throughput</td><td></td></tr>
</table>

Table 12. Indicators categorised according to dimensions and support areas.

<table>
<tr><th rowspan="2">Dimensions</th><th colspan="2">Resource Related Indicators</th></tr>
<tr><th>Labor</th><th>Equipment and Building</th></tr>
<tr><td>Time</td><td></td><td>Equipment downtime</td></tr>
<tr><td>Quality</td><td></td><td></td></tr>
<tr><td>Cost</td><td>Labor cost</td><td>Maintenance cost</td></tr>
<tr><td>Productivity</td><td>Labor productivity</td><td>Warehouse utilization</td></tr>
</table>

and hence they are subject to more control. It could be seen that the receiving and storage activities are the least covered ones. This shows that the statement of Gu, Goetschalckx, and McGinnis (2007) that ‘the research on receiving is limited’, is still valid. This could give some insights for future research, especially about transversal indicators for inbound processes.

The empty cells in Table 11 do not mean that there is no indicators to measure the activity/process. It signifies that none of the analysed papers has reported an indicator related to the activity/process. For example, in the case of time vs. inventory cell, inventory coverage could be used as an indicator for this purpose. Also for inventory management, there is a vast literature about the subject that is not included in this literature review. In the specific case of activity costs, it is not surprising to see a lot of empty cells since it is complicated and time consuming to perform activity based costing. Therefore, the managers prefer using cost-related metrics to measure global processes rather than specific activities.

5.2 *Resource related indicators*

Some indicators are directly related to resources used in the warehouse. Such indicators impact all warehouse activities. Therefore, instead of presenting them in Table 11, we choose to classify them as ‘resource related indicators’. There are two major resources: labour and equipment. The facilities are considered in the same group as equipment. The related indicators are given in Table 12.

Analysing Table 12 we note that three cells are empty: time vs. labour, labour vs. quality and equipment vs. quality. The time vs. labour cell is usually a data included in several productivity indicators. For the cell quality vs. labour, this result is expected because the quality of work is usually measured for each activity separately (e.g. accuracy in picking, shipping; see Table 11). Finally, the cell quality vs. equipment presents no indicators even if measures like number of equipment failures already exist. One reason for this empty cell is because our work does not consider papers regarding maintenance area.

6. Future research directions

Warehouses are essential for logistics operations and they have been extensively studied in the literature. However, the research effort focusing on warehouse performance measurement is not so abundant as for logistics performance. Based on the analysis of the selected papers, we highlight several future research directions in warehouse management.

- We have seen in previous discussions that indicators for inbound processes are not so abundant as for outbound processes. In particular, no transversal indicators are found for the inbound processes to measure the performance of the warehouse in terms of quality, cost and productivity. The company's results are usually measured by its outbound performance. However, this performance could extensively be influenced by how well the inbound processes are carried out. Therefore, the inbound performance is as important as the outbound performance and effects the global results of the warehouse. Further studies dealing with inbound indicators and their impact on the outbound as well as the global performance should be considered.
- There are different types of warehouses. For instance, the manufacturing company can own the warehouse in which only their products are processed. A warehouse could be a distribution center or owned by a third party logistics provider in which several products coming from different suppliers are treated. Or, a warehouse could be a retailer's warehouse. In all these cases, the key performance issues can differ since the goals may differ. Similarly, the management policies within a warehouse may also affect the way the performance needs to be measured. For instance, for a warehouse implementing crossdocking techniques, the time related performance measures are more crucial compared to those which do not implement this technique. One future research direction is to investigate to what extend the warehouse mission influence the choice of indicators for performance evaluation.
- The performance of administrative personnel in warehouse operations is another point for analysis. The indicators found in papers usually focus on operational labour. However, the administrative process has also an important role in the warehouse performance. For instance, indicators like order lead time and number of perfect orders are directly impacted by the administrative task performance. Nevertheless, the performance of the warehouse administration is not measured separately and its impact on the other performance indicators are rarely investigated. This could be an another research direction to improve the global warehouse performance.
- Indicators about 'reverse logistics' have already been developed to evaluate backorder operations, for example. The productivity and costs of these operations are important for the enterprise as a whole since they involve customer satisfaction. However, papers integrating these operations with the main warehouse performance indicators are still missing. Papers regarding the impact of returns in forward warehouse performance processes can bring some insights about this issue.
- An important subject in progress is the sustainability issues in logistics. Sellitto et al. (2011) measure environmental performance of logistics operations comparing emissions and waste indicators with the maximum levels allowed by ISO 14001. Matopoulos and Bourlakis (2010) go further including indicators of the three pillars of sustainability (economic, environmental, social) to evaluate warehouses. Sustainable operations have been widely studied in past years, but the inclusion of metrics in warehouse management have still place for examination.
- Another challenge for the academic research community is to evaluate the influence of each indicator on the warehouse performance. A growing number of survey papers have already treated the subject, but these works are limited to the cases studied (e.g. Voss, Calantone, and Keller 2005; De Koster and Balk 2008). It could be helpful to have a strategy map showing the influence of each parameter on the warehouse performance in terms of cost, time and customer satisfaction. Furthermore, the complexity of warehouse operations has led companies to adopt a large number of indicators. This can complicate the manager's evaluations when assessing the overall warehouse performance. The indicator characteristics make difficult the evaluation of their structural relationships, since different indicators can have opposite objectives (e.g. the level of a cost indicator shall decrease, while a quality indicator level shall be maximised). It is valuable to assess the integrated warehouse performance considering these structural relationships among the indicators.
- The early works on warehouse management are first focused on examining the processes and identifying areas where an efficient management could improve the performance of the warehouse. These early techniques do not necessarily need extensive information technology (IT) tools. However, in the last decade, we observe an increasing complexity in the warehouse operations. This complexity is very well demonstrated by the implementation of sophisticated IT tools in warehouses and DCs. Since 2000, more complicated algorithms and simulations start to appear in publications on warehouse management as well. These articles follow the same trend and propose utilisation or development of decision support systems for performance evaluation and performance improvement in warehouses. Information systems, such as warehouse management system (WMS), are recognised as useful means to manage resources in the warehouse (Lam, Choy, and Chung 2011). The trend of using information systems in warehouse

management is a growing tendency and the related new technologies (e.g. augmented reality, RFID, internet of things), will certainly influence the way the performance is measured and used for decision making in the future.

7. Conclusions

In this article, we propose a literature analysis on the operational warehouse performance evaluation. The content analysis method is used to study the selected papers. The warehouse performance indicators are extracted and are classified as direct or indirect measures. Direct indicators are usually expressed in simple mathematical expressions while indirect indicators consist, in many cases, of a concept measure. These concept measures are not used for daily management since they require a great quantity of data, which are sometimes difficult to obtain. So, direct indicators continue to be the basis for warehouse performance measurement.

The contributions of this article are as follows. First of all, analysing the direct indicators found in the literature, we observe that there is not always a consensus on the definitions of some of the indicators and their boundaries across the warehouse, resulting in different measures for the same metric. Therefore, we present indicator definitions based on paper database if the definitions are given and based on Warehousing Education and Research Council resources or content analysis if the definitions are not provided.

Secondly, we propose an activity-based framework to help clarifying the boundaries of the indicators. In this framework we classify indicators not only according to quality, cost, time and productivity dimensions, but also in terms of warehouse activities (receiving, storage, picking, shipping and delivery). The result of this classification shows that the number of outbound indicators is much higher than the number of inbound indicators. This is not very surprising as the warehouse activities are getting more and more customer oriented. The indicators most frequently used are: labour productivity, throughput, on-time delivery, order lead time and inventory costs.

Finally, this paper contributes to the research development by proposing several future research directions on warehouse performance evaluation.

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Appendix 1

Table A1 presents an abbreviation for author's paper to be utilised in Table A2.

Table A1. Authors abbreviation.

Paper	Abbreviation
Mentzer and Konrad (1991)	Men91
Gunasekaran, Marri, and Menci (1999)	Gun99
Kiefer and Novack (1999)	Kie99
Yang (2000)	Yan00
Ellinger, Ellinger, and Keller (2003)	Ell03
De Koster and Warffemius (2005)	Kos05
Voss, Calantone, and Keller (2005)	Vos05
Gu, Goetschalckx, and McGinnis (2007)	Gu07
Sohn, Han, and Jeon (2007)	Soh07
De Koster and Balk (2008)	Kos08
Park (2008)	Par08
O'Neill, Scavarda, and Zhenhua (2008)	One08
Rimiene (2008)	Rim08
Menachof, Bourlakis, and Makios (2009)	Men09
Wu and Hou (2009)	Wu09
Forslund and Jonsson (2010)	For10
Johnson, Chen, and McGinnis (2010)	Joh10
Lu and Yang (2010)	Lu10
Manikas and Terry (2010)	Man10
Matopoulos and Bourlakis (2010)	Mat10
Wang, Chen, and Xie (2010)	Wang10
De Marco and Giulio (2011)	Mar11
Cagliano et al. (2011)	Cag11
Lam, Choy, and Chung (2011)	Lam11
Gallmann and Belvedere (2011)	Gal11
Goomas, Smith, and Ludwig (2011)	Goo11
Johnson and McGinnis (2011)	Joh11
Karagiannaki, Papakiriakopoulos, and Bardaki (2011)	Kar11
Lao et al. (2011)	Lao11
Markovits-Somogyi, Gecse, and Bokor (2011)	Mar11
Banaszewska et al. (2012)	Ban12
Lao et al. (2012)	Lao12
Saetta et al. (2012)	Sae12
Yang and Chen (2012)	Yang12
Ramaa, Subramanya, and Rangaswamy (2012)	Ram12

Table A2. All papers and indicators.

Authors	Time									Quality													Cost						Productivity										Indirect						
	Receiving time	Putaway time	Dock to stock time	Queuing time	Order picking time	Shipping time	Delivery Lead Time	Order lead time	Equipment downtime	On-time delivery	Storage accuracy	Picking accuracy	Physical inv. ac.[a]	Shipping accuracy	Delivery accuracy	Stock-out rate	Perfect orders	Orders shipped on time	Cargo damage rate	Scrap rate	Order fill rate	Customer satisfaction	Ord. proc. cost[b]	Labor cost	Inventory cost	Distribution cost	Cost as a % of sales	Maintenance cost	Throughput	Receiving producivity	Picking productivity	Shipping productivity	Labor productivity	Inv. space util.[c]	Out. space util.[d]	Transport util.[e]	Warehouse util.[f]	Turnover	Maintenance	Flexibility	Labor	Cust. Perc.[g]	VAL activities[h]	Inventory Management	Warehouse Automation
Men91	x	x			x		x	x	x	x																	x		x	x		x	x												
Gun99										x							x												x																
Kie99								x		x			x					x	x			x	x						x		x	x										x			
Yan00								x																	x	x																			
Ell03																									x																x				
Kos05														x																		x													
Vos05										x	x				x					x		x							x												x				
Gu07	x				x	x		x																					x																
Soh07																																							x					x	x
Kos08														x																	x		x							x	x	x	x		x
Par08																																									x				
One08								x																										x	x	x							x		
Rim08								x			x	x	x										x		x				x				x	x	x		x								
Men09								x													x																								
Wu09																																									x				
For10										x																																			
Joh10																												x	x			x	x		x										
Lu10										x									x			x		x	x	x														x		x	x		x
Man10	x																												x			x	x												
Mat10	x						x																										x			x	x								
Wang10						x							x																			x					x							x	
Mar11																						x						x	x			x				x									
Cag11		x		x	x																			x	x								x												
Lam11					x																x																								
Gal11							x								x										x																			x	
Goo11																																	x								x				
Joh11																					x											x					x	x					x		
Kar11				x																													x												
Lao11																x					x	x																							
Mar11																																	x												
Ban12										x												x							x				x			x					x		x		x
Lao12	x															x					x	x																							
Sae12										x		x													x																				
Yang12		x						x		x		x	x			x				x	x	x									x							x		x				x	
Ram12			x					x		x			x			x	x				x		x				x		x					x											

[a]Physical inventory accuracy.
[b]Order processing cost.
[c]Inventory space utilization.
[d]Outbound space utilization.
[e]Transport utilization.
[f]Warehouse utilization.
[g]Customer perception.
[h]VAL activities – value added logistics activities.