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Quantitative models for supply chain performance evaluation: A literature review

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ABSTRACT

This paper presents a review of 84 studies published in the literature from 1995 onwards that propose quantitative models to support supply chain performance evaluation. A conceptual framework is proposed to characterize the studies according to several factors such as the purpose and scope of the model, supply chain strategy, choice of metrics, modeling uncertainty, type of model, techniques, learning capacity, type of application, data source for performance evaluation and validation approach. The reviewed papers were selected from Science Direct, Scopus, Emerald Insight and IEEE Xplore® databases, as well as the Google Scholar search tool. The results show that most of the studies evaluate more than one performance dimension and are based on multicriteria decision making techniques. AHP and DEA are the most used techniques. Pairwise comparisons and the fuzzy set theory are the dominant approaches to deal with uncertainty. Most studies have reported real case applications and do not include a validation procedure. The paper also discusses some research opportunities and suggestions of further studies brought about by reviewing the current body of knowledge on quantitative models for supply chain performance evaluation.

1. Introduction

Supply chains include different organizations, such as suppliers, manufacturers, transporters, warehouses and retailers. Supply chain management is the integration of planning, implementing and controlling all business processes associated with material and information flow and the transformation of goods from the raw material stage to the end user (Handfield & Nichols, 1999; Lambert, Cooper, & Pagh, 1998; Melo, Nickel, & Saldanha-da-Gama, 2009). The main objective of supply chain management is to minimize overall costs while delivering value to customers and other stakeholders, by producing and distributing goods in the right quantity, to the right place, at the right time and in a sustainable way (Ko, Tiwari, & Mehnen, 2010; Seuring, 2013).

Performance measurement can be defined as the process of evaluating quantitatively and/or qualitatively the effectiveness and the efficiency of an activity or a business processes (Neely, Gregory, & Platts, 1995). General benefits of evaluating performance include assessing and controlling progress, highlighting accomplishments, improving understanding of key processes, identifying potential problems and providing insight about possible future improvement actions, among others (Ahi and Searcy, 2015b). Evaluating the effectiveness and efficiency of a supply chain involves using metrics related to various performance objectives such as cost, agility, responsiveness, flexibility, sustainability, among others (Webster, 2002). Evaluating supply chain performance is a complex undertaking mainly because this is a transversal process, involving several players, which contributes to various barriers such as decentralizing historical data, a lack of cohesion between metrics and poor communication between reporters and users (Lohman, Fortuin, & Wouters, 2004; Naini, Aliahmadi, & Jafari-Eskandari, 2011).

The literature on supply chain performance evaluation includes a wide range of studies, including conceptual frameworks of metrics (Gunasekaran, Patel, & Tirtiroglu, 2001), surveys to identify the metrics mostly used (Gunasekaran, Patel, & Mcgaughey, 2004), case studies (Cuthbertson & Piotrowicz, 2011) and quantitative models to support the performance evaluation process (Chithambaranathan, Subramanian, Gunasekaran, & Palaniappan, 2015). Over the last decade, quantitative models have been increasingly investigated as a way to support the supply chain evaluation and management. Various types of techniques have been studied for such an application, including multicriteria decision making (Chithambaranathan, Subramanian, Gunasekaran et al., 2015), statistical (Ahi & Searcy, 2015a, 2015b), mathematical programming (Gong, 2008), artificial intelligence (Ganga & Carpinetti, 2011) and simulation techniques (Bhaskar & Lallement, 2008). Due to the variety of

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studies, literature reviews are needed to classify different types of research, examine the general trends of this research area and help identify research gaps. Fahimnia, Tang, Davarzani, and Sarkis (2015) presented a bibliometric analysis of 489 papers on quantitative models to support supply chain risk management. Brandenburg, Govindan, Sarkis, and Seuring (2014) conducted a review of 134 papers on quantitative models that address sustainability aspects in supply chains. Seuring (2013) reviewed 36 papers on quantitative models that also address sustainability in supply chains. Ko et al. (2010) carried out a review of papers on quantitative models that address various aspects of supply chain management, including manufacturing flow management, order fulfilment, demand management, supplier relationship management, product development and returns management. Melo et al. (2009) reviewed papers on quantitative models to support supply chain facility location decisions.

Although there are some review papers on quantitative models to support supply chain management, none of them focus on the analysis of quantitative models for supply chain performance evaluation. Therefore, the objective of this paper is to present a review of papers that propose quantitative models to support supply chain performance evaluation so as to answer some research questions such as what are the most used techniques, how the performance metrics are chosen, what are the data sources to evaluate performance, among others.

To guide the analysis of the reviewed papers and to answer the research questions, a conceptual framework is proposed to characterize the studies according to several factors such as the purpose and scope of the model, supply chain strategy, choice of metrics, modeling uncertainty, type of model, techniques, learning capacity, type of application, data source for performance evaluation and validation approach. The study analyzed 84 papers searched for on the Science Direct, Scopus, Emerald Insight and IEEE Xplore® databases, as well as the Google Scholar search tool. The time span considered for this study was the past two decades, from 1995 onwards. The papers were also classified according to the year of publication, journal and geographic location of the author's filiation.

The paper is organized as follows: Section 2 provides details of the conceptual framework proposed. Section 3 presents the database search procedures and keyword strings. Section 4 presents and discusses the results of the review. Section 5 summarizes the research gaps and trends. Finally, conclusions are drawn in Section 6.

2. A framework to analyze quantitative models for supply chain performance evaluation

The main objective of this proposed framework is to highlight the factors used to analyze and characterize the quantitative models for supply chain performance evaluation reviewed in the literature. Fig. 1 presents the factors that comprise the model.

The factors proposed in the model were based on reviews about quantitative models on supply chain management (Brandenburg et al., 2014; Fahimnia et al., 2015; Govindan, Soleimani, & Kannan, 2015; Melo et al., 2009) as well as qualitative studies concerning supply chain management (Cuthbertson & Piotrowicz, 2011; Farahani, Rezapour, Drezner, & Fallah, 2014; Gattorna, 2010). They are grouped into factors related to modeling and factors related to application and validation. The connections shown by the arrows mean the interdependence between the factors. The issues implicit in each of the factors are commented on next.

- **Purpose:** although the purpose of all the studies was performance evaluation, some of them aim to support prediction of performance (prediction of lag indicators based on lead indicators or projecting performance stability over time), while others propose to identify performance gaps based on targets or benchmarks.
- **Supply chain strategy:** this considers the competitive strategy adopted by the supply chain. Five main strategies were identified in the studies reviewed: lean, agile, flexible, green and sustainable (Farahani et al., 2014; Gattorna, 2010). Lean supply chains are characterized by high volume, low variety, low cost, predictable demands and lead times, high reliability and low risk. Agile supply chains are designed for responsiveness and for launching new products in the market before competitors. Their main characteristics are rapid response in unpredictable conditions, available capacity, flexible scheduling, fast decision making and delivery. Flexible supply chains are designed to meet unplanned or unplannable solutions, especially finding creative solutions. Their main features are related to flexibility, ability to problem resolution, speed and measures of innovation (Gattorna, 2010). Green supply chains focus on how a firm utilizes its suppliers' processes, technology and capability, and integrates environmental concerns to enhance competitive advantages. It is a facet of the supply chain that promotes reduction, reuse and recycling of resources involved in both upstream and downstream activities (Naini et al., 2011). Sustainable supply chain strategy involves integrating environmental and social aspects with economic considerations, known as the triple-bottom-line (Brandenburg et al., 2014).
- **Scope:** considers whether the model deals with a broad evaluation of performance or if considers only a single dimension of performance, such as agility or flexibility.
- **Choice of metrics:** this considers whether the choice of metrics was based on specialist opinion, on other studies or on a particular performance measurement conceptual framework.
- **Modeling uncertainty:** this refers to the approach used to model uncertainty. In supply chain performance evaluation, uncertainty relates to the lack of precision of the scores of the alternatives, as well as the relative importance of different criteria. This imprecision may be due to: subjective evaluation by multiple decision makers, inexistence of historical data and difficulty of assessing intangible aspects of supply chain performance (Brandenburg et al., 2014; De Boer, Wegen, & Telgen, 1998). Modeling uncertainty can be based, for instance, on pairwise comparisons or stochastic variables (Govindan et al., 2015; Melo et al., 2009).
- **Type of model:** this groups the models according to the nature of the techniques used to aid the evaluation process (Brandenburg et al., 2014; Govindan et al., 2015): multicriteria decision making (MCDM), statistical, mathematical programing, simulation and artificial intelligence (AI) techniques.
- **Techniques:** this refers to the technique(s) used in the decision model (Govindan et al., 2015). They can be used in a combined or single approach. A combined approach proposes the sequential application of two or more techniques.
- **Learning capacity:** this refers to the adaptation capacity of the decision model to the application environment. While some models are trained based on judgments of the decision makers, others are based on supervised learning algorithms.
- **Type of application:** this groups the studies into real or illustrative numerical applications. It also considers the economic sector of real applications (Melo et al., 2009).
- **Data source for performance evaluation:** this groups the studies according to the data source used for quantifying supply chain performance. For instance, some studies are based on historical data, while others are simulated or based on judgments.
- **Validation approach:** this considers whether the study includes a validation approach and the techniques used for validation.

3. Paper selection procedure

The papers were searched for on the following academic databases: Science Direct (www.sciencedirect.com), Scopus (www.scopus.com), Emerald Insight (www.emeraldinsight.com) and IEEE Xplore® (ieeexplore.ieee.org). An additional search was made using the Google Scholar search engine (scholar.google.com). The string "supply chain

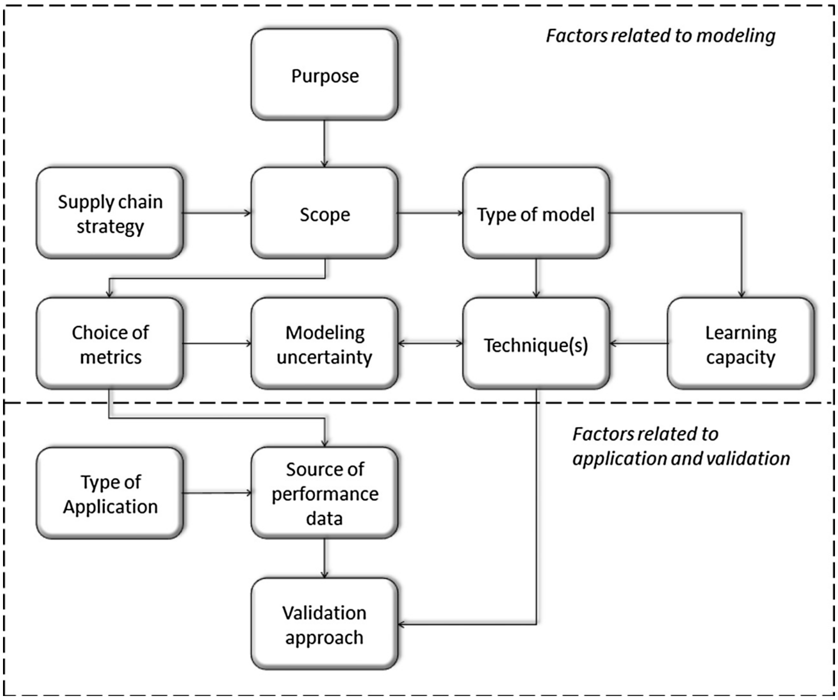

Fig. 1. Framework to analyze quantitative models for supply chain performance evaluation.

performance evaluation" was used to search for papers on the databases, which followed the steps described next:

- Step 1: Insert the string into the database search field;
- Step 2: Refine the search results by year of publication, from 1995 onwards. This time window was chosen since most of the developments on this subject have taken place over the past two decades;
- Step 3: Filter the search a second time to select only papers published in academic journals;
- Step 4: Order the papers by relevance according to the criteria defined by each database;
- Step 5: Select the first thousand results;
- Step 6: Select papers dealing with quantitative models for supply chain performance evaluation. The selection was based on the analysis of the title, abstract and keywords of each paper;
- Step 7: Eliminate duplicated results.

Table 1 presents the number of papers of the different databases resulting from using the searching procedure in each step. Regarding step 3, selecting papers published in journals was only done manually in step 6 for Scopus and Emerald databases and Google Scholar, as they do not filter the results by the type or source of publication. Furthermore, as the Emerald database and Google Scholar do not classify the results by relevance, step 4 was not followed in these cases. In step 6, in some cases, selecting or excluding papers was only possible after reading the main body of the paper. Excluded papers refer to conceptual models for supply chain performance evaluation, as well as studies related to supplier selection and performance evaluation, intra organizational performance measurement, collaborative networks, collaborative practices and demand forecasting in supply chains. After following the proposed steps, a total of 84 papers were selected.

Table 1
Databases and results of search procedure.

Database	Steps of the search and selection procedure						
	1	2	3	4	5	6	7
Science direct	63,311	52,472	43,659	43,659	1.000	30	30
Emerald	15,478	13,314	13,314	13,314	1.000	21	21
IEEE Xplore	461	461	23	23	23	4	4
Scopus	1754	1558	754	754	754	37	12
Google Scholar	1,690,000	152,000	152,000	152,000	1000	39	17
Number of selected papers							84

4. Characterization and discussion of results

Fig. 2(a) shows the distribution of these publications over the years. It can be seen the steady increase in publications, with a preponderance of the selected papers in the period from 2012 onwards. Fig. 2(b) presents the distribution of publications by countries of affiliation of respective authors. In cases where the authors of the same publication are from different countries, the publications are counted more than once. It can be observed that there is a high frequency of publications from China, followed by Iran and India. Table 2 presents a list of 55 different journals in which the papers were published, separated by year of publication. A relatively high occurrence of publications in the International Journal of Production Economics and the Production Planning and Control can be seen, followed closely by the Supply Chain Management Journal.

In the following section, the papers are analyzed considering the factors of the framework presented in Fig. 1.

4.1. Purpose, supply chain strategy and scope

Table 3 presents a brief description of the studies presented in the papers. In this table, the papers are classified according to the purpose and scope of the model. All of them have the purpose of performance evaluation although seven studies propose the use of benchmarking (Dey & Cheffi, 2013; Jalalvand, Teimoury, Makui, Aryanezhad, & Jolai, 2011; Joshi, Banwet, & Shankar, 2011; Nikfarjam, Rostamy-Malkhalifeh, & Mamizadeh-Chatghayeh, 2015; Sahu, Datta, & Mahapatra, 2014, 2015; Wong & Wong, 2007), while three other studies propose the use of a predictive approach to estimate lagging metric results based on the values of the leading metrics or to evaluate the supply chain performance stability over time (Abolghasemi, Khodakarami, & Tehranifard, 2015; Ganga & Carpinetti, 2011; Ip, Chan, & Lam, 2011). Regarding the scope, most of the studies (68 out of 84) present a broad evaluation of

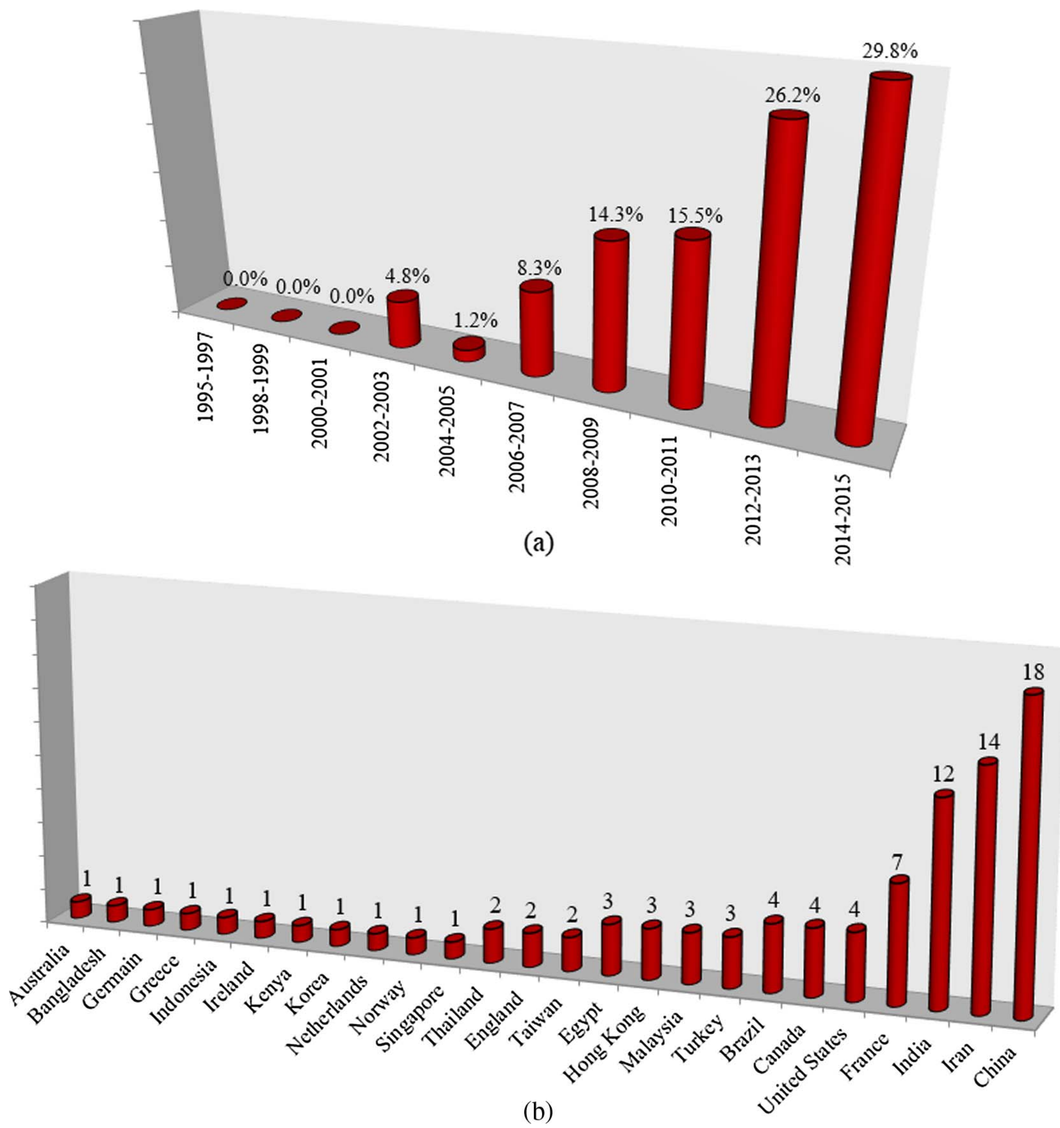

Fig. 2. Distribution of publications grouped by biennium (a) and by country (b).

performance, considering more than one performance dimension. The other studies focus on evaluating only one performance dimension, such as agility, flexibility, responsiveness, collaboration, environmental and efficiency.

Fig. 3(a) presents the type of supply chain strategy dealt with in the papers. Most of the studies do not consider a specific strategy (79.8% of the studies), while others adopt particular competitive strategies such as sustainable (7.1%), green (6.0%), agile (3.6%), lean (2.4%) and flexible (1.2%) strategies.

4.2. Choice of metrics and modeling uncertainty

Fig. 3(b) presents the approaches adopted by the authors to choose the set of metrics used in the studies. More than thirty percent of the studies based their choice of metrics on previous studies. Forty percent of the studies used metrics chosen either by specialists or by the authors with no further justification of choices. The other studies base their choices on widely known performance evaluation systems such as SCOR® and Balanced Scorecard (BSC).

Fig. 4 presents different approaches used in the studies to deal with uncertainty. First, 58 out of 84 papers propose approaches to support decision making under uncertainty. It can be seen in Fig. 4 that pairwise comparison between input variables is the main approach, proposed by 19 studies. The use of fuzzy number morphology or fuzzy inference rules is also quite frequent in the reviewed papers. In this case, the parameters of the fuzzy membership functions can be chosen so as to better represent judgments made by the decision makers to evaluate the supply chain performance on different metrics. In some studies, the stochastic approach is also used to model probability distributions associated to the model variables. Less common approaches are rough set, grey system and two-tuple theories. The fuzzy set theory is also used in combination with other approaches such as pairwise comparison, stochastic techniques and the grey system theory.

In general, to deal with uncertainty due to imprecise data and subjective judgments, the approaches identified in the studies rely on mathematical resources such as membership functions, interval numbers, pairwise comparison or a combination of them. The parameters of the membership functions and interval numbers can be chosen so as to better represent the linguistic or numeric values used by each decision maker to evaluate the alternatives regarding different performance metrics. Using pairwise comparisons is also suitable for support decision making problems when there is a lack of information. However, it limits the number of alternatives and metrics that can be evaluated simultaneously. Saaty (1980) suggests that the number of metrics or alternatives to be evaluated using pairwise comparisons should be limited to nine so as not to impair human judgment and its consistency.

Table 2
Journal title and year of publication of the reviewed papers.

Journals	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Total
International Journal of Production Economics														1	1		1		1		1	5
Production Planning & Control													1		1				2	1		5
Supply chain management: An International Journal									1								1	1		1		4
Benchmarking: An International Journal																				1	2	3
European Journal of Operational Research														1			2					3
Expert Systems with Applications																	2	1				3
Journal of Cleaner Production														1					1		1	3
Computers & Industrial Engineering																		1	1			2
Applied Mathematical Modelling																				1	1	2
Business Process Management Journal																					2	2
Grey Systems: Theory and Application																				1	1	2
IEEE System Journal																		1		1		2
Int. J. of Advanced Manufacturing Technology									1										1			2
International Journal of Production Research																			1		1	2
Int. J. of Productivity and Performance Management																			1	1		2
J. of Industrial Engineering and Management																			1		1	2
Journal of Intelligent Manufacturing																		1	1			2
Advance J. of Food Science and Technology																					1	1
African Journal of Business Management																1						1
Agriculture and Agricultural Science Procedia																					1	1
Annals of Operations Research												1										1
Applied Soft Computing													1									1
Asia Pacific Journal of Marketing and Logistics														1								1
British Food Journal																			1			1
Computers & Operations Research																		1				1
Computers in Industry													1									1
Decision Support Systems															1							1
Ecological Economics																	1					1
Electrical Power and Energy Systems																			1			1
Engineering Applications of Artificial Intelligence														1								1
IEEE Transactions on Automation Science and Eng.											1											1
IEEE Transactions on Systems, Man, and Cyb.																1						1
Industrial Management & Data Systems													1									1
INMATEH - Agricultural Engineering																			1			1
Int. Journal of Advanced Engineering Technology																	1					1
International Journal Of Engineering And Science																					1	1
Int. J. of Industrial Engineering & Production Res.																1						1
Journal of Bionic Engineering																			1			1
J. of Construction Engineering and Management																		1				1
Journal of Industrial Engineering															1							1
Journal of Information & Computational Science																					1	1
Journal of Manufacturing Systems																			1			1
Journal of Manufacturing Technology														1								1
Journal of Network and Computer Applications														1								1
Journal of Software																		1				1
Kybernetes															1							1
Management & Data Systems																	1					1
Management Decision									1													1
Maritime Policy & Management																					1	1
Measuring Business Excelence													1									1
Procedia - Social and Behavioral Sciences																		1				1
Production												1										1
Resources, Conservation and Recycling																	1					1
Transportation Research																					1	1
Uncertain Supply Chain Management																					1	1

Table 3
Brief description, purpose and scope.

Source	Author(s)	Purpose	Brief description of the study	Scope
Science direct	Berrah and Cliville (2007)	Performance evaluation	A performance measurement system model of supply chains	Broad evaluation
	Yeh et al. (2007)	Performance evaluation	Performance evaluation of supply chain management by the six sigma DMAIC process	Broad evaluation
	Bhaskar and Lallement (2008)	Performance evaluation	Performance evaluation focusing on the activity routing in a distributed supply chain	Broad evaluation
	Comelli, Féniès, and Tchernev (2008)	Performance evaluation	A model for combined evaluation of financial and physical flows	Broad evaluation
	Gong (2008)	Performance evaluation	A model for evaluation supply chain flexibility	Flexibility
	Jain et al. (2008)	Performance evaluation	A new approach for evaluating agility in supply chains	Agility
	Tsoulfas and Pappis (2008)	Performance evaluation	A model for environmental performance analysis of supply chains	Broad evaluation
	Cai, Liu, Xiao, and Liu (2009)	Performance evaluation	A framework for performance evaluation and improvement of the iterative key performance indicators in a supply chain context	Broad evaluation
	Xu et al. (2009)	Performance evaluation	Application of rough data envelopment analysis to supply chain performance evaluation	Broad evaluation
	Chen and Yan (2011)	Performance evaluation	Performance evaluation and internal resource waste analysis of supply chains	Broad evaluation
	Chuu (2011)	Performance evaluation	Fuzzy linguistic approach for evaluating the flexibility in a supply chain	Flexibility
	El-Baz (2011)	Performance evaluation	Fuzzy performance measurement of a supply chain	Broad evaluation
	Erol, Sencer, and Sari (2011)	Performance evaluation	Evaluation of sustainable supply chain management based on environmental, social and economic aspects	Broad evaluation
	Ganga and Carpinetti (2011)	Performance prediction	A fuzzy logic approach to predict supply chain performance	Broad evaluation
	Joshi et al. (2011)	Benchmarking	A framework for performance improvement and benchmarking of supply chains	Broad evaluation
	Naini et al. (2011)	Performance evaluation	A performance measurement system for environmental supply chain management	Environmental
	Cho, Lee, Anh, and Hwang (2012)	Performance evaluation	A performance measurement framework for service supply chain management	Broad evaluation
	Olugu and Wong (2012)	Performance evaluation	Performance measurement of forward and reverse supply chains	Broad evaluation
	Uysal (2012)	Performance evaluation	An integrated model for sustainable performance measurement in supply chain	Broad evaluation
	Wu et al. (2012)	Performance evaluation	Performance evaluation of supply chain networks with assembly structure under system disruptions	Broad evaluation
	Bas (2013)	Performance evaluation	Holistic analysis of electricity supply chain aiming performance evaluation and to understand the interdependencies of processes	Broad evaluation
	Fan, Zhang, Wang, Yang, and Hapeshi (2013)	Performance evaluation	A model based on Balanced Scorecard for supply chain performance evaluation	Broad evaluation
	Tavana et al. (2013)	Performance evaluation	A network epsilon-based DEA model for supply chain performance evaluation	Broad evaluation
	Mirhedayatian et al. (2013)	Performance evaluation	A novel network data envelopment analysis model for evaluating green supply chain management	Broad evaluation
	Shafiee, Lotfi, and Saleh (2014)	Performance evaluation	Supply chain performance evaluation with data envelopment analysis and balanced scorecard approach	Broad evaluation
	Ahi and Searcy (2015a)	Performance evaluation	Assessing sustainability in the supply chain based on a triple bottom line approach	Broad evaluation
	Bukhori, Widodo, and Ismoyowati (2015)	Performance evaluation	Performance evaluation of poultry supply chain	Broad evaluation
	Chithambaranathan, Subramanian, Gunasekaran et al. (2015) and Chithambaranathan, Subramanian, and Palaniappan (2015)	Performance evaluation	Environmental performance evaluation of a service supply chain	Environmental
	Nikfarjam et al. (2015)	Benchmarking	Measuring supply chain efficiency	Broad evaluation
	Tajbakhsh and Hassini (2015)	Performance evaluation	Evaluation of sustainability of supply chain networks	Broad evaluation
Scopus	Halman and Voordijk (2012)	Performance evaluation	Balanced framework for measuring performance of supply chains in house building	Broad evaluation
	Yang and Jiang (2012)	Performance evaluation	An analytic hierarchical model and a new membership transformation method to evaluate the overall performance of supply chains	Broad evaluation
	Bai and Sarkis (2013)	Performance evaluation	Supply chain performance measurement focus on reverse logistics flexibility evaluation	Flexibility
	Behrouzi and Wong (2013)	Performance evaluation	An integrated stochastic-fuzzy modeling approach for supply chain leanness evaluation	Broad evaluation
	Gou, Shen, and Chai (2013)	Performance evaluation	Evaluation of the service-oriented catering supply chain by the fuzzy hierarchy of comprehensive evaluation method	Broad evaluation
	Jakhar and Barua (2014)	Performance evaluation	An integrated model for supply chain performance evaluation and decision-making	Broad evaluation
	Li (2013)	Performance evaluation	An integrated approach to evaluating the production system in closed-loop supply chains	Broad evaluation
	Vinodh et al. (2013)	Performance evaluation	A model for agile supply chain assessment using linguistic values	Broad evaluation
	Wang (2013)	Performance evaluation	Supply chain performance evaluation of fresh agricultural products	Broad evaluation
	Abolghasemi et al. (2015)	Performance prediction	A new approach for risk and performance evaluation of supply chain	Broad evaluation
	Sha, Zhen, Cui, and Guo (2015)	Performance evaluation	Evaluation of the efficiency of supply chains	Efficiency
	Xiyao and Hankun (2015)	Performance evaluation	Evaluation method for supply chain performance based on balanced score card	Broad evaluation

(*continued on next page*)

Table 3 (*continued*)

Source	Author(s)	Purpose	Brief description of the study	Scope
Emerald	Chan and Qi (2003)	Performance evaluation	A performance measurement method for supply chain management	Broad evaluation
	Chan, Qi, Chan, Lau, and Ip (2003)	Performance evaluation	A model based on fuzzy logic for performance measurement of supply chains	Broad evaluation
	Sharma and Bhagwat (2007)	Performance evaluation	Performance evaluation of the supply chain performance from the four perspectives (finance, customer, internal business process, learning and growth)	Broad evaluation
	Wong and Wong (2007)	Benchmarking	Supply chain performance measurement system using DEA modeling	Broad evaluation
	Theeranuphattana and Tang (2008)	Performance evaluation	A performance measurement method for supply chain management based on the SCOR® model	Broad evaluation
	Varma, Wadhwa, and Deshmukh (2008)	Performance evaluation	Combination of AHP and balanced scorecard for evaluating performance of the petroleum supply chain	Broad evaluation
	Yang (2009)	Performance evaluation	Integrative performance evaluation for supply chain system based on logarithm triangular fuzzy number-AHP method	Broad evaluation
	Ip et al. (2011)	Performance prediction	An integrated approach to modeling supply chain performance and stability	Broad evaluation
	Jalalvand et al. (2011)	Benchmarking	A method based on SCOR® to evaluate and compare supply chains of an industry	Broad evaluation
	Bai, Sarkis, Wei, and Koh (2012)	Performance evaluation	Evaluation of the ecological sustainable performance measures for supply chain management	Broad evaluation
	Fattahi et al. (2013)	Performance evaluation	A model for measuring the performance of a meat supply chain	Broad evaluation
	Vaidya and Hudnurkar (2013)	Performance evaluation	A model for multi-criteria performance evaluation of a chemical supply chain	Broad evaluation
	Sahu et al. (2014)	Benchmarking	Performance evaluation and benchmarking of supply chains	Broad evaluation
	Kumar and Banerjee (2014)	Performance evaluation	An instrument to measure supply chain collaboration	Collaboration
	Varsei et al. (2014)	Performance evaluation	Evaluation of sustainability of supply chains with multidimensional indicators	Broad evaluation
	Arif-Uz-Zaman and Ahsan (2014)	Performance evaluation	Performance measurement of the lean supply chain	Broad evaluation
	Chithambaranathan, Subramanian, Gunasekaran et al. (2015) and Chithambaranathan, Subramanian, Palaniappan (2015)	Performance evaluation	An innovative framework for performance analysis of members of supply chains	Broad evaluation
	Kumar et al. (2015)	Performance evaluation	Dynamic performance assessment of supply chain process	Broad evaluation
	Pungchompoo and Sopadang (2015)	Performance evaluation	Supply chain performance measurement model based on the combination of structural equation modeling and analytical hierarchy process	Broad evaluation
	Sahu et al. (2015)	Benchmarking	Appraisement and benchmarking of supply chain performance	Broad evaluation
	Shabani and Saen (2015)	Performance evaluation	Evaluation of performance and definition of benchmarks for green supply chain	Environmental
IEEE Xplore	Chen, Amodeo, Chu, and Labadi (2005)	Performance evaluation	Modeling and performance evaluation of supply chains	Broad evaluation
	Albuquerque, Maciel, Lima, and Zimmerman (2010)	Performance evaluation	Performance evaluation of inventory and outbound distribution of supply chain	Broad evaluation
	Agami, Saleh, and Rasmy (2012)	Performance evaluation	A hybrid dynamic framework for supply chain performance improvement	Broad evaluation
	Agami, Saleh, and Rasmy (2014)	Performance evaluation	A fuzzy logic based approach for supply chain performance management	External factors
Google Scholar	Chan (2003)	Performance evaluation	Performance measurement of supply chain considering a hierarchy of performance indicators	Broad evaluation
	Sellito and Mendes (2006)	Performance evaluation	Application of Analytic Hierarchy Process for comparative evaluation of supply chains	Broad evaluation
	Liang, Yang, Cook, and Zhu (2006)	Performance evaluation	DEA models for supply chain efficiency evaluation	Efficiency
	Bhagwat and Sharma (2007)	Performance evaluation	Performance measurement of supply chain management using the analytical hierarchy process	Broad evaluation
	Bhagwat and Sharma (2009)	Performance evaluation	An integrated model for performance measurement of supply chain management	Broad evaluation
	Golparvar and Seifbarghy (2009)	Performance evaluation	Application of SCOR® model in an oil- producing company	Broad evaluation
	Jassbi et al. (2010)	Performance evaluation	An adaptive neuro fuzzy inference system for supply chain agility evaluation	Agility
	Seyedhosseini et al. (2010)	Performance evaluation	Application of adaptive neuro fuzzy inference system in measurement of supply chain agility	Agility
	Avinash and Prakash (2011)	Performance evaluation	A framework for performance measurement system of supply chain management	Broad evaluation
	Clivillé and Berrah (2012)	Performance evaluation	Overall performance measurement of a supply chain	Broad evaluation
	Dey and Cheffi (2013)	Benchmarking	Green supply chain performance measurement using the analytic hierarchy process: a comparative analysis of manufacturing organizations	Environmental
	Kocaoglu, Gülsün, and Tanya (2013)	Performance evaluation	A SCOR® based approach for measuring a benchmarkable supply chain performance	Broad evaluation
	Bhattacharya et al. (2014)	Performance evaluation	Green supply chain performance measurement using fuzzy ANP-based balanced scorecard: a collaborative decision-making approach	Environmental
	Khamseh and Zahmatkesh (2015)	Performance evaluation	Supply chain performance evaluation using robust data envelopment analysis	Broad evaluation
	Omar, Waweru, and Rimiru (2015)	Performance evaluation	Fuzzy logic framework for qualitative evaluation of supply chain responsiveness	Responsiveness
	Omrani and Keshavarz (2015)	Performance evaluation	A performance evaluation model for supply chains of shipping company in Iran	Broad evaluation
	Sellitto, Pereira, Borchardt, Silva, and Viegas (2015)	Performance evaluation	A SCOR-based model for supply chain performance measurement: application in the footwear industry	Broad evaluation

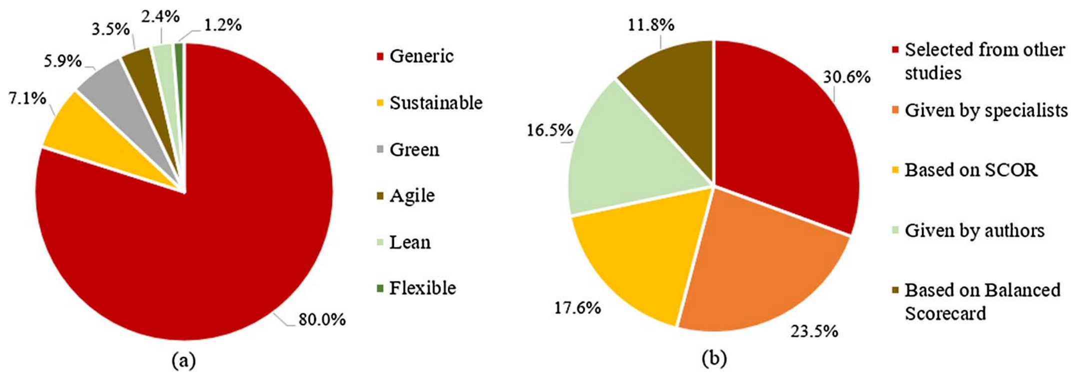

Fig. 3. Supply chain strategies (a) and approaches to performance metric selection (b).

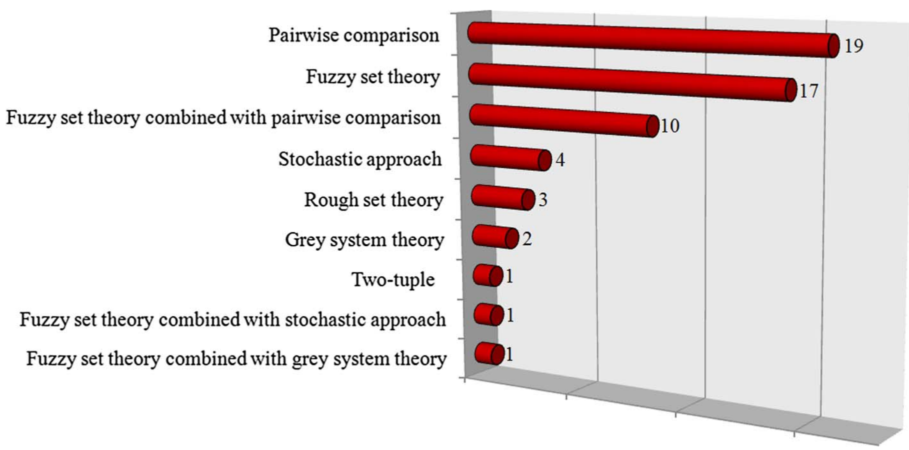

Fig. 4. Distribution of publications according to the approach for model uncertainty.

4.3. Type of model, techniques and learning capacity

Fig. 5 groups the quantitative models according to the nature of the techniques. Table 4 lists the techniques included in each type of model considered in this review. MCDM techniques are the most common type adopted (50.0%), followed by mathematical programing (21.4%), artificial intelligence (11.9%), simulation (6.0%) and statistical techniques (4.8%). MCDM techniques are also combined with mathematical programing (4.8%) and artificial intelligence (1.2%) techniques.

Fig. 6 presents all the quantitative techniques found in the reviewed papers and their respective frequency of use. As can be seen, although a large number of techniques have been used for this problem domain, AHP (Analytic Hierarchy Process) and DEA (Data Envelopment Analysis) are the most common ones. Linear programing, fuzzy inference and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) are techniques which are also quite often used. Considering all the 49 different techniques identified in the reviewed studies, most of them are used only once. This is the case of the techniques grouped under the label "new MCDM method based on the fuzzy set theory", which includes uncommon and unnamed techniques.

Considering the 53 studies that adopt a single technique (63.1%), presented in Fig. 7, AHP and DEA are also the most frequent ones, followed by fuzzy inference and ANFIS (Adaptive Network-based Fuzzy Inference System). In Fig. 8, for studies that propose the sequential application of two or more techniques (31 studies or 36.9%), AHP and DEA are again the most frequently used techniques. In these studies, AHP is mostly used to weigh the metrics according to the comparative judgments of the decision makers.

Depending on the technique used, different functionalities can be added to the performance evaluation model. For instance,

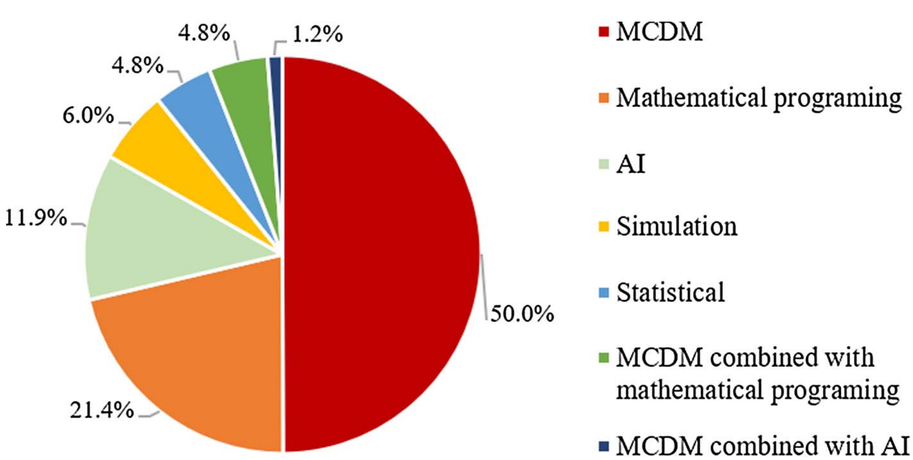

Fig. 5. Distribution of the types of quantitative models.

Table 4
Techniques included in each type of model.

Type of model	Techniques
MCDM	AHP, fuzzy AHP, fuzzy ANP (Analytic Network Process), MACBETH (Measuring Attractiveness by a Categorical Based Evaluation Technique), TOPSIS, fuzzy TOPSIS, fuzzy method based on the modified LOWGA (Linguistic Ordered Weighted Geometric Averaging), Two-tuple, fuzzy multi-attribute utility, DEMATEL (Decision Making Trial and Evaluation Laboratory), ELECTRE (Elimination and Choice Expressing Reality), VIKOR (Visekriterijumska Optimizacija I Kompromisno Resenje), fuzzy VIKOR, fuzzy weighted average, average arithmetic, analytic hierarchical model, rough set theory, grey system theory, neighborhood rough set methodology, multistage fuzzy evaluation and new MCDM method based on comparisons
Mathematical programming	DEA, Linear Programming, non-linear programming, pre-emptive goal programming, Rough programming, cost transformation matrix, multi-objective optimization
Artificial intelligence	Fuzzy association rules (data mining), fuzzy inference system, genetic algorithm, artificial neural network and ANFIS (Adaptive Network-based Fuzzy Inference System)
Stochastic	Probability theory, ARIMA (Auto Regressive Integrated Moving Average), integrated stochastic-fuzzy approach and stochastic Petri nets
Simulation	*Discrete event simulation,* cyclical aggregation method, Bayesian networks, queueing theory and dynamic systems

benchmarking studies between supply chains can be supported by using AHP and fuzzy AHP techniques since they allow for a structured comparative analysis of performance levels. Simulation techniques, such as Petri nets and the queueing theory, are able to model the dynamic behavior of the supply chain flows and performance over a time window. Moreover, fuzzy inference systems are able to model the linear and non-linear cause and effect relationships between lagging and leading performance indicators, making it very useful to predict the performance of supply chains.

Regarding the learning capacity, Fig. 9 shows that only 11.9% of the reviewed papers use techniques that enable quantitative modeling of the relationship between the input and output variables so as to adapt the model to the application environment. While the models based on fuzzy inference (Mamdani architecture) are trained based on the

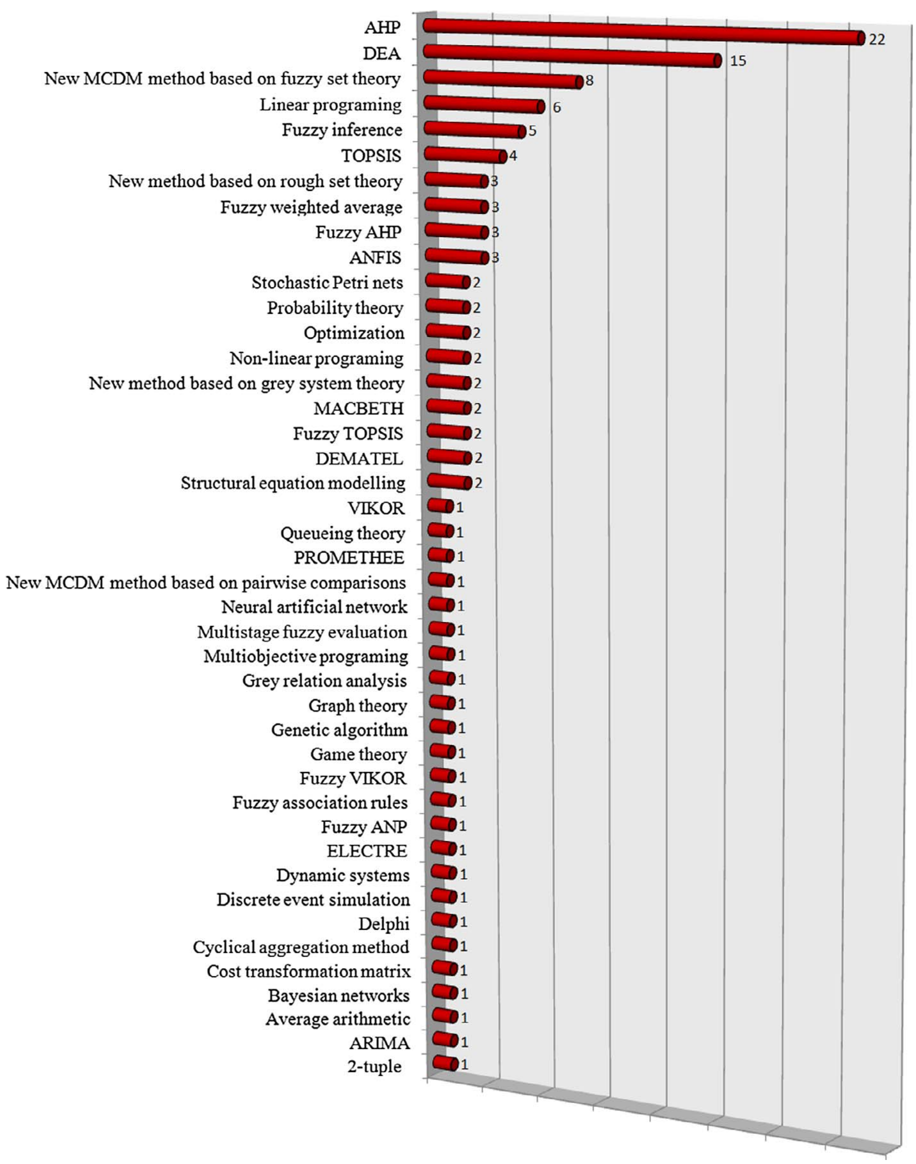

Fig. 6. Frequency of using quantitative techniques.

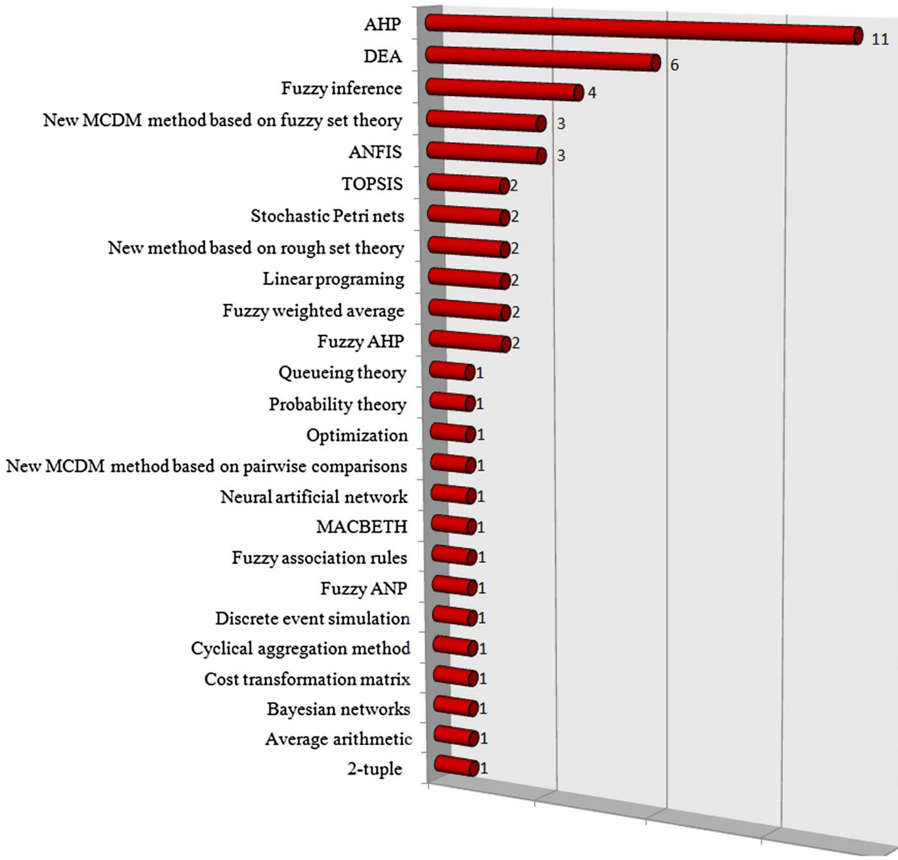

Fig. 7. Frequency of studies that adopt a single technique.

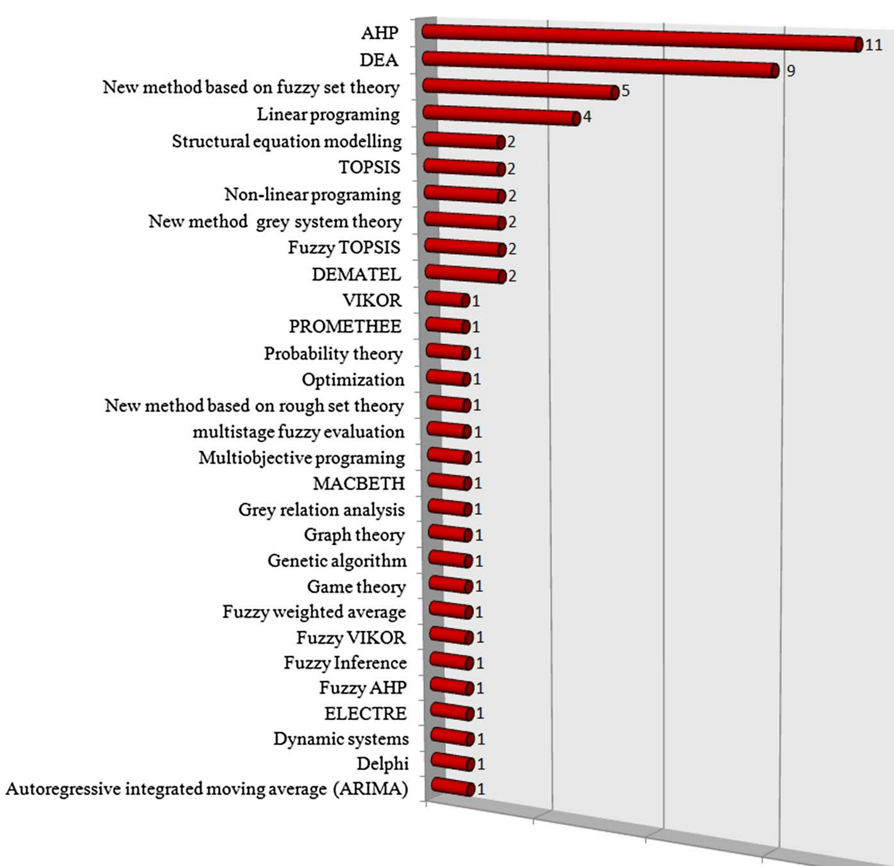

Fig. 8. Frequency of studies that adopt a combination of techniques.

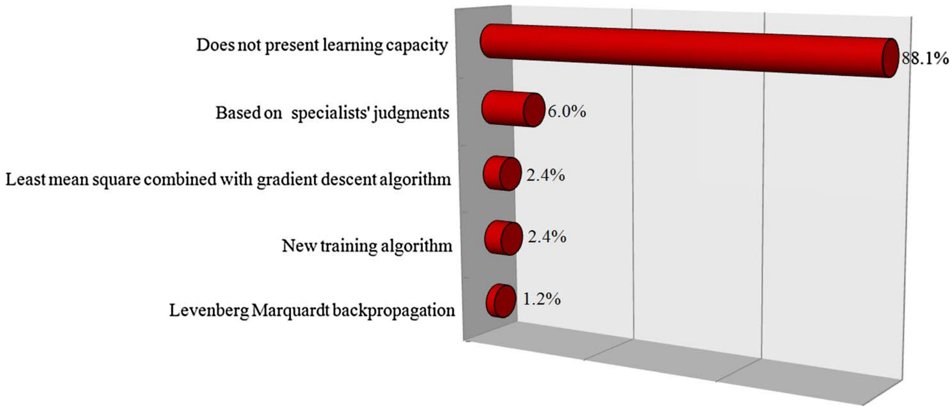

Fig. 9. Distribution of studies according to learning capacity and used method.

linguistic judgements of the decision makers concerning the consequences of the decision rules, models based on Artificial Neural Networks and ANFIS are based on supervised learning algorithms. These supervised learning algorithms include new training algorithms, as well as traditional methods such as the Least Mean Square combined with gradient descent and the Levenberg Marquardt backpropagation.

4.4. Application and validation

Regarding the type of application, 51 out of a total of 84 studies have reported real case applications, as opposed to illustrative applications of the other studies. Fig. 10 presents the distribution of the real applications by industry. Applications in the automotive and food industries were dominant, followed by applications in the electro-electronic and chemical industries. The relatively large number of applications in the automotive industry seems to be a consequence of its pioneering application of techniques and practices in supply chain management. As for the food industry, it is probably justified by its need to have an effective and efficient logistic performance.

In general, the data source for the real case applications was based on the judgments of specialists, historical data or a combination of both types. As for the illustrative applications, the data sources were simulation, other studies and the specialists' judgments.

Fig. 11(a) shows the distribution of these types of data source. It can be seen that the specialists' judgments are the most used data source, representing 47.6% of all the applications. As illustrated in Fig. 11(b), most of the studies (66.7%) limit to presenting the application results with no further analysis or validation. Therefore, only 33.3% of all the applications reported in the studies have carried out any sort of validation of results. 9.5% of the studies performed sensitivity analysis of the output variables by varying the values of the input variables. Statistical tests such as hypothesis tests, response surface and analysis of

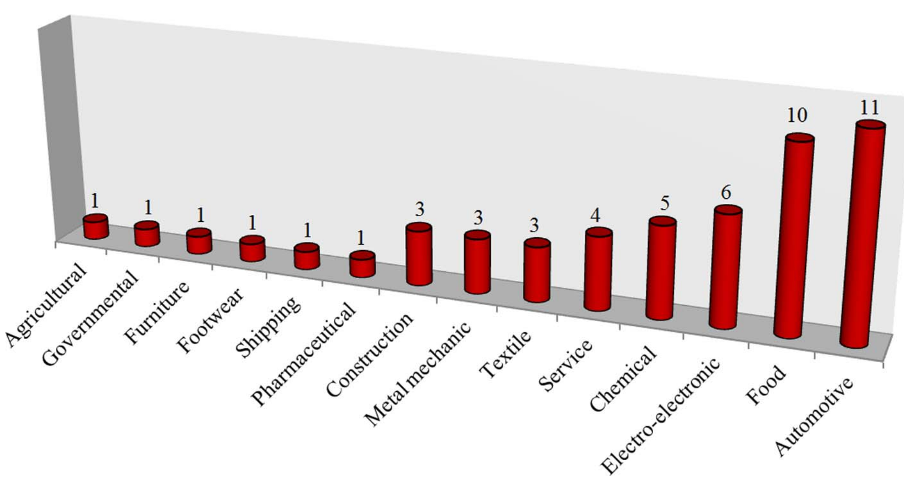

Fig. 10. Distribution of real applications by industry.

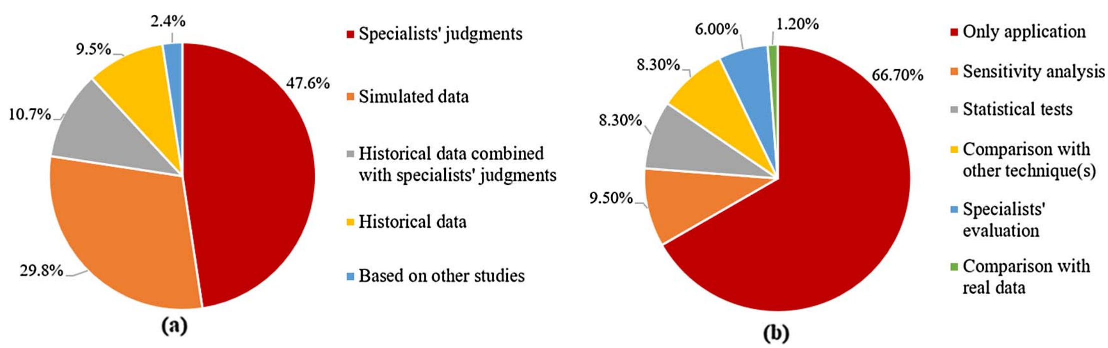

Fig. 11. Data source to evaluate supply chain performance in the published studies (a) and approaches to validation of application results (b).

variance were carried out in only 8.3% of the studies. Furthermore, 8.3% of the studies analyzed the consistency of the application results by comparing them with the results obtained from by different techniques. Finally, evaluating the results from specialists and comparing them with real data were the sort of validation adopted by respectively 6.0% and 1.2% of the studies.

5. Suggestions of further studies

Analysis of the reviewed papers pointed out some interesting opportunities of further studies. First of all, regarding comparative studies, although there are some studies that compare the results of the application of a particular technique with the results obtained from using of other techniques (Chuu, 2011; Kumar, Mukherjee, & Adlakha, 2015; Wang, 2013; Wu, Dong, Fan, & Liu, 2012; Xiyao & Hankun, 2015; Xu, Li, & Wu, 2009; Yeh, Chen, & Chi, 2007), there are no comparative studies that point out the advantages and drawbacks of using different techniques to support supply chain performance evaluation. Since the adequacy of the techniques depend on the characteristics of the problem domain, in order to decide which technique to use, one must take into account the alignment of the particularities of the problem at hand with the characteristics of the technique (Lima, Osiro, & Carpinetti, 2014). Therefore, there is still a need for comparative studies of methods in the context of supply chain performance evaluation.

Regarding the supply chain strategies considered by the reviewed papers, there are few models that focus on evaluating flexible, lean and agile strategies. Therefore, new studies could focus on developing new quantitative models to evaluate the suitability of using specific techniques for the particularities of these competitive strategies. Although sustainable and green strategies have been the most adopted ones, several models based on these strategies include only performance metrics related to environmental and social aspects and do not consider management aspects (Chithambaranathan, Subramanian, Gunasekaran et al., 2015; Uysal, 2012; Varsei, Soosay, Fahimnia, & Sarkis, 2014). Furthermore, using models based on a single performance dimension (Bai & Sarkis, 2013; Chithambaranathan, Subramanian, Gunasekaran et al., 2015; Chuu, 2011; Gong, 2008; Jain, Benyoucef, & Deshmukh, 2008; Jassbi, Seyedhosseini, & Pilevari, 2010; Kumar & Banerjee, 2014; Seyedhosseini, Jassbi, & Pilevari, 2010) is not adequate for real situations as it provides a limited view of the supply chain overall performance. Thus, further applications of these models should include other performance dimensions and metrics according to the business processes and strategic objectives of the evaluated supply chain. Further studies could also include applications in different industry sectors, such as agricultural, governmental, furniture, footwear, shipping and pharmaceutical industries, which so far have received little attention, as indicated in Fig. 10.

Concerning the performance evaluation across the supply chain tiers, most of the reviewed studies propose the evaluation of the supply chain based on the perspective of the focal company regarding its own performance and the performance of its first tier suppliers and first tier customers (Arif-Uz-Zaman & Ahsan, 2014; Behrouzi & Wong, 2013; Berrah & Cliville, 2007; Olugu & Wong, 2012; Theeranuphattana & Tang, 2008; Vinodh, Devadasan, Vimal, & Kumar, 2013; Yeh et al., 2007). There are studies that broaden the evaluation scope by considering four or more layers of the supply chain (Bas, 2013; Fattahi, Nookabadi, & Kadivar, 2013; Mirhedayatian, Azadi, & Saen, 2013; Tavana, Mirzagoltabar, Mirhedayatian, Saen, & Azadi, 2013). However, some of them evaluate intracompany performance, without including intercompany metrics to evaluate the performance of the supply chain as a whole (Mirhedayatian et al., 2013; Tavana et al., 2013). Therefore, further studies should also consider widening the scope of performance evaluation of the supply chain, but in doing that it is important to include intercompany metrics that aggregate performance data from the different layers under evaluation.

As far as techniques are concerned, although the search procedure has identified the use of 49 different techniques for supply chain performance evaluation, there are still some other techniques that have not yet been used. Therefore, further studies could also consider using techniques such as ORESTE (Organization Rangement Et Synthese De Donnes Relationnelles), ANP, SMART (Simple Multi Attribute Rating Technique), intuitionistic fuzzy sets and hesitant fuzzy sets. QFD (Quality Function Deployment) and fuzzy QFD could also be applied to support decisions regarding the weighing of the performance metrics that compose aggregated overall supply chain metrics based on the relationship between competitive requirements and the metrics.

Another valuable suggestion of using a decision making technique to supply chain performance evaluation is the use of fuzzy TOPSIS to perform benchmarking studies. The benchmarks in each metric would be given by the fuzzy positive ideal solution (FPIS). Therefore, the Euclidian distance (Chen, 2000) to the FPIS for each metric of each supply chain could be used to compare the performance against the benchmarks in each metric.

Concerning predictive supply chain performance evaluation models, further suggestions of studies could include developing new models based on the SCOR metrics in combination with artificial neural networks such as multilayer perceptron (MLP), radial basis function (RBF) and ANFIS. By using these techniques, the predictive model can be adapted to the environment of application based on historical data. Still another suggestion of further study could include the application time delay neural network (TDNN) to analyze and project the stability over time of the supply chain performance metrics.

6. Conclusion

This paper presented a literature review of 84 studies that propose quantitative models to support supply chain performance evaluation. A conceptual framework was proposed to analyze and characterize the reviewed papers according to the purpose and scope of the model, supply chain strategy, choice of metrics, modeling uncertainty, type of model, techniques, learning capacity, type of application, data source for performance evaluation and the validation approach.

The results show that most of the studies were published from 2012 onwards in a wide range of journals. More than 80% of the studies present a broad scope of evaluating performance, considering more than one performance dimension, assessed by metrics mainly selected from other studies or given by specialists. Most of the quantitative models are based on multicriteria decision making techniques and do not possess learning capacity. AHP and DEA are the most used techniques, either in single or combined applications. To deal with uncertainty, pairwise comparisons and the fuzzy set theory are the dominant approaches. Approximately 60.7% of the studies have reported real case applications, and the automotive and food industries are the dominant ones. Quantification of performance was mostly based on specialists' judgments and data simulation. In general, the studies do not include a validation procedure. However, some studies perform sensitivity analysis, statistical tests or other validation procedures.

The review of these 84 papers has led to identifying the current body of knowledge on quantitative models for supply chain performance evaluation and, therefore, it has helped to bring light to various research opportunities and suggestions of further studies as presented in Section 5.

Another contribution of this study is the conceptual framework proposed for analyzing the reviewed papers, based on 11 factors related to modeling, using and validating quantitative models for supply chain performance evaluation. Apart from using this framework in other review studies, it is envisaged that this framework can also be used to:

- guide the development of new quantitative models;
- evaluate the adequacy of particular quantitative models for the requirements of the application environment;
- guide comparative analysis of quantitative models for supply chain performance evaluation.

Finally, a limitation of this study is that, although the literature search was carried out on the main databases considering a wide time window, it may be the case that some studies available on other databases were missed. Therefore, this study is not exhaustive and can be complemented by further studies.

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