INTEGRATIONS AND APPLICATIONS OF ANALYTIC HIERARCHY PROCESS WITH DATA ENVELOPMENT ANALYSIS – A LITERATURE REVIEW

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ABSTRACT

The scope of the AHP (Analytic Hierarchy Process) and the DEA (Data Envelopment Analysis) is widened when they are integrated to create the DEAHP. This method has boundless flexibility and varied applicability. Furthermore, the scope, flexibility, and applicability are also increased when DEAHP is integrated with other approaches and methods. This paper reviews the literature that discusses this integration with DEAHP. On the basis of a defined search criterion, related articles appearing in international journals from 2000 to 2018 were collected and analyzed so that the following five questions could be answered: (1) Which approach out of the various integrated-DEAHP approaches was most prevalent and got the utmost attention?, (2) Which of the areas of application were most often studied and found their application with integrated DEAHP approaches?, (3) Which of the specific problems were most frequently applied to integrated DEAHP approaches?, (4) What are the publication trends for the papers considering the integrated DEAHP approaches?, and (5) Which journals of international standards published what number of journal articles and among them which has the highest number of articles on the approach of integrated DEAHP? This literature review shows that the integrated DEAHPs are able to tackle the inadequacies of the stand-alone DEAHPs. This article allows the researcher to think about new application areas and specific problem areas where an integrated DEAHP approach could be effectively and efficiently applied. The novelty of this paper lies in the fact that this is a one of a kind literature review that considers the integrated DEAHP approach along with stand-alone DEAHP with its applications.

Keywords: Integrated Data Envelopment Analysis-Analytic Hierarchy Process; AHP; DEA; DEAHP; literature review

1. Introduction

Lately, there have been many application-based papers developed in the field of integrated approaches of the Analytic Hierarchy Process and Data Envelopment Analysis (DEA/AHP). In this globalized society, changing business scenarios demand the most efficient and effective ways to manage an organization's business operations in every application area related to multi-criteria decision making (MCDM). This paper will aid academic and industry researchers and decision makers in utilizing the integrated DEAHP approach for various business problems in different application areas. This literature review identifies advances and new trends of the stand-alone and integrated DEAHP and its applications and problems from the business perspective between 2000 to 2018. This integration of AHP/DEA with other approaches is widely applied in the field of performance and efficiency measurement and optimization. Besides these, it also finds its application in quality measurement and ranking of different products or services in every sector namely education, engineering, manufacturing, government, management, industry, social, political, personal and even sports. For every organization, performance is a multi-dimensional phenomenon that addresses the quality, efficiency, cost, delivery, and flexibility aspects of the organization which relate to its improved performance. Organizational performance needs to be flexible, robust and competitive enough for the organization to survive and grow and gain an edge over competitors in the dynamic and vibrant scenario of the global and national economy.

For instance, measurements of efficiency, quality, performance, and rank have been addressed using numerous approaches by a number of different researchers with diversified levels and dimensions for consideration. A various number of tools and techniques for the aforementioned indicators have been used which include the Analytic Network Process (ANP), Analytic Hierarchy Process (AHP), Data Envelopment Analysis (DEA), goal programming (GP), linear programming (LP), Slacks-Based Measure (SBM), Assurance Region (AR), Grey Relational Analysis (GRA), Technique for Ordering Preference by Similarity to Ideal Solution (TOPSIS), Total Cost of Ownership (TCO) Quality Deployment Function (QFD), Balanced Scorecard (BSC), and Suppy Chain Operations Reference (SCOR) model, to name a few. Some structural modeling approaches include Interpretive Structural Modelling (ISM), Decision Making Trial and Evaluation Laboratory (DEMATEL), and Structural Equation Modelling (SEM). Benchmarking of performance emphasizes both the inter and intra-organizational levels. Recently, integrated approaches (AHP-DEA model, Delphi-AHP-TOPSIS, Fuzzy-AHP-Fuzzy-TOPSIS, BSC-ANP-DEMATEL, BSC-AHP, BSC-ISM-ANP, SCOR-BSC, DEMATEL- ANP- VIKOR, and Dependence-based interval-valued evidential reasoning (DIER)-BSC) have also been propounded for the measurement of performance and analysis. The most popular set of tools for managers engaged in multi-criteria decision making are DEA, AHP, and ANP. There have been quite a few examples in the past literature of integrated approaches with DEAHP, such as DEAHP-Fuzzy, DEAHP-LP, DEAHP-GP, DEAHP-Simulation, DEAHP-ABC, EAHP-SBM, DEAHP-TCO, DEA-VAHP, DEAHP-AR, DEAHP-Gower plot, DEAHP-GRA, Delphi-DEAHP-LP, DEAHP-

Fuzzy-QFD-LP, DEAHP-TOPSIS-Fuzzy, and 2-level SOM-DEAHP-AR, to name a few.

Before the integrated DEA/AHP was introduced, the stand-alone AHP was sufficient for a wide variety of fields which are related to MCDM (multi-criteria decision-making). Thomas L. Saaty introduced AHP in the 1970s. The AHP was developed by many researchers such as Sinuany-Stern, Mehrez, and Hadad (Sinuany-Stern et al., 2000) and Thomas L. Saaty (Saaty, 2004). The AHP is a subjective method which helps analyze both qualitative and quantitative criteria to generate important weights of the decision criterias and the relative performance measures of the alternatives in terms of each individual's decision criteria. Ho (2008) noticed that when the AHP is integrated with other approaches, it leads to a far more practical and trustworthy decisions than with the stand-alone AHP. Hence, the attention shifted in the direction of integrated-AHP and its realistic applications.

There have been only 5 publications which reviewed the literature about AHP in the last decade (2007-2016), which is quite limited in number. Ho (2008) reviewed 66 papers from 1997 to 2006, and concluded that approaches like integrated-AHP-QFD and integrated-AHP-GP were the most extensively applied approaches. The paper also observed that the logistics sector was the most diverse area of application for the integrated-AHP approach. Ho & Ma (2018) followed the previous work by comparing the papers in the 2008 article with the 88 papers published between 2007 and 2016.

According to Ho (2008), the AHP is one of the most widespread MCDM approaches. However, the AHP has been criticized to a great extent for the problem of rank reversal. The eigenvector method, which is used for determing the priorities in AHP, has been criticized by Bana e Costa and Vansnick (2008) because it violates the condition of order-preservation (COP). The numerical examples given by Bana e Costa and Vansnick were examined by Wang, Chin, and Luo (2009). They re-examined the concept of oveall judgements, and it was clearly shown that the criticisms were not justified. The criticism of Bana e Costa and Vansnick has also been argued by Kulakowski (2015). This article argued that the problem of the prioritization procedure followed in the AHP was not inherent, rather the issue arose because of the inconsistencies which were found between the elements of the pairwise-comparison matrix. The inconsistency measurement which was taken for the matrix as a wholes does not detect the inconsistencies that are present between the elements of the pairwise-comparison matrix (Kulakowski, 2015).

However, on the contrary, the DEA is a data-oriented approach which is in a way based on mathematical programming. Charnes et. al. (1978) introduced DEA, and it is one of the most efficient methods that is primarlily used for evaluating the relative efficiency of DMUs (Decision Making Units). The performance evaluations of scale efficiency, technical efficiency, allocative efficiency, and cost efficiency are usually carried out using this approach. The objective function value of a linear programming model is basically efficiency.

There are many bibliographies in the area of DEA in the existing literature, e.g. Emrouznejad et al. (2008), Emrouznejad and Thanassoulis (1996a, 1996b, 1997), Seiford (1994, 1997), Gattoufi et al. (2004a, 2004b), and Tavares (2002). From 1978 to 2016, there were 9881 DEA-related articles which were published only in journals (excluding any articles published as a chapter, book or working paper). 94% of the

papers related to DEA were published by less than four authors, and about 34% of the papers have two authors. Energy, industry, banking, education, and healthcare were found to be the most popular application areas of DEA (Emrouznejad & Yang, 2017).

Sinuany-Stern et al. (2000) claimed that the key objective of the AHP-DEA model is to eliminate the subjective evaluation of AHP and to overcome the ranking inefficiency of DEA. With the AHP-DEA approach, the judgment matrix is formed using basic AHP models and then DEA is used to rank the DMUs (Decision Making Units). As per the aforementioned paper, this method eliminates the subjective evaluation of AHP and overcomes the ranking inefficiency of DEA. First, the DEA is run separately for each of the units. Second, the pairwise-evaluation matrix which was generated in stage one is utilized to rank-scale the units using the AHP. Both the AHP and DEA are commonly used and have limitations.

The evolution of the AHP was comprehensively detailed in Ho (2008). Similarly, the literature review in Seiford (1996) outlines the evolution of the DEA. Even though Ho (2008) and Seiford (1996) have made a significant contribution to the AHP and DEA literature as stand-alone approaches, there are two significant knowledge gaps that were the motivation for conducting this study. First, all of the works mentioned in the two previous studies include approaches that are integrated with AHP and DEA in a stand-alone manner. With the onset of DEA/AHP (DEAHP), which overcomes the limitations of AHP, several other approaches seem to fit with DEAHP streamlined to various problem areas and application areas. Second, both of the review articles mentioned previously primarily emphasize the commonly studied AHP with the integration of other approaches and the stand-alone AHP approach during a particular time period. Also, these review articles do not show a relative comparative analysis and do not analyze the integrated approaches application-wise, problem-wise, trend-wise, journal-wise, and even popularity-wise. In order to fill these two gaps, an exhaustive review of highly relevant journal articles between 2000 to 2018 have been presented by this paper to analyze the applications and integrations of DEAHP.

In this paper, we consider the literature concerning DEA/AHP between 2000 and 2018. Therefore, 72 papers have been studied with varied approaches and applications that include a diverse set of practical problems. The application area is very wide because of the flexibility and ease of use with a variety of specific problems. This combination of different approaches with DEAHP (also referred to as integrated DEAHP approaches) is able to make a decision with more accurately than the stand-alone DEAHP. These approaches were selected because of their wide applicability, popularity, and accomplishment in making decisions.

The mechanism of the DEAHP is described briefly in the next section. The tools integrated with the DEAHP and their applications are critically explained in the subsequent sections. Analysis of the stand-alone-DEAHP approaches and integrated-DEAHP approaches, suggestions which are applicable for future work, and conclusions for this work on literature are discussed in the last few sections.

2. DEAHP

The DEAHP consists of six stages, which are developed into a flowchart as shown in Figure 1. Stage 1 breaks down a complex MCDM problem into its constituent parts. In these parts, every criterion, sub-criteria, and the alternatives are arranged into

multiple hierarchical levels. Subsequently, in stage 2, each cluster is compared in the same level in a pairwise manner which may be based on the decision-maker's knowledge and experience. Some degree of inconsistency may occur in it since the comparisons are carried out through personal or subjective judgments. Stage 3 constructs the DEA problem where the efficiency is calculated for each criterion taken as DMU. Stage 4 identifies if all the hierarchical levels (criteria, sub-criteria, and alternatives) have finished comparision. If the answer is "No", then a pairwise comparison matrix is developed again. If the answer is "Yes", then it moves to stage 5 of synthetization, where the efficiency of the alternatives is calculated. Finally, stage 6 develops the overall priority ranking where the judgments can then be synthesized to determine the priority ranking of each criterion and its alternatives.

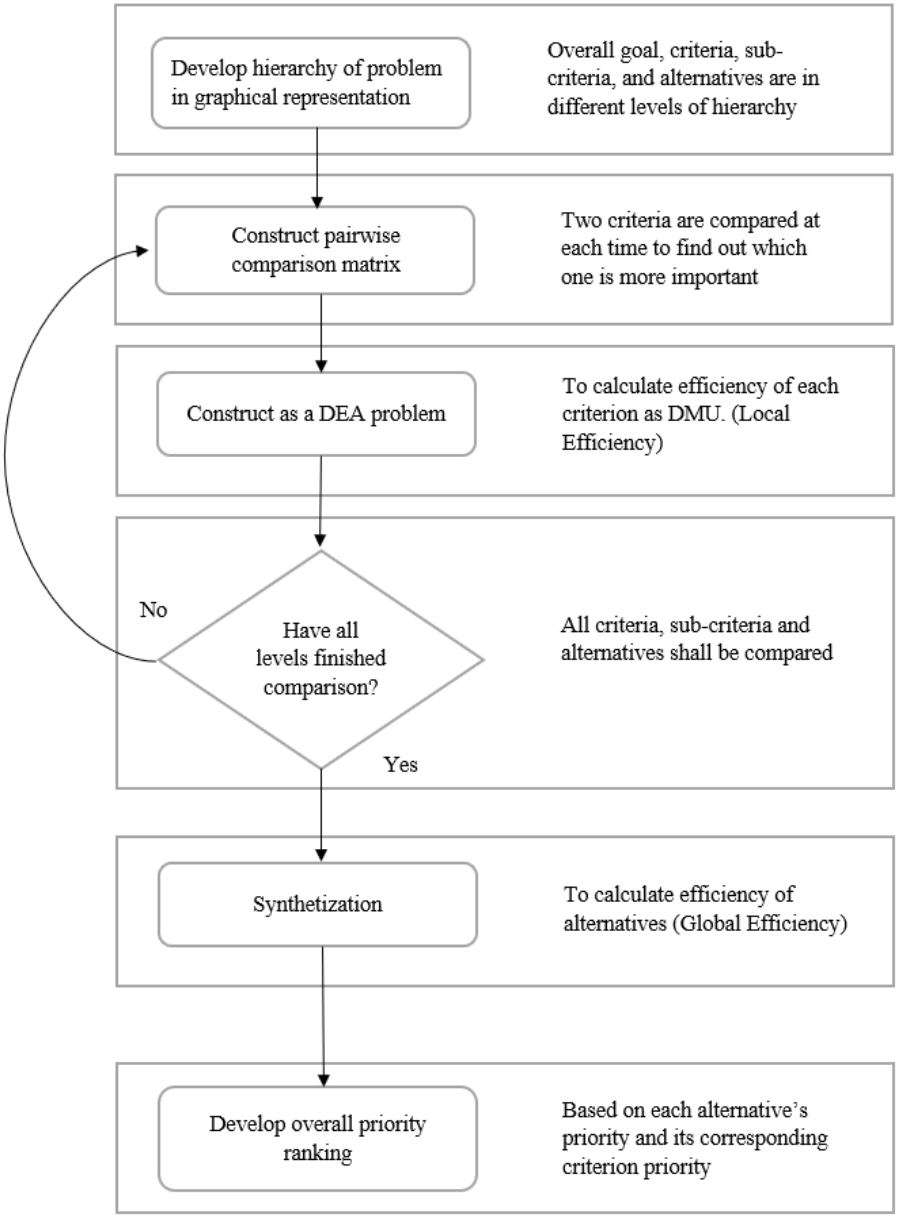

Figure 1 Flowchart of the DEAHP (Data Envelopment Analysis – Analytic Hierarchy Process)

3. Research methodology

Since this literature review focuses on the recently created integrated approach of the stand-alone DEAHP, all the journal articles are published between 2000 to 2018. The following illustration in Figure 2 represents the research methodology.

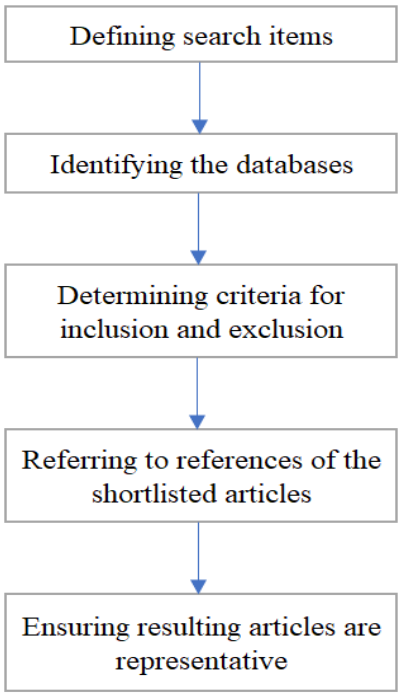

Figure 2 Flowchart of the research methodology published by Ho & Ma (2018)

This paper followed a very lucid search, inclusion, exclusion, shortlisting and review given by Ho & Ma (2018). Initially, the search terms were defined, and then keywords/abstracts/titles were searched using the terms "Integrated Data Envelopment Analysis-Analytic Hierarchy Process" (shortened to keywords like DEAHP, AHP/DEA, integrated DEAHP, integrated AHP/DEA, integrated DEA/AHP) which were utilized in the process of searching within the databases.

Second, a wide variety of academic databases were used to find relevant journal articles. These databases included Emerald, EBSCOhost, Elsevier, ScienceDirect, JSTOR, Taylor & Francis, ProQuest, World Scientific, Scientific Research, IEEExplore, MDPI, MetaPress, Ingenta, Wiley, and Springer. Only PRPs (peer-reviewed papers) which were printed and published in English and in international level journals were chosen to ensure an elevated relevance level. Conference papers, book chapters, textbooks, dissertations of doctoral and master's level, and notes were not considered for this process of review.

In the third step, the journal articles were screened on the basis of a determined criterion. Using the criterion, all the abstracts of the articles along with relevant informative portions of the papers were scrutinized to identify whether the article addressed the integrated-DEAHP approach or the stand-alone-DEA/AHP approach with its applications rather than addressing only AHP or DEA or integrated AHP without DEA or integrated DEA without AHP. However, it must be kept in mind that

the journal articles which proposed approaches for re-modifying DEAHP, like a linear programming method for the generation of weights from a pairwise-comparison matrix which tends to be the most favorable (Wang et. al., 2008); weight derivation in the case of DEA and aggregation in the case of AHP (Ramanathan, 2006); and ranking decision-making units (DMUs) using approach of integrated fuzzy-DEA-fuzzy-AHP (Alem et. al., 2013) were also considered as these papers were well-tested and evaluated on a few hypothetical examples which did not follow any specific applications. The authors successfully demonstrated their work based on these hypothetical examples. Also, an application-based literature review paper by Ho (2008) was considered for this paper. We tried to include the maximum number of papers because this paper deals with the focused approach of DEAHP. The state-of-the-art and prominent integrated-DEAHP approach and its varied applications can be studied by enabling this filtering criterion. The criteria for filtration screened out those journal articles which did not achieve even one of these criteria of filtration.

In the fourth step, a careful evaluation of all the lists of references of these shortlisted articles was carried out to make sure that any other related and highly relevant articles were not missed in the search process.

Finally, an exhaustive review of the content of each journal article was done to make sure that the paper was aligned with the context and was fit in the context of the integrated-DEAHP approaches and stand-alone DEAHP approach. This analysis resulted in 72 journal articles for this study.

Five questions were asked of the 72 collected articles, which include: (i) which of the integrated-DEAHP approaches were most prevalent and widely appreciated?, (ii) in which fields/areas did the integrated-DEAHP approaches find a varied number of applications?, (iii) which kind of specific problems were addressed using integrated-DEAHP approaches?, (iv) what are the publication trends for the papers considering the integrated DEAHP approaches?, and (v) which journals of international standards published how many journal articles and among them which have the highest number of articles on the approach of integrated DEAHP?

4. Stand-alone DEAHP approaches and applications

There are many papers that demonstrate the method and more specifically the applications of the DEAHP in its stand-alone form. It should be noted that even the stand-alone DEAHP is a combination of AHP and DEA. In the DEAHP, the DEA part removes the limitations of AHP which are rank reversal, element dominance, and row dominance issues. Therefore, this method produces better output weights that can be applied to different business scenarios. Forty-one journal articles were identified that applied the stand-alone DEAHP without the integration of any other approaches with their categorization of application areas and specific problems as shown in Table 1.

These journal articles focus on specific problem statements such as supplier evaluation and selection (Sevkli et al, 2007; Moon & Kang, 2015; Aji & Hariga, 2013; Yadav & Sharma, 2015), economic performance assessment (Lin et al., 2011) that comes under performance evaluation and efficiency measurement, and the problem of evaluation and selection of a warehouse (Korpela et al., 2007) that comes under business unit evaluation. The results of DEA and AHP have been combined by

Sueyoshi et al. (2009) to tackle the problem of critical business-unit selection and evaluation in a rental car business.

Table 1
The stand-alone DEAHP approach and its application areas and specific problems

Approach	Authors	Application areas	Specific Problems
DEA-AHP (General)	William Ho (2008)	Literature Review	Literature Review
	Antonio et al. (2012)	Higher education	Performance evaluation & Efficiency measurement
	Pakkar (2015)	Banking	Multiplicative aggregation of financial ratios
	Ahmad (2006)	Manufacturing	Business unit evaluation
	Aji & Hariga (2013)	E-Commerce	Supplier evaluation and section
	Pakkar (2014)	Iron / Steel	Performance evaluation & Efficiency measurement
	Amin & Toloo (2007)	Manufacturing	Facility Layout Selection
	Azadeh et al. (2011)	Banking / Mining	Personal productivity evaluation
	Cai & Wu (2001)	Financial	Process evaluation
	Omid & Zegordi (2015)	Manufacturing	Performance evaluation & Efficiency measurement
	Moon & Kang (2015)	Defence Industry	Supplier evaluation and section
	Giokas & Pentzaropoulos (2008)	Telecommunication	Performance evaluation & Efficiency measurement
	Hadad & Hanani (2011)	Manufacturing	Product evaluation and selection
	Banwet & Deshmukh (2008)	R & D	Performance evaluation & Efficiency measurement
	Kasap & Kiriş (2013)	Energy	Business unit evaluation
	Kavurmaci & Üstün (2016)	Environment	Quality evaluation
	Kengpol & Tuammee (2015)	Logistics	Business unit evaluation
	Korpela et al. (2007)	Process	Business unit evaluation
	Lin et al. (2011)	Government	Performance evaluation & Efficiency measurement
	Lozano & Villa (2009)	Logistics	Business unit evaluation
	Zarei et al. (2012)	Manufacturing	Performance evaluation & Efficiency measurement
	Foroughia & Esfahani (2012)	Airlines	Business unit evaluation

	Pakkar (2016)	Government	Performance evaluation & Efficiency measurement
	Ramanathan (2006)	Multiple Industries	Performance evaluation & Efficiency measurement
	Saleeshya & Babu (2012)	Manufacturing	Business unit evaluation
	Sevkli et al. (2007)	Manufacturing	Supplier evaluation and section
	Shirouyehzad et al. (2013)	Hotel	Business unit evaluation
	Singh & Aggarwal (2014)	Human resource	Performance evaluation & Efficiency measurement
	Sinuany-Stern et al. (2000)	Manufacturing	Performance evaluation & Efficiency measurement
	Sueyoshi et al. (2009)	Rental cars	Business unit evaluation
	Tseng & Lee (2009)	Electronics	Process evaluation
	Wang et al. (2008)	Manufacturing	Risk assessment
	Yadav & Sharma (2015)	Manufacturing	Supplier evaluation and section
	Yang & Kuo (2003)	Electronics	Facility Layout Selection
	Zhang & Fu (2012)	Logistics	Performance evaluation & Efficiency measurement
	Ertay et al. (2006)	Manufacturing	Facility Layout Selection
	Saen et al. (2005)	Government	Performance evaluation & Efficiency measurement
	Takamura & Tone (2003)	Government	Location Evaluation
	Wang et al. (2008)	Higher education	Expert evaluation and selection
	Wang & Chin (2009)	Higher education	Expert evaluation and selection
	Mirhedayatian & Saen (2011)	Higher education	Expert evaluation and selection
Total	**41**		

It was clearly shown by Wang et al. (2008), Mirhedayatian and Saen (2011), and Wang and Chin (2009) that the approach of integrated-DEAHP for derivation and aggregation of weights in the AHP was erroneous. Sometimes, the method resulted in counter-intuitive priority vectors for inconsistent pairwise-comparison matrices which highly restricted its application. Therefore, to address these drawbacks, the above researchers reassessed the integrated DEAHP approach by using examples such as research fellow recruitment (Wang et al., 2008), and university president recruitment (Wang & Chin, 2009; Mirhedayatian & Saen, 2011), all of which fall under expert evaluation and selection.

The other problems studied included facility layout design selection (Yang & Kuo, 2003; Amin & Toloo, 2007; Ertay et al., 2006), government agency location selection

and evaluation (Takamura & Tone, 2003), a supplier efficiency and productivity measurement problem that falls under performance evaluation and efficiency measurement (Sinuany-Stern et al., 2000; Zarei et al., 2012; Omid & Zegordi, 2015; Giokas & Pentzaropoulos, 2008), assessment and optimization of personal productivity (Azadeh, 2011), financial performance assessment (Pakkar, 2014), agility-enablers identification and agility measurement that falls under business unit evaluation (Saleeshya & Babu, 2012), bridge risk assessment (Wang et al., 2008), emerging logistics performance evaluation and efficiency measurement (Zhang & Fu, 2012), evaluation and selection of business firm unit (Ahmad et al., 2006; Kasap & Kiris, 2013), institutional efficiency measurement that falls under performance evaluation and efficiency measurement (Antonio et al., 2012), service units evaluation as in the case of business unit evaluation (Shirouyehzad & Lofti, 2013), ground water quality evaluation (Kavurmaci & Üstün, 2016), comparison of appropriate decision support of HR practices on organizational performance which falls under process evaluation (Tseng & Lee, 2009), manpower performance evaluation and efficiency measurement (Singh & Aggarwal, 2014), multiplicative aggregation of financial ratios (Pakkar, 2015), port logistics performance as in the case of business unit evaluation (Lozano & Villa, 2009), quantitative risk assessment in multi-modal green logistics (Kengpol & Tuammee, 2015), relative efficiency measurement (Foroughia & Esfahani, 2012), road safety performance (Pakkar, 2016), selection of best alternative for forklifts purchase (Hadad & Hanani, 2011), synthetic financial evaluation (Cai & Wu, 2001) and performance evaluation (Saen et al., 2005; Banwet & Deshmukh, 2008).

Ramanathan (2006) demonstrated performance evaluation and efficiency measurement on a few hypothetical examples where DEA (data envelopment analysis) was propounded. Here, the DEA was used for the generation of local weights of alternatives from the pair-wise comparison judgment matrices which is used in the AHP.

A literature review paper, Ho (2008) concentrated on literature from 1997 to 2006 with a wide view and huge number of diversified applications of AHP/DEA.

5. Integrated DEAHP approaches and applications

5.1 Integrated-DEAHP and fuzzy-set theory

The concept of fuzzy-set theory empowers decision-makers to consider uncertainty or fuzziness by rendering interval judgments. According to Table 2**,** the fuzzy (DEAHP-fuzzy) approach has been applied in 14 articles. The table shows their categorization of application areas and specific problems.

Table 2
The integrated DEAHP-fuzzy set theory approach and its applications

Approach	Authors	Application areas	Specific Problems
DEAHP-Fuzzy	Li et al. (2016)	Logistics	Business unit evaluation
	Loron et al. (2015)	Construction	Project/program evaluation and selection
	Alem et al. (2013)	Multiple Industries	Performance evaluation & Efficiency measurement
	Huang & Chi (2015)	Tourism	Location Evaluation
	Che et al. (2010)	Financial	Process evaluation
	Çalik et al. (2018)	Government	Performance evaluation & Efficiency measurement
	Gupta et al. (2018)	Logistics	Project/program evaluation and selection
	Hadi-Vencheh & Mohamadghasemi (2011)	Manufacturing	Inventory control (multiple criteria ABC inventory classification)
	Kumar et al. (2014)	Telecommunication	Expert evaluation and selection
	Kuo et al. (2010)	Manufacturing	Supplier evaluation and section
	Lee et al. (2010)	Energy	Process evaluation
	Lee et al. (2011)	Energy	Technological evaluation
	Lee et al. (2013)	Energy	Resource allocation
	Parameshwaran et al. (2009)	Manufacturing	Business unit evaluation
Total	**14**		

The integrated DEAHP-fuzzy approach has been applied to efficiency measurement and performance evaluation (Lee et al., 2010; Lee et al., 2011; Alem et al., 2013; Çalik, 2018) along with benchmarking (Parameshwaran, 2009). Alem et al. (2013) demonstrated his work using a few hypothetical examples. Several articles applied the integrated DEA/AHP-fuzzy approach for efficiency allocation (Lee et al., 2013), customers' preference analysis and relative efficiency measurement (Kumar et al., 2014), efficiency measurement (Li et al., 2016), supplier evaluation and selection/performance evaluation (Kuo et al., 2014), inventory control (multiple criteria ABC inventory classification) (Hadi-Vencheh & Mohamadghasemi, 2011), efficient loaning decision making (Che et al., 2010), intelligent building assessment (Loron et al., 2015), competitiveness evaluation (Huang & Chi, 2015) and extended capacitated sustainable transportation problem (Gupta et al., 2018).

5.2 Integrated DEAHP and mathematical programming

The integrated DEAHP approach combined with mathematical programming approaches was used in four articles from 2008 to 2018 as shown in Table 3 with their categorization of application areas and specific problems. These mathematical programming approaches were LP (linear programming) and GP (goal programming). In these approaches, the relative importance of criteria and alternatives was evaluated and quantified by the DEAHP. The objective function or constraints of a mathematical programming model were then incorporated with the DEAHP-derived weights. Apart from these, there are other mathematical

programming approaches like MOLP (multi-objective linear programming), DP (dynamic programming) and, MILP (mixed-integer linear programming) which have not been integrated with DEAHP.

Table 3
The integrated DEAHP-mathematical programming approaches and their applications

Approach	Authors	Application areas	Specific Problems
DEAHP-GP	Jatuphatwarodom et al. (2018)	Manufacturing	Supplier evaluation and section
DEAHP-GP	Kumar & Babu (2012)	Manufacturing	Supplier evaluation and section
DEAHP-LP	Falsini et al. (2012)	Logistics	Supplier evaluation and section
DEAHP-LP	Wang et al. (2008)	Multiple Industries	Multiple Problem Areas
Total	**4**		

5.2.1 Integrated DEAHP-GP approach

Kumar and Babu (2012) used the integrated DEAHP-GP approach. This framework makes use of a multi-stage process which is comprised of approaches, namely DEA, AHP and PGP (pre-emptive goal programming) applied to the problem of supplier selection and evaluation in IT service and general manufacturing sectors. First, this framework makes use of an AHP-based methodology to decide whether to choose outsourcing or not and then from whom to outsource. After this, a DEA-based method was followed, where the relative efficiencies of the priority sources, identified by AHP were determined. Finally, the best source from the given number of sources for the given targets of the outsourcer was identified by an AHP-PGP formulation.

Jatuphatwarodom et al. (2018) exhibited extended goal programming (EGP) along with the combined approach of AHP and DEA so that managerial decision support could be provided. Initially, the DEA was used in a descriptive sense to provide information regarding the efficiency for a set of units. After that, the AHP was used to determine the importance of criteria which arises from decision problem(s) which are in turn related to the improvement of unit-efficiency. In the final stage, in order to improve unit-efficiency, EGP was used in a prescriptive sense for the selection of a set of specific actions. Two specific multi-objective situations in the Thai silk industry were used as case studies for the proposed methodology. These involved supplier selection and inventory management with multiple conflicting goals and objectives. In the aforementioned case studies, the DEA was used to provide efficiency estimates of current suppliers and processes. After that, the AHP was used to determine the relative importance of criteria for the improvement of efficiency in the supply chain processes. In order to deal with high levels of inconsistency, adaptations were made to an automated inconsistency reduction algorithm. The relationship between the decision maker's confidence and consistency was then investigated. In the final stage, an EGP model was built to recommend actions for improvement to the supply chain processes.

5.2.2 Integrated DEAHP-LP approach

Falsini et al. (2012) applied the integrated DEAHP-LP approach in supplier evaluation and selection which proposed an evaluation method in the logistics sector that aims at providing an efficient and effective decision support system to select suppliers. This system is easy to use, avoids limitations in the application field and is able to effectively manage multi-criterion complexity. An integrated-DEAHP-LP method for generating the most favorable weights from a pairwise-comparison matrix was demonstrated by Wang et al. (2008). A LP (linear programming method) for the generation of the most favorable weights (LP-GFW) from pairwise-comparison matrices was given by this article. The variable-weight concept of DEA into the priority scheme of the AHP was incorporated by this method to generate the most favorable weights for the underlying criteria and alternatives based on a crisp pairwise comparison matrix. Precise weights for perfectly consistent pairwise comparison matrices and approximate weights for inconsistent pairwise comparison matrices were generated by this LP-GFW method. These weights are not significantly different than Saaty's principal right eigenvector weights. In the article, rank preservation methods and the issue of aggregation of local but the most favorable weights are also discussed. To demonstrate its significant advantages and potential applications over some of the previously prevailing priority methods, four hypothetical numerical examples were examined using the LP-GFW method.

5.3 Integrated DEAHP and simulation

One article was found that applied the integrated DEAHP and simulation (DEAHP-simulation) approach for performance evaluation and efficiency measurement in the railway sector as shown in Table 4 with the categorization of application area and specific problem**.**

Table 4
The integrated DEAHP-simulation approach and application

Approach	Authors	Application areas	Specific Problems
DEAHP-Simulation	Azadeh et al. (2008)	Railways	Performance evaluation & Efficiency measurement
Total	**1**		

To improve and optimize the railway system by means of efficiency assessment and performance optimization an integrated simulation, multiple decision analysis, and multivariate analysis were presented by Azadeh et al. (2008). Moreover, the integrated model was based on the AHP and DEA which was integrated with computer simulation. The optimum alternatives can be selected by considering multiple qualitative and quantitative outputs and inputs when using the integrated AHP and DEA model with simulation. To begin with, the system being studied was model verified and validated by the computer simulation. After that, the weight of any qualitative criteria (outputs or input) was determined by the AHP methodology. In the end, the multi-objective model was solved by using the DEA model. This allows the best alternative(s) as well as the mechanism for optimizing the current system to be identified.

5.4 Integrated DEAHP and other approaches

Seven papers were found that applied the integrated DEAHP with other approaches as shown in Table 5 with their categorization of application areas and specific problems, such as ABC (Activity Based Costing), SBM (Slacks-Based Measure),

TCO (Total cost of ownership), VAHP (Voting AHP), Assurance Region (AR), Grey Relational Analysis (GRA), and Gower Plot.

Table 5
The integrated DEAHP-other approaches and their applications

Approach	Authors	Application areas	Specific Problems
DEAHP-ABC	Zhang et al. (2012)	Electronics	Supplier evaluation and section
DEAHP-SBM	Yuan et al. (2013)	Environment	Resource allocation
DEAHP-TCO	Ramanathan (2007)	Supply chain management	Supplier evaluation and section
DEA-VAHP	Soltanifar & Lotfi (2011)	Healthcare	Performance evaluation & Efficiency measurement
DEAHP-AR	Lai et al. (2015)	Airlines	Performance evaluation & Efficiency measurement
DEAHP-Gower plot	Li & Ma (2008)	Business Administration	Location Evaluation
DEAHP-GRA	Prasad et al. (2017)	Iron / Steel	Supplier evaluation and section
Total	**7**		

The first paper by Zhang et al. (2012) applied the integrated DEAHP-ABC for supplier evaluation and selection in the electronics sector. This article suggested a hybrid and integrated model, based on DEAHP and ABC (activity-based costing) so that the overall efficiency of suppliers and costs (which includes indirect costs and direct costs) could be evaluated. Comprehensive decision support for the selection and evaluation of suppliers can be derived with the help of this model. The order quantity from the preferred suppliers can be integrated with the decision regarding the selection of suppliers by using this hybrid model. Simultaneously, in a single model, a few factors of relevance like the past delivery performance of suppliers, the purchasing budget of the buyer and capacity constraints were considered.

The second article by Yuan et al. (2013) applied integrated DEAHP-SBM which focused on disaster vulnerability assessment and resource allocation. This article developed an integrated index which contained sensitivity, exposure, and adaptive capacity so that regional vulnerability to the drought in China could be measured. The same indicator was calculated by the approach which integrated the SBM (slacks-based measure) model with the DEA along with AHP which was in turn based on a genetic algorithm. The reasons behind drought vulnerability were provided by the calculated integrated index with the integrated-DEAHP approach. Consequently, the proposal for available mitigation strategies for different drought-vulnerable areas was given.

The third article discussed the outcomes of combining AHP and TCO (Total cost of ownership) along with the application of DEA as a way to combine subjective and objective information. This article has been suggested by Ramanathan (2007) which integrates the DEA-TCO-AHP model and applies it to the supplier selection problem. This model is the first work to find its application in the problem of supplier selection.

The fourth article by Soltanifar & Lotfi (2001) applied DEA-Voting AHP for benchmarking, efficiency assessment and performance optimization in healthcare (nursing home) and commercial banks. This article presents a method for ranking efficient DMUs by means of the Voting-Analytic Hierarchy Process (VAHP). A few ranking models in DEA were reviewed in this article along with their strengths and weaknesses. Next, a method for ranking efficient DMUs by VAHP was presented.

The fifth journal article by Lai et al. (2015) applied integrated DEAHP-AR for evaluating the performance efficiency of airports. This article used the AHP and MCDM method for integrating the weightings of output and input variables into AR (Assurance Region) and DEA. In the empirical analysis, 24 major international airports were taken into consideration. This article concluded that the discriminatory power in the suggested model of DEAHP-AR is greater and better than the basic DEA model while the efficiency of airports was being measured. The comparison of operational efficiency between airports can be done effectively by practitioners and policy-makers using this approach. This will help in the generation of more informed decisions.

The sixth paper by Li & Ma (2008) used DEAHP and the Gower plot technique to rank decision alternatives in space/location selection and evaluation. With the integration of AHP, DEA, and Gower plot techniques, an iterative method of ranking decision alternatives was developed. To narrow the range of preferences of the decision maker, a DEA model with modification was first used by this developed method. Then, in order to demonstrate the ordinal and cardinal inconsistencies of these preferences, the decision alternatives' tentative ranks which were computed by embedding the preferences of the decision maker were depicted by means of Gower plots. After that, until the inconsistencies come within the tolerance, the decision maker keeps adjusting the preferences in an iterative manner.

The seventh paper by Prasad et al. (2017) applied DEAHP-GRA for supplier evaluation and selection in the steel manufacturing sector. This article offered a hybrid methodology using AHP, DEA and Grey Relational Analysis (GRA) for assessing suppliers and for picking the best supplier for an organization. In this work, the suppliers' performance scores and efficiencies were discovered using the DEA methods of cross-efficiency and super-efficiency, respectively. The total list of efficient suppliers showing high-performance levels was based on cross-efficiency scores and super-efficiency scores. The best supplier was discovered using GRA methodology.

5.5 Integrated DEAHP and multiple approaches

Five articles found their applications with the integration of DEAHP with more than one approach or method (DEAHP-multiple approach), as illustrated in Table 6 with their categorization of application areas and specific problems. Two of the papers combined the fuzzy-set theory and the DEAHP with other different methods or approaches like TOPSIS (Rezaei-Shouroki et al., 2017) and QFD-LP (Kamvysi et al., 2014). There are three other journal articles that combined the DEAHP with multiple approaches, but have not considered fuzzy-set theory for integration with DEAHP. Moreover, these three other papers have integrated DEAHP with 2-Level SOM & AR (Yu & Lee, 2013), Delphi-LP (Raut, 2014) and QFD-DEANP (Kamvysi et al., 2010). Hence, two papers by Kamvysi et al. (2014) and Raut (2014) used the integrated DEAHP approach and LP approach along with other approaches. Again, there are

two papers about QFD-DEANP that used the integrated DEAHP approach and QFD approach along with other approaches (Kamvysi et al., 2010; Kamvysi et al. 2014).

Table 6
The integrated DEAHP-multiple approaches and their applications

Approach	Authors	Application areas	Specific Problems
DEAHP, FUZZY, QFD, LP	Kamvysi et al. (2014)	Higher education	Course design evaluation and selection
DEAHP, Delphi, LP	Raut (2014)	Pharmaceuticals	Supplier evaluation and section
DEAHP, 2-Level SOM, AR	Yu & Lee (2013)	Nano Technology	Technological evaluation
DEAHP, TOPSIS, FUZZY	Rezaei-Shouroki et al. (2017)	Energy	Location Evaluation
DEAHP, QFD, DEANP	Kamvysi et al. (2010)	Banking	Service evaluation and selection
Total	**5**		

Yu & Lee (2013) applied the integrated DEAHP with 2 Level SOM & AR for the evaluation and selection of nano-technology. A method of AHP-rating was used for assessing the importance of emerging technology alternatives rather than pairwise comparison since there are a large number of alternatives that are independent to each other. The importance value was termed as the AHP score within this paper. Finally, the cumulative score of each emerging technology alternative was calculated using the suggested method by means of the addition of the scores of AHP and of DEA of the alternatives. The emerging technology alternatives' cumulative scores indicate the most promising emerging technology.

Rezaei-Shouroki et al. (2017) used integrated DEAHP with TOPSIS for evaluating and selecting locations for wind farm/wind energy. The method of DEA and a list of technical, economic and geological factors were utilized in this paper for prioritization and ranking of thirteen cities in the Fars' province with respect to their appropriateness for the building of a wind farm. The validity of the obtained results was evaluated using FTOPSIS and AHP.

Kamvysi et al. (2014) applied the integrated DEAHP-Fuzzy-QFD-LP in higher education to evaluate and select course design. The usage of a substitute alternate framework to prioritize the requirements of students was suggested and tested using QFD (quality density function). More explicitly, to account for the inherent subjectivity of human judgments, a Fuzzy-AHP and LP (LP-GW-AHP) method which is based on DEA was integrated with QFD (QFD-LP-GW-Fuzzy-AHP). Capturing and prioritizing the requirements of students with respect to the learning outcomes of courses within the academic course design's process was evaluated on the effectiveness of the proposed framework. The robustness of the prioritization solution was assessed with a sensitivity analysis. The implications were discussed for the specifications of the design of the course.

Kamvysi et al. (2010) applied the integrated DEAHP as QFD-DEAHP-DEANP in the Greek banking sector to evaluate the banking services so that the best selection could be presented to help customers choose their bank according to their preference of banking services mix. This article used DEAHP so that the relationship-matrix of

HOQ (house of quality) was completed. Also, a methodological framework to complete the roof matrix of HOQ was developed while using the DEAHP approach, and it was based on the DEA and ANP techniques which gave rise to DEANP. The implementation of QFD along with the abovementioned quantitative approaches was studied utilizing data from the Greek banking sector and a comparative analysis was conducted.

The paper by Raut (2014) was applied to the pharmaceutical sector where the DEAHP was combined with the Delphi-LPP multi-criteria decision-making approach to select a supplier and to allocate a system for order quantity. The methodology which was based on integrated-Delphi-AHP-DEA-LPP (DADLP) was used. This methodology was organized into a four phases. The initial phase was the Delphi-method. In the Delphi method, a new and consistent scale for measurement was developed after identifying, synthesizing and prioritizing important factors and sub-factors of performance. The AHP and DEA-LP based MCDM was developed for both quantitative and qualitative factors in the selection of suppliers. The product characteristics were matched with supplier characteristics (using supplier ratings derived from pair wise comparisons) by the AHP method to determine the strategy of the supply-chain qualitatively. The efficient suppliers were evaluated and determined from the selected suppliers, mathematically using DEA. The variations of pair-wise comparisons in AHP will affect the final order quantity because AHP ratings are taken as input by LP and DEA.

6. Observations and discussions

This literature review looked at 72 journal articles published between 2000 and 2018 that studied the stand-alone DEAHP approach and integrated DEAHP with other approaches. 31 articles were identified that applied the integrated DEAHP approach with other approaches, and the rest of the 41 articles concentrated on the stand-alone DEA/AHP approach without being associated with a third approach. Methods such as simulation, mathematical programming, fuzzy-set theory, and others were found to have been combined with the integrated DEAHP approach. Some of the articles used more than one approach (multiple approaches). The stand-alone DEAHP approach and integrated DEAHP along with other approaches are summarized in Tables 1 – 6 with their categorization of application areas and specific problems. Based on the categorization of these 72 journal articles, five questions can be answered: (1) Which integrated-DEAHP approach was most prevalent and received the utmost attention?, (2) Which areas of application were most often studied and found their application with integrated DEAHP approaches?, (3) Which of the specific problems were most frequently applied to integrated DEAHP approaches?, (4) What are the publications trends for the papers considering the integrated DEAHP approaches?, and (5) Which journals of international standards published how many journal articles and among them which have the highest number of articles on the approach of integrated DEAHP? Over and above answering these queries, this journal article also seeks to reiterate the work in Ho (2008) and, in some manner to further extend its work from integrated AHP to integrated DEAHP.

6.1 The most prevalent integrated-DEAHP approach

The foremost query seeks to identify the most prevalent approach of integrated-DEAHP. As tabulated in Tables 2–5, 26 articles out of a total of 72 used the integrated DEAHP approach with only one method. However as shown in Table 6, in 5 of the articles two or more methods were integrated with the DEAHP approach

(also known as integrated DEAHP-multiple approaches). As observed in Tables 2–5, the fuzzy-set theory (14 out of 26 articles) was the most prevalent method integrated with the DEAHP, followed by mathematical programming (4 articles), simulation (1 article), and some others (7 articles), including VAHP (Voting AHP), TCO (Total cost of ownership), Gower plot, ABC (Activity Based Costing), SBM (Slacks-Based Measure), Assurance Region (AR), and Grey Relational Analysis (GRA).

It can be seen from Table 6 that a varied number of integrated DEAHP-multiple approaches exist. A major part of these selected studies integrated the DEAHP with 2 methods (4 out of 5 articles), followed by 3 methods (1 article). As no single approach overpowers another in the combination, the most prevalent method applied in the integrated DEAHP-multiple approaches was determined by developing Table 7. The top three methods were fuzzy-set theory (2 out of 5 articles), LP which is a subset of mathematical programming (2 articles) and QFD (2 articles) which is followed by TOPSIS (1 article), AR (1 article), Delphi (1 article), DEANP (1 article) and 2-Level SOM (1 article) as shown in Table 7.

Table 7
Summary of methods (other than DEAHP) used in the integrated DEAHP-multiple approaches

Methods	**Number of Articles**	**Authors**
Fuzzy set theory	2	Kamvysi et al. (2014), Rezaei-Shouroki et al. (2017)
LP	2	Kamvysi et al. (2014), Raut (2014)
QFD	2	Kamvysi et al. (2010), Kamvysi et al. (2014)
TOPSIS	1	Rezaei-Shouroki et al. (2017)
AR	1	Yu & Lee (2013)
Delphi	1	Raut (2014)
DEANP	1	Kamvysi et al. (2010)
2-Level SOM	1	Yu & Lee (2013)

Based on the written and tabulated observations above, it can be seen that the integrated DEAHP-fuzzy approach gained major attraction and attention between 2009 and 2018. Furthermore, linear mathematical programming (LP), quality density function (QFD) and fuzzy-set theory were found to be commonly integrated with the DEAHP in the integrated DEAHP-multiple approaches. From Table 2**,** fuzzy set theory was integrated with DEAHP in 14 out of 31 journal articles. The key rationale is that the crisp pairwise-comparison in conventional DEAHP is unable to bear ambiguity or vagueness. Thus, in an uncertain pairwise-comparison environment, fuzzy-numbers and linguistic terms have been extensively used (Lee, 2009; Liang, 2015). Unambiguously, the fuzzy-set theory has the additional benefit of being similar to human-reasoning in its use of approximate information and uncertainty to address MCDM problems when information is incomplete and imprecise (Chan & Kumar, 2007).

6.2 The most frequently studied area of application

The next query aimed to find out the most frequently studied area of application. As illustrated in Table 8, there are 28 application areas and 1 literature review that has

been applied to different fields. Among the application areas mentioned in Table 8, manufacturing has attracted the maximum attention, followed by logistics, government, energy, higher education, electronics, multiple industries, airlines, banking, environment, iron/steel, financial, telecommunications, business administration, construction, defence industry, e-commerce, healthcare, hotel industry, human resource, nano-technology, pharmaceuticals, process, R & D, railways, rental cars, supply chain management and tourism sectors. One paper was a literature review paper.

Among 16 articles dedicated to the manufacturing sector, the approach of the fuzzy-set theory was extensively used in combination with DEAHP, including 3 integrated DEAHP-fuzzy approaches and 2 integrated DEAHP-goal programming approach (DEAHP-mathematical programming).

Table 8
Summary of application areas

Application areas	**Approaches**	**Number of articles**	**Sub-Total**	**Authors**
Airlines	DEA-AHP (General)	1	2	Foroughia & Esfahani (2012)
	DEAHP-AR	1		Lai et al. (2015)
Banking	DEA-AHP (General)	2	3	Pakkar (2015)
				Omid & Zegordi (2011)
	DEAHP-QFD-DEANP	1		Kamvysi et al. (2010)
Business Administration	DEAHP-Gower Plot	1	1	Li & Ma (2008)
Construction	DEAHP-Fuzzy	1	1	Loron et al. (2015)
Defence Industry	DEA-AHP (General)	1	1	Moon & Kang (2015)
E-Commerce	DEA-AHP (General)	1	1	Aji & Hariga (2013)
Electronics	DEA-AHP (General)	2	3	Tseng & Lee (2009)
				Yang & Kuo (2003)
	DEAHP-ABC	1		Zhang et al. (2011)
Energy	DEA-AHP (General)	1	5	Kasap & Kiriş (2010)
	DEAHP-Fuzzy	3		Lee et al. (2011) Lee et al. (2013) Lee et al. (2017)
	DEAHP-TOPSIS-Fuzzy	1		Rezaei-Shouroki et al. (2013)

Environment	DEA-AHP (General)	1	2	Kavurmaci & Üstün (2016)
	DEAHP-SBM	1		Yuan et al. (2013)
Financial	DEA-AHP (General)	1	2	Cai & Wua (2001)
	DEAHP-Fuzzy	1		Che et al. (2010)
Government	DEA-AHP (General)	4	5	Lin et al. (2011)
				Pakkar (2016)
				Saen et al. (2018)
				Takamura & Tone (2005)
	DEAHP-Fuzzy	1		Çalik et al. (2003)
Healthcare	DEA-VAHP	1	1	Soltanifar & Lotfi (2011)
Higher education	DEA-AHP (General)	4	5	Antonio et al. (2014)
				Wang et al. (2008)
				Wang & Chin (2009)
				Mirhedayatian & Saen (2011)
	DEAHP-Fuzzy-QFD-LP	1		Kamvysi et al. (2012)
Hotel	DEA-AHP (General)	1	1	Shirouyehzad et al. (2013)
Human resource	DEA-AHP (General)	1	1	Singh & Aggarwal (2014)
Iron / Steel	DEA-AHP (General)	1	2	Pakkar (2014)
	DEAHP-GRA	1		Prasad et al. (2017)
Literature Review	DEA-AHP (General)	1	1	Ho (2008)
Logistics	DEA-AHP (General)	3	6	Kengpol & Tuammee (2015)
				Lozano & Villa (2009)
				Zhang & Fu (2012)
	DEAHP-Fuzzy	2		Li et al. (2016)
				Gupta et al. (2018)
	DEAHP-LP	1		Falsini et al. (2012)
Manufacturing	DEA-AHP (General)	11	16	Ahmad et al. (2006)
				Amin & Toloo (2007)
				Omid & Zegordi (2015)

				Hadad & Hanani (2011) Zarei et al. (2012) Saleeshya & Babu (2012) Sevkli et al. (2007)
	DEAHP-Fuzzy	3		Sinuany-Stern et al. (2000) Wang et al. (2008) Yadav & Sharma (2015) Ertay et al. (2011) Hadi-Vencheh & Mohamadghasemi (2010) Kuo et al. (2009)
	DEAHP-GP	2		Parameshwaran et al. (2012) Jatuphatwarodom et al. (2018) Kumar & Babu (2012)
Multiple Industries	DEA-AHP (General)	1	3	Ramanathan (2006)
	DEAHP-Fuzzy	1		Alem et al. (2013)
	DEAHP-LP	1		Wang et al. (2008)
Nano Technology	DEAHP-AR-2 Level SOM	1	1	Yu & Lee (2013)
Pharmaceuticals	DEAHP-Delphi-LPP	1	1	Raut (2014)
Process	DEA-AHP (General)	1	1	Korpela et al. (2007)
R & D	DEA-AHP (General)	1	1	Banwet & Deshmukh (2008)
Railways	DEAHP-Simulation	1	1	Azadeh et al. (2008)
Rental cars	DEA-AHP (General)	1	1	Sueyoshi et al. (2009)
Supply chain management	DEAHP-TCO	1	1	Ramanathan (2007)
Telecommunication	DEA-AHP (General)	1	2	Giokas & Pentzaropoulos (2008)
	DEAHP-Fuzzy	1		Kumar et al. (2014)
Tourism	DEAHP-Fuzzy	1	1	Huang & Chi (2015)
Total		**72**	**72**	

A graphical representation of the application areas and corresponding number of articles is summarized below.

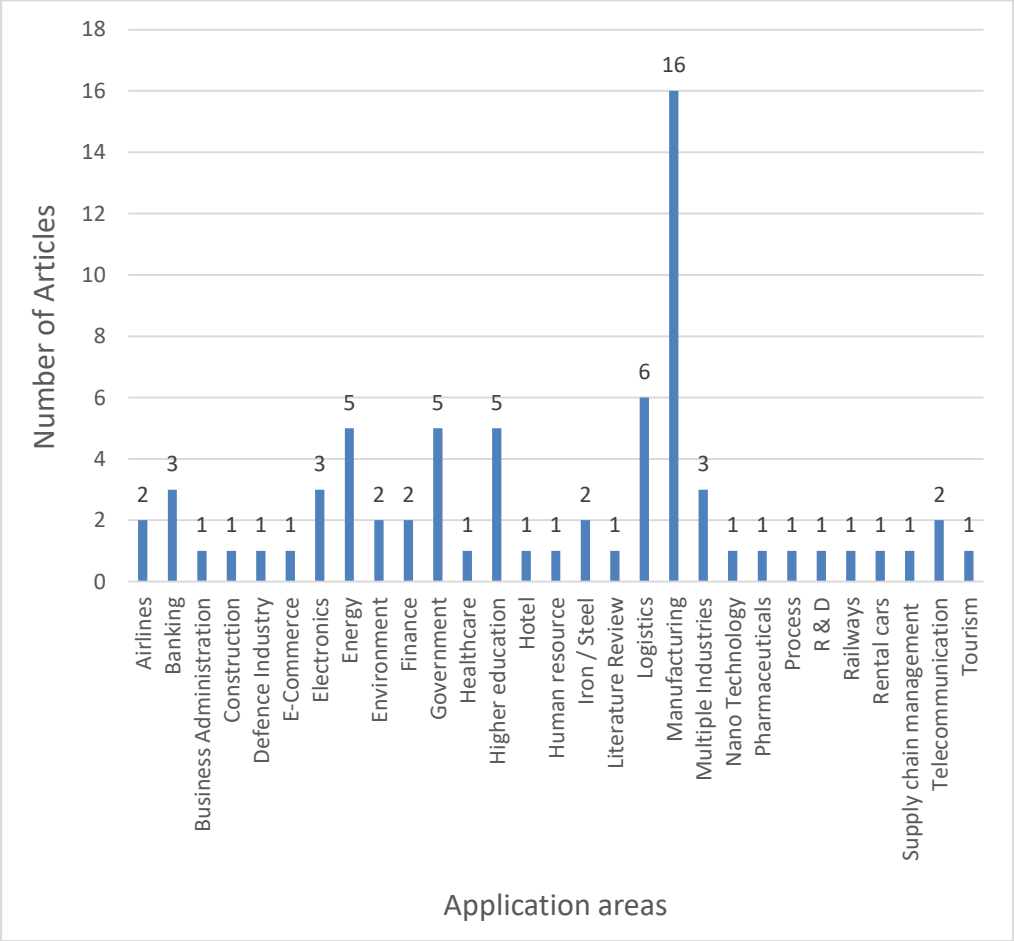

Figure 3 Summary of application areas and their corresponding number of articles

6.3 The most frequently studied specific problem

The third query aimed to discover the most frequently studied specific problem. Table 9 shows that 1 literature review and 19 problems were studied. The problem of performance evaluation & efficiency measurement gained the maximum attention, followed by evaluation and supplier selection, evaluation of a business unit, evaluation of a process, evaluation and selection of an expert, evaluation of a location, selection of a facility layout, allocation of resources, evaluation and selection of a project/program, evaluation and selection of a product, evaluation and selection of a service, technological evaluation, multiplicative aggregation of financial ratios, course design evaluation and selection, inventory control (multiple criteria ABC inventory classification), multiple problem areas, personal productivity evaluation, quality evaluation and risk assessment. One paper was developed as a literature review.

18 of 72 articles addressed performance evaluation and efficiency measurement out of which 5 articles applied integrated DEAHP which includes 2 papers with integrated DEAHP-fuzzy approach, 1 paper with integrated DEAHP-AR, 1 paper with integrated DEA-VAHP and 1 paper with integrated DEAHP-simulation.

Table 9
Summary of specific problems

Specific Problems	**Approaches**	**Number of articles**	**Sub-Total**	**Authors**
Business unit evaluation	DEA-AHP (General)	9	11	Foroughia & Esfahani (2012) Ahmad et al. (2006) Korpela et al. (2007) Kasap & Kiriş (2013) Shirouyehzad et al. (2013) Kengpol & Tuammee (2015) Lozano & Villa (2009) Saleeshya & Babu (2012) Sueyoshi et al. (2009)
	DEAHP-Fuzzy	2		Li et al. (2016) Parameshwaran et al. (2009)
Course design evaluation and selection	DEAHP-Fuzzy-QFD-LP	1	1	Kamvysi et al. (2014)
Expert evaluation and selection	DEA-AHP (General)	3	4	Wang et al. (2008) Wang & Chin (2009) Mirhedayatian & Saen (2011)
	DEAHP-Fuzzy	1		Kumar et al. (2014)
Facility Layout Selection	DEA-AHP (General)	3	3	Yang & Kuo (2003) Amin & Toloo (2007) Ertay et al. (2006)
Inventory control (multiple criteria ABC inventory classification)	DEAHP-Fuzzy	1	1	Hadi-Vencheh & Mohamadghasemi (2011)
Literature Review	DEA-AHP (General)	1	1	Ho (2008)
Location Evaluation	DEA-AHP (General)	1	4	Takamura & Tone (2003)
	DEAHP-Fuzzy	1		Huang & Chi (2015)
	DEAHP-TOPSIS-Fuzzy	1		Rezaei-Shouroki et al. (2017)

	DEAHP-Gower plot	1		Li & Ma (2008)
Multiple Problem Areas	DEAHP-LP	1	1	Wang et al. (2008)
Multiplicative aggregation of financial ratios	DEA-AHP (General)	1	1	Pakkar (2015)
Performance evaluation & Efficiency measurement	DEA-AHP (General)	13	18	Lin et al. (2011) Pakkar (2016) Saen et al. (2005) Antonio et al. (2012) Singh & Aggarwal (2014) Pakkar (2014) Zhang &Fu (2012) Omid & Zegordi (2015) Zarei et al. (2012) Sinuany-Stern et al. (2000) Ramanathan (2006) Banwet & Deshmukh (2008) Giokas & Pentzaropoulos (2008)
	DEAHP-Fuzzy	2		Çalik et al. (2018) Alem et al. (2013)
	DEAHP-AR	1		Lai et al. (2015)
	DEA-VAHP	1		Soltanifar & Lotfi (2011)
	DEAHP-Simulation	1		Azadeh et al. (2008)
Personal productivity evaluation	DEA-AHP (General)	1	1	Azadeh et al. (2011)
Process evaluation	DEA-AHP (General)	2	4	Tseng & Lee (2009) Cai & Wua (2001)
	DEAHP-Fuzzy	2		Lee et al. (2010) Che et al. (2010)
Product evaluation and selection	DEA-AHP (General)	1	1	Hadad & Hanani (2011)

Service evaluation and selection	DEAHP-QFD-DEANP	1	1	Kamvysi et al. (2010)
Project/program evaluation and selection	DEAHP-Fuzzy	2	2	Loron et al. (2015)
				Gupta et al. (2018)
Quality evaluation	DEA-AHP (General)	1	1	Kavurmaci & Üstün (2016)
Resource allocation	DEAHP-Fuzzy	1	2	Lee et al. (2013)
	DEAHP-SBM	1		Yuan et al. (2013)
Risk assessment	DEA-AHP (General)	1	1	Wang et al. (2008)
Supplier evaluation and selection	DEA-AHP (General)	4	12	Moon & Kang (2015)
				Aji & Hariga (2013)
				Sevkli et al. (2007)
				Yadav & Sharma (2015)
	DEAHP-Fuzzy	1		Kuo et al. (2010)
	DEAHP-LP	1		Falsini et al. (2012)
	DEAHP-GP	2		Jatuphatwarodom et al. (2018)
				Kumar & Babu (2012)
	DEAHP-Delphi-LPP	1		Raut (2014)
	DEAHP-ABC	1		Zhang et al. (2011)
	DEAHP-GRA	1		Prasad et al. (2017)
	DEAHP-TCO	1		Ramanathan (2007)
Technological evaluation	DEAHP-Fuzzy	1	2	Lee et al. (2011)
	DEAHP-AR-2 Level SOM	1		Yu & Lee (2013)
Total		**72**	**72**	

A graphical representation of specific problems and corresponding number of articles is summarized below.

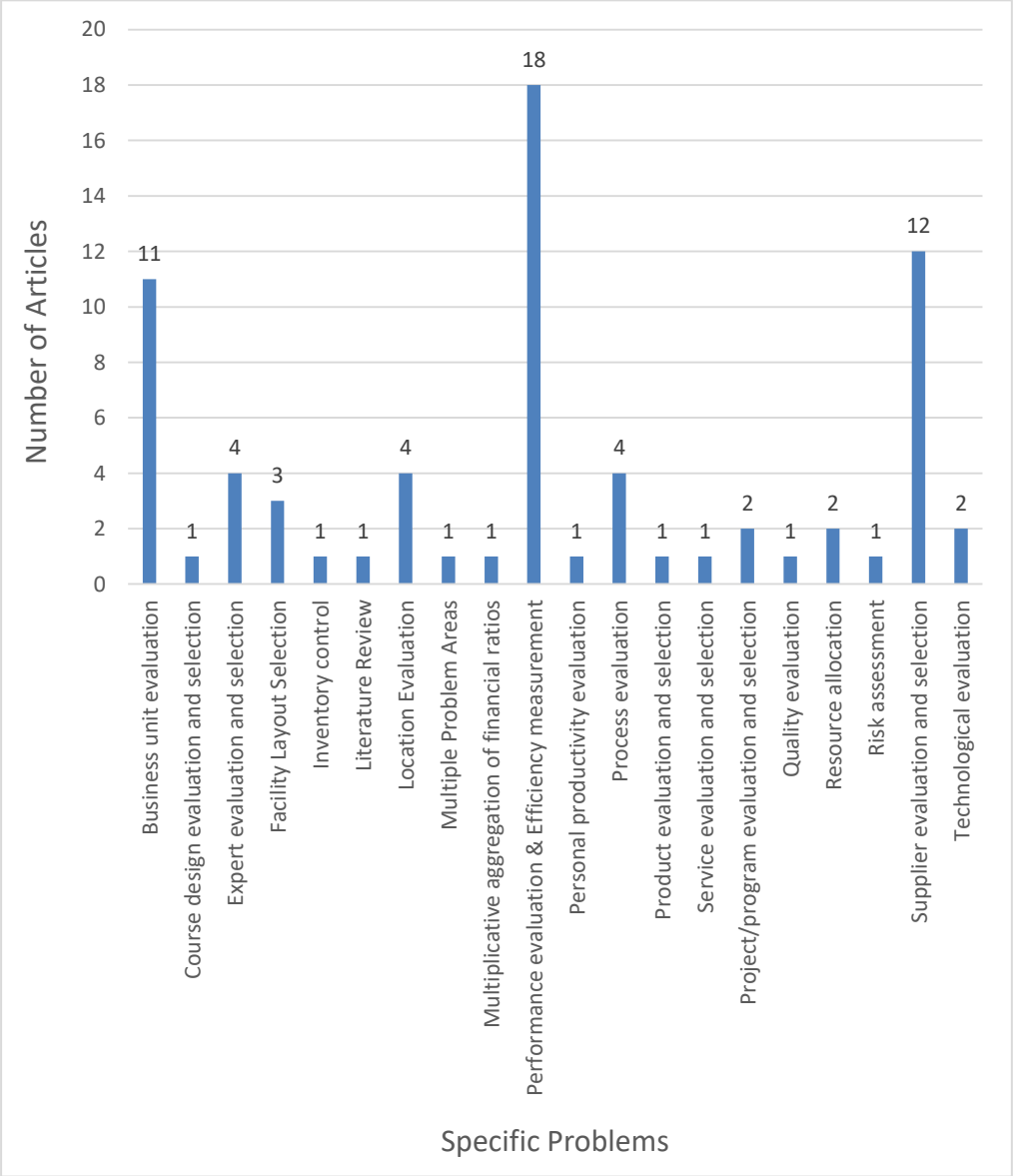

Figure 4 Summary of specific problems and their corresponding number of articles

6.4 Publication trends

Table 10 presents the distribution of the 72 journal papers over the last two decades (19 years to be precise) for both stand-alone DEAHP and integrated DEAHP with other approaches.

Table 10
Distribution of the number of journal articles since 2000

Years	Number of articles			
	Standalone DEA/AHP approach	**Integrated DEAHP approach**		
	Integration with no method	**Integration with one method**	**Integration with multiple methods**	**Total**
2000	1	0	0	1
2001	1	0	0	1
2002	0	0	0	0
2003	2	0	0	2
2004	0	0	0	0
2005	1	0	0	1
2006	3	0	0	3
2007	3	1	0	4
2008	5	3	0	8
2009	4	1	0	5
2010	0	3	1	4
2011	4	4	0	8
2012	5	2	0	7
2013	3	3	1	7
2014	2	1	2	5
2015	5	3	0	8
2016	2	1	0	3
2017	0	1	1	2
2018	1	3	0	2
Total		**26**	**5**	**72**
	41	**31**		

There are 41 articles that considered stand-alone DEAHP with the integration of no other approach to be sufficient to address the paper's problem definition. However, there are 31 journal articles that specifically applied integrated DEAHP approaches. Out of these 31 articles which have applied integrated DEAHP, there are 26 articles which have integrated DEAHP with only one method. 5 papers found the need for more than one approach to be integrated with DEAHP to satisfy the problem definition. The articles for the stand-alone DEAHP were published between 2000 to 2018. There are 31 journal articles for the integrated DEAHP approach from 2007 to 2018. Based on Table 10, it is clearly visible that stand-alone DEAHP has been equally used in terms of numbers of articles published in both decades. It cannot be overlooked that there were no papers published before 2006 for the integrated DEAHP approach, but this fact is substantiated with the increase in the number of publications on the subject after 2007. Also, in 2010, papers with the integration of multiple approaches to DEAHP began to be published. Papers with integrated DEAHP approaches have attracted more attention since 2007 and it is estimated that it will continue to do the same after 2018 with the changing needs of the competitive business environment.

A graphical representation of publication trends and corresponding number of articles is summarized below.

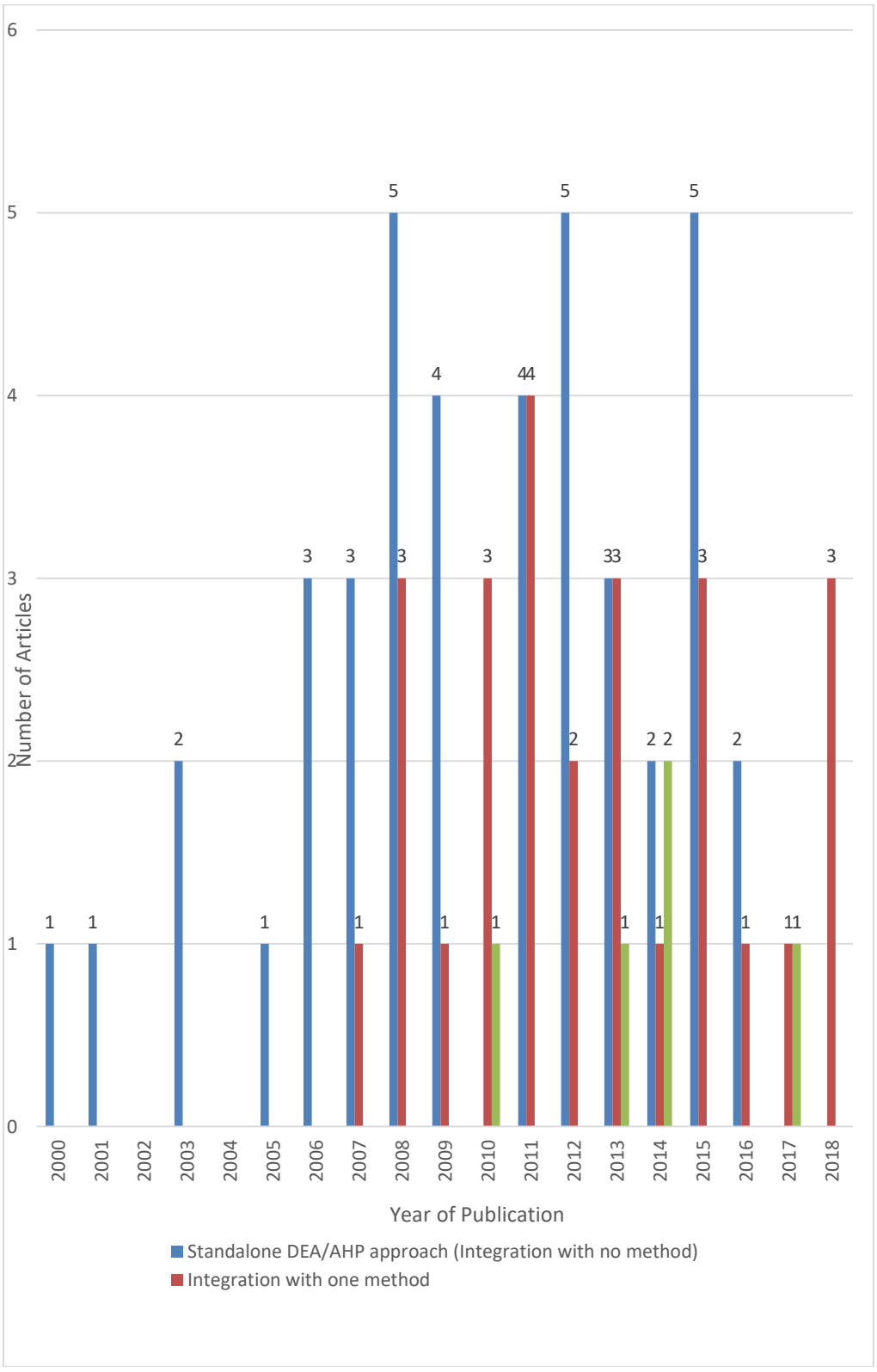

Figure 5 Summary of publication trends and their corresponding number of articles

6.5 The most frequently published journal

Table 11 lists all of the international journals in which integrated DEAHP and stand-alone DEAHP approaches were published.

Table 11
Summary of journals

Journals	Number of articles	Authors
African Journal of Business Management	1	Antonio et al. (2012)
American Journal of Operations Research	1	Pakkar (2014)
Annals of Operations Research	1	Jatuphatwarodom et al. (2018)
Applied Mathematics and Computation	2	Saen et al. (2005), Azadeh et al. (2008)
Computers & Industrial Engineering	3	Amin & Toloo (2007), Wang et al. (2008), Soltanifar & Lotfi (2011)
Computers & Operations Research	3	Ramanathan (2006), Wang et al. (2008), Lozano & Villa (2009)
Decision Science Letters	1	Omid & Zegordi (2015)
Decision Support Systems	1	Wang et al. (2008)
Energy Sources, Part B: Economics, Planning, and Policy	1	Kasap & Kiriş (2013)
Environmental Monitoring and Assessment	1	Kavurmaci & Üstün (2016)
European Journal of Industrial Engineering	1	Parameshwaran et al. (2009)
European Journal of Operational Research	6	Yang & Kuo (2003), Ho (2008), Sueyoshi et al. (2009), Wang & Chin (2009), Lin et al. (2011), Kamvysi et al. (2014)
Expert Systems with Applications	5	Tseng & Lee (2009), Che et al. (2010), Hadi-Vencheh & Mohamadghasemi (2011), Azadeh et al. (2011), Yu & Lee (2013)
Information Sciences	1	Ertay et al. (2006)
International Journal of Applied Decision Sciences	1	Aji & Hariga (2013)
International Journal of Business and Systems Research	1	Saleeshya & Babu (2012)
International Journal of Hydrogen Energy	3	Lee et al. (2010), Lee et al. (2011), Rezaei-Shouroki et al. (2017)
International Journal of Information Technology & Decision Making	2	Ahmad et al. (2006), Li & Ma (2008)
International Journal of Logistics Systems and Management	2	Hadad & Hanani (2011), Raut (2014)
International Journal of Operational Research	1	Alem et al. (2013)

International Journal of Production Economics	1	Korpela et al. (2007)
International Journal of Production Research	4	Sevkli et al. (2007), Zhang et al. (2011), Falsini et al. (2012), Kengpol & Tuammee (2015)
International Journal of Productivity and Performance Management	1	Banwet & Deshmukh (2008)
International Journal of Productivity and Quality Management	1	Shirouyehzad et al. (2013)
International Journal of Services and Operations Management	1	Kumar & Babu (2012)
International Journal of Simulation: Systems, Science & Technology	1	Huang & Chi (2015)
International Journal On Advances in Information Sciences and Service Sciences	1	Zhang & Fu (2012)
International Transactions in Operational Research	2	Sinuany-Stern et al. (2000), Cai & Wua (2001)
Journal of Applied Operational Research	1	Pakkar (2015)
Journal of Enterprise Information Management	1	Yadav & Sharma (2015)
Journal of Information and Communication Convergence Engineering	1	Moon & Kang (2015)
Journal of the Operational Research Society	1	Mirhedayatian & Saen (2011)
Journal of the Operations Research Society of China	1	Singh & Aggarwal (2014)
Journal of Traffic and Transportation Engineering	1	Li et al. (2016)
Management Science Letters	2	Foroughia & Esfahani (2012), Zarei et al. (2012)
Mitigation and Adaptation Strategies for Global Change	1	Yuan et al. (2013)
Production Planning & Control: The Management of Operations	1	Kuo et al. (2010)
Renewable and Sustainable Energy Reviews	1	Lee et al. (2013)
Resources Policy	1	Gupta et al. (2018)
Socio-Economic Planning Sciences	1	Takamura & Tone (2003)
Supply Chain Management	1	Ramanathan (2007)
Systems	1	Pakkar (2016)
Technological and Economic Development of Economy	1	Çalik et al. (2018)
Telecommunications Policy	1	Giokas et al. (2008)
Telematics and Informatics	1	Kumar et al. (2014)
The Journal Tehnički vjesnik – Technical Gazette (TV-TG)	1	Loron et al. (2015)
TheTQM Journal	1	Kamvysi et al. (2010)
Transport Policy	1	Lai et al. (2015)
Uncertain Supply Chain Management	1	Prasad et al. (2017)
Total	**72**	

Of the existing 49 journals, 26 have published articles that applied integrated DEAHP and 31 have published articles that applied stand-alone DEAHP. The top three highlighted journals for publication of works related to DEAHP and integrated DEAHP are *European Journal of Operational Research*, followed by *Expert Systems with Applications*, and *International Journal of Production Research*. There is a clear indication that stand-alone DEAHP and integrated DEAHP are spreading their wings in journals of different fields while exploring different application areas.

7. Future work

There is still space for integrated-DEAHP approaches, mainly when the integrations are with multiple methods. There are many areas where integrated DEAHP can be applied to the marketing sector which have not yet been touched by the integrated DEAHP approach. Hence, some recommendations can be pushed for newer applied working areas of the integrated DEAHP approaches. For example, risk management in the supply-chain is considered one of the trending research topics in the field of supply-chain management/operations and it has gained a substantial amount of attention (Ho et al., 2015). Yet, the amalgamation of both downstream and upstream strategies of risk-mitigation in the selection of suppliers has not been studied to a great extent (Ho et al., 2015). Hence, we propose to apply the integration of DEAHP with other approaches in unexplored application areas. For instance, integrated DEAHP approaches could be explored in retail space optimization and allocation for better and more efficiently performing stores. The ultimate aim is to maximize the utilization of the total space available in the planning period and minimize the total cost. Furthermore, we propose the application of the integration of DEAHP to TCO (total cost of ownership), green initiatives, and CSR (corporate social responsibility) for developing a sustainability performance management model which will be holistic in nature for the assessment of suppliers of sustainable SMEs (small and medium-sized enterprise) in emerging economies. Additionally, a procurement contract could be designed by a game model so that the mutual benefits of both the suppliers and the manufacturers could be maximized.

8. Conclusion

This paper reviewed the literature on the approaches with integrated-DEAHP and stand-alone DEAHP along with their applications which were published between 2000 and 2018. This paper uses the criteria for search and filtration which was previously used in Ho (2008). Researchers were able to gain insights about the noteworthy and state-of-the-art integrated-DEAHP approaches and their respective applications from this criterion. Moreover, they can be equipped with valuable acumen for the application, development and publishing of novel integrated-DEAHP approaches in high-ranking journals. The summarized findings of this article, in a nutshell, can be outlined as follows. First, the integrated-DEAHP-fuzzy approach became the most prevalent between 2000 and 2018. Second, the most widespread area of application is the manufacturing sector. Third, the problem area of performance evaluation and efficiency measurement is the most commonly studied problem. This is predictable, but also logical that integration of DEAHP with more than one method will gain more academic attraction and attention. In the the end, it is recommended that a few nascent areas of applications for newer integrations of

DEAHP be explored. These areas and integrations could assist researchers in filling research gaps in the available literature.

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