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Invited Review

Multiple criteria decision aiding for finance: An updated bibliographic survey

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ABSTRACT

Finance is a popular field for applied and methodological research involving multiple criteria decision aiding (MCDA) techniques. In this study we present an up-to-date bibliographic survey of the contributions of MCDA in financial decision making, focusing on the developments during the past decade. The survey covers all main areas of financial modeling as well as the different methodological approaches in MCDA and its connections with other analytical fields. On the basis of the survey results, we discuss the contributions of MCDA in different areas of financial decision making and identify established and emerging research topics, as well as future opportunities and challenges.

1. Introduction

The increasing complexity and volatility of the global financial system has led to increasing use of sophisticated analytic techniques for analyzing financial data and supporting financial decisions. These techniques have their roots in the work of Markowitz on portfolio selection and of Black, Scholes, and Merton on models of pricing contingent claims.

The theory of finance is mostly concerned with developing normative and descriptive models of the financial world involving the actions/decisions of firms, individuals, and policy makers (regulators), as well as the effects of such actions and decisions at the macro and micro levels. Such models are essential for understanding the financial environment and the context in which financial decisions are made. But making financial decisions in actual situations requires the combination of financial theory with prescriptive and constructive tools that provide guidance and support customized to the requirements of the particular problem at hand.

A wide range of techniques and approaches can be useful in this context, ranging from statistical and econometric methods to soft operations research, optimization models, data mining, and soft computing, among others. Among such disciplines, multiple criteria decision aiding (MCDA) has appealing distinctive features that are well suited for financial decision making.[1] A variety of MCDA techniques allow the handling of uncertainty and the dynamic nature of financial decisions, as well as the investigation and enhancement of the traditional bi-criterion risk-return trade-off, on which many financial decisions are based, through a richer multidimensional scheme.

According to the survey of Steuer and Na (2003), the first contributions of MCDA in the field of finance started to appear during the 1950s and 1960s and were focused on goal programming models for capital budgeting decisions (see, for instance, Charnes, Cooper, & Ijiri, 1963; Charnes, Cooper, & Ferguson, 1955). Steuer and Na (2003) presented a first survey of the relevant literature up to 2001. Since then MCDA has progressed significantly, and the field of finance has also experienced major changes, driven by the intensifying globalization and increasing volatility of the markets as well as the introduction of new regulatory requirements and new financial products and services.

In this context, we extend the previous survey of Steuer and Na (2003), providing up-to-date bibliographic coverage of the

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[1] In this paper we shall use the term MCDA as interchangeable with MCDM (multiple criteria decision making), although the two terms imply different philosophies regarding the way multiple criteria decision problems are tackled (Roy & Vanderpooten, 1996).

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applications of MCDA in financial decision making, focusing on the developments from 2002 up to 2014. The new survey of the literature highlights methodological trends and new application areas that have emerged over the past decade and enables the identification of opportunities and challenges for researchers working at the intersection of MCDA and finance.

The rest of the paper is organized as follows. Section 2 explains the role of MCDA in financial decision making, whereas Section 3 is devoted to the survey of the literature and the analysis of the main findings. Finally, Section 4 concludes the paper and presents future research directions on the basis of the conducted survey.

2. The role of the multiple criteria paradigm in financial decisions

Before proceeding to the survey of the relevant literature, it is important to analyze the actual relevance of MCDA to the financial operation of firms and organizations, their goals, and the way financial decisions are made in practice. This can be done from multiple perspectives. For instance, Zopounidis and Doumpos (2013) describe the multidimensional nature of risk and return and the contributions of the prescriptive and constructive paradigms of MCDA (Bouyssou, Marchant, Pirlot, Tsoukiàs, & Vincke, 2006) as opposed to normative and descriptive financial theories and models (for a more detailed analysis see Doumpos & Zopounidis, 2014). In this section, we base the discussion on the main theories about the objectives of firms (in line with Spronk, Steuer, Zopounidis, & Ehrgott, 2005) and emphasize that MCDA is relevant for financial decisions irrespective of whether one agrees or not that firms (should) have a single objective or multiple objectives. To this end, we employ the relevant literature, primarily from the finance point of view.

It is well known that finance theory has adopted the principle of shareholder value maximization as the only meaningful objective that corporations should pursue. Jensen (2001) justifies this unidimensional approach, arguing that it is impossible to maximize in more dimensions and that doing so would actually leave managers with no objective. According to Jensen, shareholder value maximization overcomes such difficulties while being consistent with society's goal to maximize social welfare, assuming that there are no monopolies and externalities.

Stakeholder theory provides an alternative view, which relies mostly on a strategic management perspective. In particular, stakeholder theory advocates that corporate objectives should represent the interests of all stakeholders (e.g., employees, customers, suppliers, shareholders, the community, etc.), rather than focusing solely on the shareholders of a firm (Freeman, Harrison, Wicks, Parmar, & de Coll, 2010). In this setting, financial performance measures are still regarded as being important, but they are considered incomplete as they cannot describe, in full, the corporate value creation process. Consequently, heavy reliance on such measures may fail to identify the problems that organizations face (Harrison & Wicks, 2013; Richard, Devinney, Yip, & Johnson, 2009). Issues and concepts like business ethics, corporate governance, sustainability, accountability, and corporate social responsibility, among others, are highly relevant in this framework, thus leading an enhanced and extended view compared to shareholder theory (Pfarrer, 2010). Steuer and Na (2003) and Hallerbach and Spronk (2002) further note the different risk attitudes and time preferences that stakeholders usually have, their different perceptions of value, as well as information asymmetries and transaction costs. Clearly, the consideration of all these factors in the financial decision making process suits very well the MCDA paradigm.

However, MCDA is also relevant from the perspective of the traditional shareholder value theory. Indeed, the creation of long-term market value is impossible without making sure that all critical functions of the organizational strategy and operation of a firm are realized in an effective manner (e.g., managing human resources, developing new products, selecting investments, etc.). Jensen (2001) uses the term *enlightened value maximization* to describe this integration of the multiple dimensions of a firm under the global goal of shareholder value maximization. MCDA fits well with such an integrated shareholder–stakeholder point of view, as it provides a much-needed framework for modeling and exploring the trade-offs involved in financial decisions that firms face at different levels (e.g., risk-return trade-offs, strengths, weaknesses, challenges, opportunities, etc.). Such a framework is also useful for supporting the construction of acceptable solutions through an iterative analytical learning process.

Bhaskar and McNamee (1983) further argue that even if a firm does focus on shareholder value maximization, this is often too broadly defined, thus requiring the introduction of multiple proxy goals that can be translated to everyday terms. As an example consider an organization such as a bank, whose operation depends on a wide range of very different and complex processes, including credit portfolio management (global risk management policies, credit scoring, loan pricing, etc.), asset-liability management, branch network organization, internal audit and control, and customer relationship management, just to name a few. Inevitably, operational decisions for all such functions are based on multiple decision criteria (and constraints), even if the organization's overall objective is to maximize the wealth of its shareholders. For instance, from a credit risk management perspective credit granting decisions should minimize the expected losses, but this requires the consideration of financial and non financial attributes that describe the likelihood of default and the losses for each obligor.

The literature provides similar evidence for corporate finance, too. For instance, Graham and Harvey (2001) surveyed 392 chief financial officers of North American firms (USA and Canada) and found that executives rely on practical, informal rules when choosing capital structure, focusing primarily on issues such as financial flexibility, credit ratings, earnings per share, and recent stock price appreciation. Similar results have also been reported for European firms (Brounen, de Jong, & Koedijk, 2006), whereas in an earlier survey, Moore and Reichert (1983) found that in addition to traditional financial management techniques, large US firms often use a variety of analytical methods, usually from different areas, including goal programming among others.

In an investment setting, the overview of Fabozzi, Focardi, and Jonas (2007) on the current practices and trends in portfolio selection shows that portfolio managers use a variety of risk measures and approaches beyond the traditional mean-variance framework of Markowitz. The different views on the concept and measurement of risk have been an active area of research and debate over the past couple of decades, particularly after the establishment of value-at-risk systems, their adoption by regulators, and the failures observed in multiple instances (including the recent worldwide financial crisis). Several scholars have advocated for the need to establish and use *coherent risk measures* that meet well-grounded properties (Artzner, Delbaen, Eber, & Heath, 1999; Szegö, 2005). However, as Ortobelli, Rachev, Stoyanov, Fabozzi, and Biglova (2005) note, "even if we can identify some desirable features of an investment risk measure, probably no unique risk measure exists that can be used to solve every investor's problem." Indeed, risk is a subjective concept and different investors have different perceptions of risk; and this holds true even if all investors follow the expected utility maximization principle that is the basis of traditional investment decision theory (similar to shareholder value maximization in corporate finance). Guégan and Tarrant (2012) provide theoretical results supporting the use of multiple risk measures in a broader supervisory context for financial institutions as the only way to avoid the ambiguity in describing the risks they take and the associated actual loss distribution.

The above examples and discussion indicate that financial decisions at the operational and even strategic level have multidimen-

sional aspects, which are realized in various forms. Irrespective of how this translates to the overall objective(s) of a firm, dealing with financial decisions in a multidimensional/multicriteria setting can result in more informed outcomes, which are robust against unrealistic modeling and data assumptions (i.e., model risk, Christodoulakis & Satchell, 2008).

3. Bibliographic survey

The first bibliographic survey related to the applications of MCDA in finance was conducted by Steuer and Na (2003), who reviewed a set of 265 publications from 1955 up to 2001. Other smaller-scale surveys and reviews of specific areas or methods can be found in studies such as those of Aouni, Colapinto, and La Torre (2014), Xidonas and Psarras (2009), Xidonas, Mavrotas, and Psarras (2010b), and Zavadskas and Turskis (2011). For the purposes of this study, we cover the period 2002–2014, thus focusing on recent trends both in terms of methodological developments and the main areas of application. The following subsections explain the sampling methodology and discuss the obtained findings.

3.1. Methodology

To collect the bibliographic data used in this study, a number of sources were employed. The primary source was Scopus, which provides comprehensive coverage of journals, conference proceedings, and edited volumes from different publishers. Additional searches were performed on the websites of several publishers, mainly to locate journals not fully covered by Scopus throughout the whole period of the analysis.

The search was based on a combination of various relevant terms, ranging from general ones (e.g., "multiple criteria and finance" in different formats) to ones involving specific MCDA techniques and approaches (e.g., "goal programming and finance", "multiobjective optimization and finance", "multiattribute decisions and finance," etc.), as well as search terms involving specific areas in financial decision making, such as banking, financial risk management, portfolio selection, trading, credit scoring, financial distress, investment appraisal, mergers and acquisitions, etc.

The abstracts of all resulting publications were checked (manually) to exclude material not directly related to financial decision making (e.g., project portfolio selection instead of portfolios of financial assets, investment appraisals focusing on technical rather than financial considerations, etc.). Ultimately, a set of 644 publications was formed, which serves as the basis for the analysis (the complete database is available in BibTeX format at http://www.fel.tuc.gr/MCDAfinance.zip). The next subsection presents and analyzes the main findings.

3.2. Overall trends and publication outlets

An examination of the trend in the number of publications over the period of the analysis is indicative of the growth in research related to the applications of MCDA in finance. As is evident from Fig. 1, the number of publications has risen over the years, from about 10 to 20 papers in 2002 and 2003 to almost 90 publications in 2013 and 2014. This increase was almost consistent throughout the period from 2007 onwards.

Table 1 provides further details about the different types of publications. We distinguish between journal papers, articles in conference proceedings, chapters in edited volumes, and lecture notes. Overall, the studies in the compiled database have been published in 333 different publication outlets, including 202 journals, 90 conference proceedings, 21 edited volumes, and 20 lecture notes. The journal papers account for more than 75% of the total number of publications (486 journal papers out of 644 overall). Another 16% involves

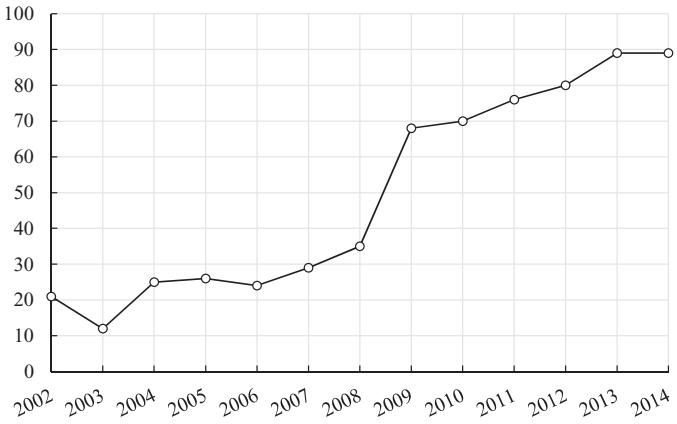

Fig. 1. Number of publications per year.

Table 1
Publications by type of outlet and year.

	Journals	Proceedings	Edited volumes	Lecture notes	Total
2002	21	0	0	0	21
2003	6	3	2	1	12
2004	20	0	0	5	25
2005	20	3	0	3	26
2006	18	4	1	1	24
2007	20	7	1	1	29
2008	26	6	3	0	35
2009	44	15	5	4	68
2010	48	13	5	4	70
2011	55	14	2	5	76
2012	64	11	1	4	80
2013	65	19	3	2	89
2014	79	7	1	2	89
Total publications	486	102	24	32	644
Total outlets	202	90	21	20	333

articles in conference proceedings (102 articles), whereas the other two publication types contribute less than 10% to the total number of published articles. In the study of Steuer and Na (2003) covering the period up to 2001, most articles (101 out of 265) were published in volumes of various sorts. Thus, there has been a clear tendency over the past decade toward journal articles instead of publications in edited volumes and related types of publications. Similar to the overall statistics of Fig. 1, the number of journal articles has increased consistently since 2006, reaching 79 articles in 2014 as opposed to just 18 in 2006.

Out of the 202 journals that have published articles related to financial applications of MCDA, 91 (about 45%) are listed in Thomson Reuters Web of Science, with a median 2013 impact factor of 1.32. Further bibliometric data about the journals were obtained from SCImago, which provides comprehensive coverage of all journals. To analyze the quality of the journals, we employed the SJR (SCImago Journal Rank) indicator and the *h* index (using the most recent data for 2013). A journal's SJR expresses the average number of weighted citations received in 2013 by the documents published over the three previous years. In contrast, the *h* index expresses the journal's number of articles that have received at least *h* citations. Furthermore, we classified the journals by their main subject areas as defined by Scopus (SCImago uses the same subject classifications).

Table 2 summarizes the above statistics for the journals in our sample classified by their main subject area. In addition to the SJR and the *h* index, the table also presents the median 2013 impact factors (collected from Thomson Reuters Web of Science) as well as the overall SJR and *h* index medians for all journals listed in each subject

Table 2
Journals' subject areas and statistics.

	Sample publications					SCImago medians	
	N	*M*	IF	SJR	*h* index	SJR	*h* index
Business, management, and accounting	38	62	1.39	0.33	13.0	0.35	11
Economics, econometrics, and finance	39	67	0.83	0.43	15.0	0.36	10
Computer science	48	137	1.49	0.54	22.5	0.44	16
Decision sciences	34	153	1.36	0.88	32.0	0.62	19
Mathematics	7	21	1.08	1.15	48.0	0.60	17
Engineering	36	46	1.69	0.39	21.0	0.32	13

N: number of publication outlets, *M*: number of articles, IF: median 2013 impact factor, SJR: median 2013 SCImago Journal Rank

area in SCImago (the same statistics for the impact factor are difficult to define because the subject classifications in Thomson Reuters Web of Science are quite different from the ones used by SCImago/Scopus).

It is evident that articles related to financial applications of MCDA are scattered over journals in different subject areas. About 18.8% of the journals (38 out of 202) belong in the area of business, management, and accounting; another 19.3% involve journals in economics, econometrics, and finance; computer science journals account for 23.8%; decision sciences and engineering journals each cover 16.8% and 17.8%, respectively, and mathematics journals account for 3.5% of the total (7 journals out of 202). This is a well-balanced distribution between journals in methodologically oriented areas and journals in business, management, economics, and finance. However, looking at the number of articles published in journals from each area gives a slightly different view. In particular, about 60% of the articles (290 out of 486) were published in computer science and decision sciences journals, whereas business/management and economics/finance journals account for about 27% of the total (129 out of 486).

Comparing the bibliometric indicators for the journals in our sample with the overall data collected from SCImago (i.e., columns 4–6 versus columns 7–8 in Table 2), it is clear that journals that have published articles related to the applications of MCDA in finance have significantly higher SJR and *h* index (with one minor exception for the SJR of business/management journals). As far as the impact factors are concerned, these are higher than one in all cases with the exception of economics/finance. For comparison, it is worth noting some category median impact factors from the Web of Science (2013 data): business: 1.38, management: 1.16, business/finance: 0.91, economics: 0.78, computer science/artificial intelligence/information systems theory and methods: 1.17/1.03/0.77, industrial engineering: 1.11, operations research and management science: 0.99. Overall, it seems that articles related to the financial applications of MCDA are published in above-average journals, in terms of their quality and popularity.

Table 3 presents the journals that have published the most MCDA papers during the period of the analysis. The 21 journals shown in the table have published 140 papers in total, thus accounting for more than 49% of the overall number of journal articles. The European Journal of Operational Research together with Expert Systems with Applications clearly stand out compared to the other journals, each having published over 40 articles.

In terms of the geography of the publications, Table 4 lists the countries with the most published articles. The identification of these countries was based on the affiliations of the authors, using an individual as well as a weighted count similar to the metrics used by Steuer and Na (2003). The individual count for a country represents the number of articles with at least one author from the country under consideration (note that the individual count in this study is defined differently from a similar metric reported by Steuer and Na, 2003). On the other hand, the weighted count takes into account all authors of an article. In particular, the weighted count for a country

Table 3
Journals publishing the most articles.

Journal	Number of articles
European Journal of Operational Research	45
Expert Systems with Applications	41
Journal of Multi-Criteria Decision Analysis	17
Applied Mathematics and Computation	12
INFOR: Information Systems and Operational Research	12
Operational Research	12
International Journal of Information Technology and Decision Making	10
Applied Soft Computing	9
Information Sciences	9
Computers and Operations Research	8
Omega	8
Technological and Economic Development of Economy	8
Annals of Operations Research	7
Economic Modelling	6
Journal of Business Economics and Management	6
Journal of the Operational Research Society	6
Computational Management Science	5
Decision Support Systems	5
International Transactions in Operational Research	4
Knowledge-Based Systems	4
Quantitative Finance	4

Table 4
Authorship counts by country.

Countries	Individual	Weighted	Countries	Individual	Weighted
China	106 (1)	88.9 (1)	France	16 (14)	8.5 (16)
USA	85 (2)	49.8 (5)	Lithuania	14 (15)	13.2 (11)
Greece	76 (3)	68.3 (2)	Portugal	13 (16)	9.3 (15)
Taiwan	63 (4)	58.5 (3)	Italy	12 (17)	8.7 (16)
Spain	57 (5)	51.5 (4)	Brazil	9 (18)	7.6 (18)
UK	51 (6)	32.0 (8)	Tunisia	9 (18)	5.7 (20)
India	39 (7)	35.4 (6)	Australia	8 (20)	4.8 (24)
Turkey	37 (8)	35.0 (7)	Singapore	7 (21)	7.0 (19)
Iran	32 (9)	30.7 (9)	Belgium	7 (21)	5.5 (21)
Canada	18 (10)	10.4 (14)	Malaysia	6 (23)	5.2 (22)
Japan	17 (11)	14.4 (10)	Korea	6 (21)	4.3 (25)
Poland	17 (11)	12.8 (11)	Netherlands	6 (23)	3.7 (26)
Germany	17 (11)	11.3 (13)	Romania	5 (26)	5.0 (23)

Note: Rankings shown in parentheses.

X and an article *Y* is defined as the ratio between the number of authors of article *Y* from country *X* to the total number of authors for the article (authors with affiliations from multiple countries are split between the countries).

The results shown in Table 4 indicate that countries such as China, USA, Greece, Taiwan, and Spain are the most active ones both in terms of the individual and weighted authorship counts. By contrast, the top five countries in the previous survey of Steuer and Na (2003) were USA (first by a large margin), Netherlands, Greece, UK, and Canada, while China was 12th, Spain was 16th, and Taiwan was 22nd.

3.3. Topics and methods

The articles in the compiled database cover a variety of areas related to financial decision making and use different MCDA methodological approaches. In distinguishing between the various topics, we took into consideration all three main areas of finance, including corporate finance, investments, and financial markets and institutions. On the basis of these main areas, 12 subcategories were defined corresponding to the main fields of research in terms of the application domains of MCDA methodologies in financial decision making (articles related to specific financial risk management topics outside the 12 main categories were classified in a separate group). The main ares identified in this survey include:

- Accounting and auditing: although accounting and auditing are distinct research areas from finance, they are closely related to many financial decisions, mainly regarding corporate finance. MCDA methods have been used to support accounting/auditing decisions and relevant practices in areas such as cost accounting (Cicone, Udaeta, Grimoni, & Galvão, 2008), management accounting (Frezatti, Agiar, Guerreiro, & Gouvea, 2011), financial fraud detection (Gaganis, 2009; Pasiouras, Gaganis, & Zopounidis, 2007), and internal audit controls (Sueyoshi, Shang, & Chiang, 2009), among others.
- Asset evaluation: asset evaluation refers to the screening, assessment, and trading of financial assets for investment purposes. It is an integral part of investment decisions and portfolio selection and management, but it requires different techniques and analytic tools based on discrete MCDA methods (as opposed to optimization models used in the portfolio optimization process; Xidonas, Mavrotas, Krintas, Psarras, & Zopounidis, 2012). Asset evaluation is usually implemented in terms of fundamental factors (see, for instance, Albadvi, Chaharsooghi, & Esfahanipour, 2007, Sevastjanov & Dymova, 2009, and Xidonas, Mavrotas, & Psarras, 2009b, among others) as well as in the context of active trading strategies based on technical indicators (e.g., Huck, 2010; Ng, Liang, Li, Yeung, & Chan, 2014).
- Banking: banking applications cover a wide spectrum of areas related to banking management. Among others these include the performance and stability of banks (Doumpos & Zopounidis, 2010), loan portfolio management and credit granting, asset-liability management (Kosmidou & Zopounidis, 2004), the organization of bank branch networks (Bravo & Plà-Santamaria, 2012; Ferreira, Santos, & Rodrigues, 2010), and e-banking services (Hu & Liao, 2011).
- Energy finance: the energy and commodity markets have developed rapidly over the past couple of decades. The relevant applications of MCDA methods relate to portfolio management and trading, pricing, market operation issues, and so on in the energy and commodity markets.
- Capital budgeting and financial planning: capital budgeting and financial planning constitute major areas of research in finance as well as management science. MCDA methods have been used to design budget allocations and financial plans in both the private (Frezatti et al., 2011) and the public sector (Gómez, Ríos Insua, Lavín, & Alfaro, 2013), as well as for individuals (Cai & Ge, 2012).
- Corporate financial performance analysis: the assessment of corporate financial performance has been a popular topic of research with several applications of MCDA, which allow the aggregation of multiple performance attributes (financial and non financial) while taking into account the particular characteristics of different business sectors (construction, transportation, health care, agriculture, etc.; Iazzolino, Laise, & Marraro, 2012).
- Country risk analysis: country risk refers to the likelihood that a country will face difficulties in meeting its debt obligations toward its creditors. The importance of this type of analysis has risen over the past decades as financial crises have caused major turmoil in various countries, with the most recent being the sovereign debt crisis in Europe. MCDA techniques have been used to support economic forecasting (Blair, Mandelker, Saaty, & Whitaker, 2010), to construct composite indicators of country risk (Kosmidou, Doumpos, & Zopounidis, 2008), and for public debt management (Balibek & Köksalan, 2010).
- Credit risk assessment and bankruptcy prediction: similar to country risk, credit risk assessment and bankruptcy prediction refer to the likelihood that firms or individuals will default on their debt. The increasing number of defaults due to the recent credit crunch has shown that there is still much to be done in this area. MCDA methods have been used as nonparametric techniques to infer credit risk and bankruptcy prediction models from data, often facilitated by goal programming, multiobjective techniques, and evolutionary algorithms or in combination with data mining algorithms. Some examples can be found in the works of Doumpos (2012), He, Zhang, Shi, and Huang (2010), Yu, Wang, and Lai (2009), and Zhang, Gao, and Shi (2014), among others.
- Investment appraisal: investment decisions are a major part of the theory and practice of corporate finance. Financial theory relies on established financial assessment criteria (e.g., net present value, internal rate of return, payback period, etc.). In a multicriteria setting, the financial perspective is enhanced with new factors in a broader stakeholder setting (De Brucker, Macharis, & Verbeke, 2013) as well as through the introduction of formal models for preference modeling and risk analysis (Vlaev, Chater, & Stewart, 2008).
- Mergers and acquisitions: mergers and acquisitions (M&As) are strategic investments that can facilitate corporate growth by taking advantage of economies of scale and synergistic effects. They boomed during the 1980s and 1990s, while during the 2000s some stabilization trends have been observed. MCDA methods have been used to design strategic alliances, to support the identification of M&A deals and targets, and to assess the outcomes of M&As (see, Korhonen & Voutilainen, 2006, Lee, 2013, and Pasiouras, Gaganis, & Zopounidis, 2010, among others).
- Socially responsible investments (SRI): according to Eurosif's Global Sustainable Investment Review 2014, the sustainable investment market has exceeded $21 trillion globally, accounting for more than 30% of professionally managed assets. MCDA has been employed to extend traditional risk-return investment models through the introduction of non financial SRI criteria (see, among others, Ballestero, Bravo, Pérez-Gladish, Arenas-Parra, & Plà-Santamaria, 2012 and Bilbao-Terol, Arenas-Parra, & Cañal Fernández, 2012) and as a tool to analyze and explain the SRI process (Utz, Wimmer, Hirschberger, & Steuer, 2014).
- Portfolio optimization: portfolio optimization refers to the allocation of funds to a set of selected financial assets (equity, funds, fixed income assets, etc.). In the traditional mean-variance framework, the allocation is formulated as a bi-objective risk-return optimization model. As explained in Section 2, during the past two decades several advances have been made in the introduction of new coherent measures of risk. The multidimensional nature of risk (Doumpos & Zopounidis, 2014) gave rise to multiobjective and goal programming formulations, which allow the aggregation of multiple portfolio selection measures and further enable additional real features to be taken into consideration (diversification, liquidity, dividends, etc.; Steuer, Qi, & Hirschberger, 2007).

In terms of methodological approaches, we consider the four main streams of MCDA research (Pardalos, Siskos, & Zopounidis, 1995), including multiobjective optimization (MO), multiattribute utility theory (MAUT), outranking relations (OR), and preference disaggregation analysis (PDA). In addition to these main fields of MCDA research, further categories are also considered that represent particular types of

Table 5
Publications by subject area and methodological approach.

	MO	AHP	GP	EA/MH	Fuzzy	PDA	OR	DM	MAUT	TOPSIS	DEA	RBM	Other	Total
Portfolio optimization	188	11	48	64	30	1	6	2	5	2	2	1	11	262
Credit risk/bankruptcy	25	18	25	5	8	27	13	21	10	10	3	5	8	108
Asset evaluation	31	17	7	20	10	8	10	5	4	4	2	0	10	78
Banking	9	27	9	2	16	11	8	2	5	8	5	4	8	73
Corporate performance	3	16	4	1	17	5	9	1	1	11	1	3	9	51
Budg. & fin. planning	13	12	15	2	2	0	2	1	4	0	1	0	3	42
Investment appraisal	7	22	3	0	9	0	1	2	7	1	1	0	7	41
SRI	5	3	8	1	1	0	0	0	2	0	1	0	1	18
Accounting/auditing	2	6	0	1	2	8	0	2	0	0	1	1	0	17
Country risk	4	4	0	1	0	4	2	0	2	1	0	1	1	17
Energy finance	7	2	0	1	0	0	0	0	1	0	0	0	0	10
M&A	0	5	0	0	1	2	0	0	0	1	0	0	1	8
Other risk mgmt	6	8	3	1	2	1	1	1	2	1	0	0	1	22
Total	273	124	103	92	89	57	45	36	36	33	15	13	54	

Table 6
Articles using combinations (pairs) of methods.

	DEA	DM	EA/MH	Fuzzy	GP	MAUT	MO	OR	PDA	RBM	TOPSIS	Other
AHP	5	6	1	32	6	3	2	2	1	2	15	14
DEA		1	0	1	2	0	3	0	1	0	2	1
DM			5	2	6	0	18	4	10	1	4	2
EA/MH				7	1	3	82	3	5	0	0	1
Fuzzy					7	0	35	4	1	3	19	11
GP						3	8	0	7	1	2	1
MAUT							4	2	8	1	0	2
MOP								0	5	2	1	3
OR									8	1	2	3
PDA										2	0	2
RBM											1	1
TOPSIS												4

decision models and analysis techniques, namely goal programming (GP), evolutionary algorithms/metaheuristics (EA/MH), fuzzy models, rule-based models (RBM), as well as popular methods such as AHP (including ANP) and TOPSIS. In addition, we consider other methods and approaches (e.g., case-specific models and other techniques such as DEMATEL, VIKOR, grey relational analysis, etc.; these are all assigned to one major category labeled "other"), as well as combinations with data envelopment analysis (DEA) and data mining (DM) techniques (excluding purely DEA/DM papers).

Table 5 lists all of the considered application areas and methodological approaches, along with the number of papers in all combinations of these two dimensions. The last column of the table represents the number of papers in each application area, whereas the last row shows the number of papers in each MCDA methodological approach. It should be noted that these totals do not equal the row/column sums, as an article may be related to multiple financial application areas and employ a combination of MCDA methods and approaches. Table 6 provides further details on the combinations of methods that have been used. The table reports the number of papers using different pairs of approaches (we focus on pairs as the vast majority of articles –about 90%– have used at most two methods).

The summary results clearly indicate that portfolio optimization (PO) is the area that has been studied most widely with MCDA techniques, namely MO and GP. Steuer and Na (2003) also found portfolio analysis to be the most active MCDA-finance researched area in the period prior to 2002 (although they did not distinguish between PO and asset evaluation). The popularity of PO can be attributed to a number of reasons. It is a multifaceted problem that poses a number of algorithmic and modeling challenges (e.g., risk modeling, data of various types, dynamic nature, etc.), and it is relevant in various contexts including equity portfolios and portfolios of funds, as well as in the context of assets from non financial markets (e.g., energy markets and commodities). Most MO/GP models proposed for PO have relied on the combination of multiple risk measures (e.g., skewness/kurtosis, value-at-risk measures, omega ratio, systemic risk, etc.), often further considering additional goals and objectives (liquidity, dividends, diversification, etc.). EA/MH have also been very popular in PO, particularly when dealing with non-convex portfolio selection criteria and models (e.g., skewness/kurtosis, value at risk) as well as in cases where additional real features, such as cardinality constraints, are added in the analysis (Mansini, Ogryczak, & Speranza, 2014). Steuer (2013) distinguishes between three types of MCDA approaches in PO. A priori approaches use pre-specified information about the preferences of the decision maker (investor, portfolio manager) to find the most suitable efficient portfolio. GP models often employ such an approach. A posteriori approaches, on the other hand, focus on finding the complete set of efficient portfolios in a single run, without requiring the specification of preferential data. EA/MH are typically employed in this framework, particularly in more complex instances as noted above (for an overview of EA/MH in PO, see Metaxiotis & Liagkouras, 2012). A final class of procedures is based on interactive techniques that allow the progressive articulation of preferential information about the investment policy of the decision maker (see, for instance, Xidonas, Mavrotas, & Psarras, 2010a).

PO is closely related to other subject areas considered in this survey, namely asset evaluation, SRI, and energy finance. Surprisingly, only 12 publications addressed portfolio management in an integrated framework that combines PO and asset evaluation (see, Kiris & Ustun, 2012, Pendaraki, Zopounidis, & Doumpos, 2005, Pérez-Gladish, Jones, Tamiz, & Bilbao Terol, 2007, and Xidonas, Askounis, & Psarras, 2009a, among others). These works all considered the asset evaluation process in terms of fundamental factors, often realized in the context of fund management, using methodologies based mainly on AHP/ANP, OR, and PDA. MO and EA/MH techniques, on the other hand, have also been popular for asset evaluation, mainly in the

context of algorithmic trading and technical analysis (see, Bodas-Sagi, Fernández-Blanco, Hidalgo, & Soltero-Domingo, 2013, Chiam, Tan, & Al Mamun, 2009, and Ng et al., 2014, among others). It is also interesting to note that half of the papers on SRI (9 out of 18 papers) also incorporate PO aspects and six of the 18 SRI papers consider social aspects as part of the asset evaluation process. Interestingly, all but one of the SRI papers was published over the period from 2009 up to 2014, which indicates that this is an emerging trend in financial investments and portfolio management.

Except for the above investment-related topics, credit risk assessment and bankruptcy prediction have also been very popular topics, with 108 relevant papers, whereas in the previous survey of Steuer and Na (2003) this area was not identified as a distinct research subject. In this area a variety of different methodologies have been used, the most popular being MO, PDA, GP, and OR. Credit risk and bankruptcy prediction models are usually constructed from existing databases about defaults and bankruptcies (corporate or consumer data). PDA techniques commonly employ MO and GP formulations to infer decision models from existing data instances Some examples can be found in the works of Doumpos and Zopounidis (2011), Peng, Kou, Shi, and Chen (2008), and Zhang et al. (2014), among others. Similar techniques have also been used for analyzing and predicting credit ratings issued by major credit rating agencies, which are widely used by financial decision makers, investors, and regulators (Doumpos, Niklis, Zopounidis, & Andriosopoulos, 2015; Doumpos & Pasiouras, 2005), whereas other studies have focused on specialized models for areas such as mortgage lending and shipping (see Ferreira, Santos, Marques, & Ferreira, 2014, and Gavalas & Syriopoulos, 2014, among others). It is also worth noting that several studies in this area have explored combinations of MCDA methods with data mining models, such as neural networks, kernel methods, case-based reasoning, and clustering algorithms. Such combinations have been considered in three main forms: (a) using MO/GP models (often facilitated by EA/MH) for training data mining models (e.g., Pendharkar & Nanda, 2006; Zhang et al., 2014), (b) using the complex structure and representation power of data mining models for constructing accurate multicriteria risk assessment and prediction systems (e.g., Chen & Hu, 2011; Hu, 2009), and (c) using MCDA techniques to assess the performance of prediction models (e.g., Wu & Hsu, 2012).

Applications in banking have also attracted considerable interest, particularly after the global credit crunch of 2007/2008. This is highlighted by the fact that 54 out of the 73 papers on banking applications were published from 2010 up to 2014. Similar to credit risk assessment and bankruptcy prediction, banking was also not considered as a distinct research area in the survey of Steuer and Na (2003). Thus, over the past decade banking has emerged as an area of particular interest for the application of MCDA methods. Such methods applied in the banking sector include AHP/ANP (often combined with fuzzy models) as well as PDA, OR, and GP techniques. The application topics include the assessment of bank performance (e.g., Doumpos & Zopounidis, 2010; Grigoroudis, Tsitsiridi, & Zopounidis, 2013; Ioannidis, Pasiouras, & Zopounidis, 2010; Shen & Tzeng, 2014a), asset-liability management (e.g., Kosmidou & Zopounidis, 2007), bank branch management (e.g., Ferreira et al., 2010), and e-banking services (e.g., Hu & Liao, 2011; Kaya & Kahraman, 2011), among others.

Similar issues have also been considered outside the banking sector in other studies that focused on corporate performance in sectors such as transportation, agriculture, insurance, construction, etc. As is evident from Table 5, the methods used for assessing corporate performance are quite similar to the ones used in the banking sector.

As far as the other application areas are concerned, it is worth noting that in capital budgeting and financial planning we identified only 41 papers published since 2002. This is a noticeable decrease compared to the survey of Steuer and Na (2003), who found these areas to be widely researched in the period prior to 2002 (when combined they were actually more popular than portfolio analysis).

From the methodological point of view, MO is clearly the dominant approach with 273 papers. The majority of works using MO are related to PO (188 studies), followed by asset evaluation (31 studies) and credit risk assessment/bankruptcy prediction (25 papers). As shown in Table 6, a significant portion of the studies using MO combine it with EA/MH techniques (82 papers), fuzzy models (35 studies), and data mining algorithms (18 papers).

AHP/ANP has been the second most popular approach. This is a major increase when compared to the previous survey of Steuer and Na (2003), who found that only a small number of studies relied on AHP prior to 2002. Interestingly, AHP/ANP-related papers span the whole spectrum of financial applications, often combined with fuzzy models and other MCDA techniques, especially TOPSIS.

Like MO, GP has also been a popular modeling and solution approach for financial decisions in PO and credit risk/bankruptcy prediction. Capital budgeting and financial planning have also been popular topics for applications of GP models. However, in contrast to MO models, GP has been less often combined with other approaches. Among them, fuzzy models, DM, and PDA have been the most popular.

PDA has been the most popular approach for credit risk/bankruptcy prediction models. This is explained by the nature of the PDA framework, which focuses on inferring decision models from data. This characteristic suits well the context of credit risk modeling and financial distress prediction. For that purpose, the framework of PDA is usually implemented with different OR and MAUT models (e.g., Bugera, Konno, & Uryasev, 2002; Doumpos, 2012; Doumpos & Zopounidis, 2011) or in combination with DM techniques (Peng et al., 2008).

Among the other main MCDA modeling approaches, MAUT has been used in 36 studies, whereas rule-based techniques (e.g., dominance-based rough sets; Greco, Matarazzo, & Slowinski, 2013; Shen & Tzeng, 2014b) have been used in 13 publications. The small number of MAUT applications in financial decision making compared to other approaches was also reported by Steuer and Na (2003), who found only eight relevant publications in the period prior to 2002. Finally, it is worth noting that some studies (15 overall) have used DEA as a data-based multicriteria evaluation technique combined with traditional MCDA approaches such as MO, GP, AHP/ANP, and TOPSIS (Amiri, Zandieh, Vahdani, Soltani, & Roshanaei, 2010; Che, Wang, & Chuang, 2010; Yang, Wong, Xu, Liu, & Steuer, 2010). DEA provides a convenient approach for multicriteria evaluations using minimum information, as the assessments are driven by the data. However, when used in a MCDA context, DEA-based evaluation models are subject to methodological problems (for a comprehensive discussion, see Bouyssou, 1999; Tofallis, 2010).

4. Conclusions and future challenges

Financial decisions are fundamental for corporations, institutional and individual investors, policy makers, and regulators. The theory and practice of finance have evolved rapidly over the past couple of decades, keeping pace with the complexity of the global financial environment. These advances create a number of new opportunities and challenges for designing and implementing analytical tools for decision support.

MCDA has played a significant role in this context. In this paper we presented an extensive survey of the literature related to the contributions of MCDA in financial decisions over the past decade. The survey highlighted the main areas of research, both in terms of application as well as the methodological approaches that have been used. The findings indicate that portfolio management remains the most popular area. Over the past decade, however, new issues have attracted considerable interest. For instance, much research has been

devoted to asset evaluation (including trading), credit risk assessment, and banking applications. On the methodological side, except for traditional MCDA approaches (MO/GP, AHP/ANP, PDA, OR), significant research has been devoted to the intersections of MCDA with other operations research and analytic disciplines, including EA/MH, fuzzy models, and DM algorithms, which provide a rich set of possibilities for future research.

Nevertheless, there is still much room for further contributions of the MCDA paradigm in finance, taking into consideration both methodological advances and the changes in the context in which financial decisions are made. The latter is of particular importance. Over the past decade the importance of global financial markets and institutions has risen significantly, and this goes beyond the traditional equity markets that have been widely studied with MCDA techniques. The development of new investment instruments (e.g., exchange-traded funds, SRI, etc.), the developments in markets such as commodities and energy, the dominance of electronic trading (e.g., high-frequency trading), and the increasing complexity of the financial instruments and processes in such areas create a number of particular challenges and opportunities for MCDA modeling. These include, for example, the design and assessment of risk management strategies in a multidimensional modeling framework taking advantage of all advances made in financial risk measurement and financial engineering, the modeling of the uncertainties and volatility in the global markets, the analysis of market participants' preferences (e.g., market sentiment), as well as the design of dynamic decision aiding approaches that would best match the rapidly evolving nature of the financial environment. Such issues are not relevant only in an investment setting, as they also relate to financing and capital structure decisions.

At the same time, financial stability issues have been at the center of global interest among decision and policy makers in the area of finance. MCDA approaches can contribute to this field by providing an integrated/holistic view of financial stability, enabling the consideration and aggregation of all relevant factors, such as macroeconomic conditions, financial supervision, and corporate governance issues. The rich research already available in such areas is mostly explanatory in nature, and a decision aiding perspective is often missing. However as the regulatory framework has become more stringent over the years, and in order for MCDA approaches to be useful in this context they should build on the grounds of existing regulatory requirements and the findings from the extensive finance research to provide decision aid in a flexible and realistic setting.

To this end, the above noted combination of MCDA techniques with other quantitative disciplines is of particular interest, as the complexity of financial decision problems often necessitates the use of an arsenal of analytical approaches. The emphasis of MCDA on issues like problem structuring, preference modeling, decision argumentation, and criteria aggregation enhances the data analytic capabilities of statistical and data mining techniques, which are often used in financial decisions. However, when proposing hybrid and integrated methodologies, special care should be given to keeping the resulting models as simple and user-friendly as possible. Sophisticated analytic methodologies are not often used in practice, because they are far too complex for financial decision makers to understand. They emphasize too much on formulating "accurate" recommendations while ignoring the fact that the way recommendations and results are formulated is often as important as their quality.

Of course, the quality of the results is also an issue. As with all quantitative models for financial decision making, MCDA approaches also require rigorous testing and validation, not only in terms of their theoretical properties (on which there are plenty of studies in the OR/MCDA literature) but also through extensive empirical results on actual cases with realistic characteristics (in terms of data size and complexity). What is more, such empirical validation should consider financially relevant criteria instead of relying solely on statistical and other technical metrics (as an example in credit scoring, see Oliver, 2013). The robustness of MCDA models and results is also highly crucial in this context. In fact, Roy's general framework of robustness in OR/MCDA (Roy, 2010) is quite relevant for financial decisions, as it acknowledges that robustness is a multifaceted issue that is not limited to some technical parameters of a decision model (as is often considered in sensitivity analyses) or data variations (as is often assumed in statistics); rather, it involves all discrepancies between a formal analytic representation and the actual problem, which is very much relevant to what is known in finance as "model risk" (Christodoulakis & Satchell, 2008).

Finally, it is worth exploring extensions and integration of MCDA methodologies with big data analytic technologies and systems. As the financial data maintained internally within organizations or provided by external agencies become explosive in size, the scalability of MCDA techniques becomes an issue. While advanced solution techniques for MO/GP (often facilitated by EA/MH) tackle this issue in a rather efficient manner, there is still much to be done for discrete MCDA approaches (e.g., MAUT, OR, PDA, etc.). This involves both the algorithmic and computational aspects of such MCDA methods, the standardization of their computational implementation (Cailloux, Tervonen, Verhaegen, & Picalausa, 2014), their integration with existing computational systems used in practice for financial decision making, and the level of detailed output/summarizations they provide given the (often massive) data available.

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