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On the increasing importance of multiple criteria decision aid methods for portfolio selection

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ABSTRACT

In 1952, Markowitz published his famous paper on portfolio selection that transformed the field of finance. Although over 65 years have passed since then, the mean-variance model remains today the predominant model in portfolio selection. Having endured many criticisms over this period, the one that has perhaps been the most persistent is the fact that mainstream mean-variance theory is unable to accommodate additional criteria beyond expected return and variance. With investment decision-making having become more complex, this is a real problem as many problems with additional criteria exist and are only increasing in number and importance. In this paper, we review the papers that have been published that apply methods and procedures in an exact (as opposed to evolutionary) sense to address problems in portfolio selection with criteria beyond mean and variance. We also analyse the methodologies that allow the solution of the problem in a multiple criteria context, thus extending the features of the mean-variance approach that have caused portfolio theory to have such impact.

KEYWORDS

Multiple criteria decision aid; multi-objective programming, portfolio selection; security selection; portfolio optimisation

1. Introduction

Finance's status as a decision science only dates back to the 1950s with the publication of the paper on portfolio selection by Harry Markowitz (1952). This paper totally transformed the field of finance. Portfolio selection is concerned with the construction of investment portfolios containing many securities. In portfolio selection, uncertainty is automatically assumed. Otherwise, if there were certainty, one would just select the investment with the highest return and put everything into it. Areas today inextricably tied to the topic of portfolio selection include the mutual fund industry, the insurance industry, pension funds, sovereign funds, endowments, foundations, and so forth. With the stocks of the world carrying a marketcap in excess of $60 trillion, it would be hard to understate the importance of the topic to finance, economics, people's lives, and the world's economy.

To understand the transformational effect that Markowitz had on finance, one needs to understand a little about the situation in finance prior to 1952. There was essentially no theory of risk. This was even though the concepts of means, variances and covariances were not unknown at the time. Diversification was another area of frustration. Although people were aware about the dangers of putting "all of one's eggs in the same basket", there was no agreement about what exactly constituted diversification or ways to measure it. Moreover, the terms *efficient portfolio* and *optimal portfolio* had not become common terms yet. Consequently, at the time, finance had not yet entered the analytical age.

2. Emergence of mathematical programming

This, however, all changed with Markowitz's 1952 paper in which he was able to take means, variances and covariances and tie them in to the newly emerging field of mathematical programming. Looking at the paper today, one is probably struck by its simplicity, perhaps causing one to ask: "How come no one thought of this before?" The answer probably lies in the tendency of people to think only in terms of the tools that they have at their disposal. In other words, from Maslow (1968), "if the only tool you have is a hammer, you tend to treat everything as if it were a nail". But with the arrival of mathematical programming, which was new at the time of Markowitz (1952), it was now possible to see the problem of portfolio selection adeptly expressed in the form of a mathematical programme, which has turned out to be quite productive. That was why it took until then, with Markowitz's basic model being

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$$\min \left\{ \sum_{i=1}^{n} \sum_{j=1}^{n} x_i \sigma_{ij} x_j \right\} \tag{1}$$

$$s.t. \quad \sum_{i=1}^{n} E(r_i) x_i = \rho \tag{2}$$

$$\sum_{i=1}^{n} x_i = 1 \tag{3}$$

$$x_i \geq 0, \quad i = 1, \ldots, n \tag{4}$$

where r_i is the random variable for the return to be realised on security i over a future period $E(r_i)$ is the expected value of r_i; σ_{ii} is the variance of r_i; σ_{ij} is the covariance of r_i with r_j; x_i is the proportion of capital to be invested in security i; ρ is a parameter for the expected return of a resulting portfolio.

The purpose of this formulation is to compute the portfolio of minimum risk that has exactly ρ as its expected return. Rounding out the model, (3) stipulates that all capital is to be invested and (4) enforces non-negativities on the amounts invested.

With parameter ρ fixed, the model is a quadratic programme (QP). But ρ is *not* supposed to be fixed. It is to be varied over a range to trace out continuously the efficient frontier. With this not possible at the time, Markowitz created in 1956 his *critical line* method that has the ability to compute all solutions that are QP-parametrically optimal in such problems in one run to do exactly that. However, the algorithm as described in Markowitz (1956) is exceedingly difficult to understand and this has caused users to generally opt for the repetitive optimisation of (1) for different discrete values of ρ to achieve the same efficient frontier but in dotted form.

Thus, out of Markowitz (1952, 1956, 1959), Markowitz's new theory of portfolio selection took shape in the form of the following four steps:

Step 1: Formulate the mean-variance model and define with appropriate data.

Step 2: Decide if any additional constraints are to be added to the model.

Step 3: Solve for the model's efficient frontier.

Step 4: Study the efficient frontier and select from it one's optimal portfolio.

In Step 2, for example, upper bounds on the amounts invested in individual securities and sector-type constraints might be added as Markowitz's critical line algorithm could handle them as well in addition to (3) and (4).

While the mathematical side of Markowitz's mean-variance model has received enormous praise for its mathematical tractability, there is another aspect of Markowitz's above four-step approach that has probably been as equally important to its success. It is its decision-making side. By being able to provide more than one potentially optimal solution, a decision-maker is able to understand better why his or her choice of an optimal solution is optimal. Also, there is flexibility in the four-step approach in that different decision-makers can have different optimal solutions.

3. Expanded framework

One of the remarkable things about Markowitz's mean-variance framework is that, even after 65 years, it has remained largely intact, and to many it is still the gold standard in portfolio selection. While it has endured many criticisms, there is one, however, that has perhaps been the most persistent. It is that the basic model does not allow for additional criteria. While the criticism goes back at least to Lee and Lerro (1973), the need for portfolio selection to be able to include criteria beyond mean and variance has, as attested to in this paper, only been growing. But this need not detract from the fundamental structure of portfolio selection to which finance has become accustomed. In most cases, it need only be augmented.

To facilitate the many new criterion ideas that have been introduced since 1973, it is now helpful to view this growing area of portfolio selection, which we will call multi-criteria portfolio selection, where "multiple" means more than two, in terms of the five following phases:

Phase 0: Select a subset of securities to go on an approved list.

Phase 1: Formulate a mathematical programming model and define with appropriate data.

Phase 2: Decide on how additional criteria are to be modelled and whether any additional constraints are to be added to the model.

Phase 3: Solve the model to identify candidate solutions, if not the whole efficient set.

Phase 4: Study the candidate solutions and select from them one's most suitable portfolio.

Note that in this expanded framework, there is now a security analysis/evaluation part (Phase 0). In this way, the expanded framework formally recognises the integral nature of techniques such as multi-criteria sorting and classification for the construction of lists of securities approved for investment in the portfolio construction/optimisation part of the framework (Phases 1 through 4). Also, in the framework, Phase 2 allows for additional criteria to be modelled as objectives, or as constraints (as in a goal programme). While the five-phase framework is not quite as strict, it still allows the process to remain true to the risk-return principles of the original four-step approach.

A large number of multiple criteria methods have already been applied in the field of portfolio selection, in both the security analysis and optimisation parts of the above (see Al-Shammari & Masri, 2015; Aouni, Colapinto, & La Torre, 2014, Hallerbach & Spronk, 2002; Spronk, Steuer, & Zopounidis, 2016; Steuer & Na, 2003; Steuer, Qi, & Hirschberger, 2005; Steuer, Wimmer, & Hirschberger, 2013; Xidonas, Mavrotas, Krintas, Psarras, & Zopounidis, 2012; Xidonas & Psarras, 2009; Zopounidis, 1999; Zopounidis & Doumpos, 2013; and Zopounidis, Galariotis, Doumpos, Sarri, & Andriosopoulos, 2015). In these references, some authors use the term MCDM (multiple criteria decision-making) and some use the term MCDA (multi-criteria decision aid), terms which we consider virtually equivalent. Henceforth, whenever there is a choice, our preference will be to use MCDA in this paper.

Note that in this bibliographic review, we pay special attention to the formulation and structures of the portfolio selection model as these are more insightful than the solution method. An approximate formulation solved "exactly" is not evidently better than a more precise formulation solved heuristically. For example, methods in Table 1 are largely discrete choice methods which are approximate representations of a more complicated reality. Sometimes the inclusion of additional criteria and constraints can make a portfolio selection problem too complex to be solved by existing exact methods. In such cases, multi-objective evolutionary algorithms are often advised (see Metaxiotis & Liagkouras, 2012 for a comprehensive literature review on multi-objective evolutionary algorithms in portfolio selection). However, while approximately accurate solutions might be fully acceptable in other contexts, in financial portfolios, with billions of dollars often on the line, many managers would generally not wish to add algorithm risk to the long line of other risks that they face if at all possible. This is why exact methods are important and why we focus on them in this paper.

The rest of the paper is organised as follows. In Section 4, we classify the various MCDA techniques that have been applied to the security analysis/evaluation and construction/optimisation parts of portfolio selection process since Lee and Lerro (1973). Of the studies of this paper, Section 5 shows the distribution of these papers by journal and subject area category. Section 6 covers the distribution of these papers by year and country. The different criteria that have be utilised are shown in Section 7. Special variables and special constraint treatments are covered in Section 8. Section 9 concludes the paper.

4. Classification of applied techniques

A total of 116 published studies on MCDA exact methods combined with portfolio selection and management have been compiled. A search was conducted using SCOPUS focusing only on published works in scientific journals. That is, books, chapters in books, and conference proceedings articles are not included. The search terms were "portfolio selection", "securities" and "MCDM/MCDA". We have also reviewed the principal references in each of the reviewed papers in order to obtain more references not identified in our search via SCOPUS.

In this section, we classify the different MCDA techniques employed in the papers. In Table 1, we show the different techniques used in the security analysis/evaluation part (Phase 0) of the expanded framework. In this table, we observe that analytic hierarchy process (AHP)-based techniques are the most popular in the security analysis phase at about one-third of the total. Following this, we have ELECTRE-based approaches at about 16%, TOPSIS approaches at about 15%, and so forth.

In Table 2, we show the different techniques used in the portfolio construction/optimisation parts (Phases 1 through 4) of the expanded framework as they are not always the same. When not the same, they appear in both tables. In Table 2, we observe that the most written about technique used in the portfolio part of the expanded framework is goal programming at about 42%. This is followed by compromise programming at about 19%, and e-constraint methods and fuzzy mathematical programming tied at about 13% each, and so forth.

It is interesting to note in Table 1 that the preponderance of methods used in the security/evaluation phase are discrete alternative methods, whereas in Table 2 the preponderance of methods used in the portfolio construction/optimisation phases are mathematical programming procedures.

5. Distribution of papers by journal and subject area category

The distribution of studies by journal and subject area category is shown in Table 3. With regard to the journals, the journal with the largest number of reviewed papers is the *European Journal of Operational Research* (*EJOR*). With 17, this is significant because *EJOR* is a journal of very high visibility. For instance, in 2016, articles in *EJOR* were cited over 38,000 times according to Journal Citation Reports available through Thomson Reuters. This is more than any other operational research/management science journal and more than the most cited finance journal, which is the *Journal of Finance*, at 29,000. This means that when an article is published in *EJOR* it has a very good chance of being seen by others, and with 17 articles published in *EJOR*, this is very good for making known the many new innovative ideas of multiple criteria portfolio selection.

With 8 journals having 4 or more each, it is somewhat concerning that only 12 studies have been published in finance journals. The 12 come from three each in the *Journal of Portfolio Management* and the *Journal of Banking & Finance*, two each from the *Journal of Finance*

Table 1. MCDA techniques applied in security analysis/evaluation phase.

MCDA based approach	Number of articles	Studies	
AHP	14	Cheung and Liao (2009), García-Melón et al. (2016), Ho et al. (2011), Kiris and Ustun (2012), Lamata et al. (2016), Lee, Tzeng, Guan, Chien, and Huang (2009), Marasović and Babić (2011), Nguyen and Gordon-Brown (2012)	Pérez-Gladish and M'Zali (2010), Petrillo et al. (2016), Saaty, Rogers, and Pell (1980), Saraoglu and Detzler (2002), Tiryaki and Ahlatcioglu (2009), Yodmun and Witayakiattilerd (2016)
PROMETHEE	4	Albadvi et al. (2007), Bouri et al. (2002)	Marasović and Babić (2011), Martel et al. (1991)
DEMATEL	2	Ho et al. (2011)	Varma and Kumar (2012)
VIKOR	1	Ho et al. (2011)	
TOPSIS	6	Bilbao-Terol, Arenas-Parra, Cañal, and Antomil (2014), Chen and Hung (2009), Lamata et al. (2016)	Liu et al. (2012), Tiryaki and Ahlatcioglu (2005), Yodmun and Witayakiattilerd (2016)
ELECTRE	7	Chen and Hung (2009), Khoury et al. (1993), Martel, Khoury, and Bergeron (1988), Pérez-Gladish et al. (2007)	Vezmelaia, Lashgarib, and Keyghobadi (2015), Xidonas, Mavrotas, and Psarras (2009), Xidonas, Askounis, et al. (2009)
MACBETH	2	Bana e Costa and Soares (2004)	Cabello et al. (2014a)
Multigroup Hierarchical Discrimination method	1	Doumpos et al. (2000)	
Fuzzy Multicriteria Expert Systems	2	Fasanghari and Montazer (2010)	Samaras and Matsatsinis (2004)
Trade-off Analysis of stocks' attributes	1	Jog, Kaliszewski, and Michalowski (1999)	
UTASTAR	3	Samaras, Matsatsinis, and Zopounidis (2003, 2004, 2008)	
UTADIS based	1	Zopounidis, Doumpos, and Zanakis (1999)	
Total	44		

Table 2. MCDA techniques applied in portfolio construction/optimisation phases.

MCDA based approach	Number of articles	Studies	
Goal Programming	35	Abdelaziz and Masmoudi (2014), Abdelaziz, El Fayedh, and Rao (2009), Alexander and Resnik (1985), Arenas-Parra et al. (2001), Ballestero (2001), Ballestero and García-Bernabeu (2012), Ballestero, Pérez-Gladish, Arenas-Parra, and Bilbao-Terol (2009), Ballestero et al. (2012), Bilbao-Terol, Arenas-Parra, Jimenez, Pérez-Gladish, and Rodríguez (2006c), Bilbao-Terol et al. (2012, 2016a, 2016b), Bravo, Pla-Santamaría, and García-Bernabeu (2010), Briec et al. (2013), Chunhachinda, Dandapani, Hamid, and Prakash (1997), Colson and De Bruyn (1989), Cooper, Lelas, and Sueyoshi (1997), Davis, Kat, and Lu (2009), Ghahtarani and Najafi (2013), Gupta et al. (2013), Kocadagli and Keskin (2015), Kumar and Philippatos (1979)	Kumar et al. (1978), Lee and Chesser (1980), Lee and Lerro (1973), Leung et al. (2001), Masmoudi and Abdelaziz (2017), Masri (2017), Mehlawat (2016), Messaoudi et al. (2017), Pendaraki, Zopounidis, and Doumpos (2005), Powell and Premachandra (1998), Prakash et al. (2003), Tamiz et al. (2013), Trenado et al. (2014), Wu, Chou, Yang, and Ong (2007)
Compromise Programming	16	Abdelaziz et al. (2007), Amiri et al. (2011), Ballestero (1998), Ballestero and Pla-Santamaría (2003, Ballestero & Pla-Santamaría (2004, 2005), Ballestero and Romero (1996), Bilbao-Terol, Pérez-Gladish, Arenas-Parra, and Rodríguez-Uría (2006a), Bilbao-Terol, Pérez-Gladish, and Antomil (2006b), Bilbao-Terol et al. (2014)	Boswarva and Aouni (2012), Hasuikea and Katagiri (2014), Liu et al. (2012), Pérez-Gladish et al. (2007), Salas-Molina, Rodríguez-Aguilar, and Pla-Santamaria (2017), Xia et al. (2001)
ε-Constraint method	11	Ballestero (2005), Bilbao-Terol et al. (2013), Calvo, Ivorra, and Liern (2012, 2017), Chen and Huang (2009), Huang, Gwo, and Ong (2006)	Konno et al. (1993), Konno and Suzuki (1995), Moon and Yao (2011), Pardalos, Sandstrom, and Zopounidis (1994), Xidonas, Askounis, et al. (2009)
PROMETHEE V	1	Bouri et al. (2002)	
Reference Point Method	3	Cabello et al. (2014a, 2014b)	Ogryczak (2000)
MAUT	1	Ehrgott et al. (2004)	
Weighting approach	2	García, Guijarro, and Moya (2013)	Ogryczak (2000)
Reservation level driven Tchebycheff procedure	1	Kiris and Ustun (2012)	
Interactive methods	1	Shing and Nagasawa (1999)	
IPSSIS	1	Xidonas et al. (2011)	
ADELAIS	1	Zopounidis et al. (1998)	
Fuzzy Mathematical Programming	11	Alimi, Zandieh, and Amiri (2012), Ammar and Khalifa (2003), Calvo et al. (2015, 2016), Chen and Huang (2009), Gupta et al. (2008)	Hasuikea and Katagiri (2013), Hasuikea, Katagiri, and Ishiia (2009), León, Liern, and Vercher (2002), Mehlawat (2016), Yu et al. (2014)
Total	84		

Table 3. Distribution of papers by journal and subject area.

Journal MP variety	Subject Area Category	Number of papers	Year
Advances in Operations Research	Management Science and Operations Research	1	2016
Annals of Operations Research	Management Science and Operations Research; Decision Sciences	8	1993, 2000, 2016, 2017
Applied Economics	Economics and Econometrics	1	2005
Applied Mathematical Finance	Economics, Econometrics and Finance; Mathematics	1	2005
Applied Mathematics and Computation	Applied Mathematics; Computation	5	2005, 2006, 2014
Automatica	Control and Systems Engineering	1	2015
Chaos, Solitions & Fractals	Mathematics	1	2003
Computational Economics	Economics, Econometrics and Finance; Computer Science	2	1994, 1998
Computers & Industrial Engineering	Computer Science; Engineering	1	2014
Computers & Operations Research	Management Science and Operations Research;Computer Science;Mathematics	2	2009, 2011
Decision Science Letters	Decision Sciences	1	2015
Decision Sciences	Business, Management and Accounting; Decision Sciences	2	1979, 1999
Economic Modelling	Economics, Econometrics and Finance	1	2013
European Journal of Finance	Economics, Econometrics and Finance	1	2004
European Journal of Operational Research	Management Science and Operations Research; Information Systems and Management; Mathematics	17	1997, 1998, 2001, 2002, 2004, 2005, 2007, 2008, 2011, 2012, 2013, 2014
Expert Systems with Applications	Computer Science; Engineering	6	2006, 2009, 2011, 2015
Financial Analysts Journal	Economics, Econometrics and Finance; Business, Management and Accounting	2	2002
Fuzzy Economic Review	Economics, Econometrics and Finance	1	2004
Fuzzy Optimization and Decision-Making	Computer Science; Mathematics	1	2013
Fuzzy Sets and Systems	Computer Science; Mathematics	1	2009
IEEE Transactions on Fuzzy Systems	Computer Science; Engineering; Mathematics	1	2012
INFOR: Information Systems and Operational Research	Computer Science	5	2009, 2012, 2014
Information Sciences	Computer Science; Decision Sciences; Mathematics; Engineering	4	2008, 2009, 2012, 2016
International Journal of Industrial Engineering Computations	Engineering	1	2012
International Journal of Multicriteria Decision Making	Management Science and Operations Research; Business, Management and Accounting;	1	2010
International Journal of Production Economics	Management Science and Operations Research; Business, Management and Accounting; Economics, Econometrics and Finance; Engineering	2	1999, 2011
International Review of Financial Analysis	Economics, Econometrics and Finance	1	2015
International Transactions in Operational Research	Management Science and Operations Research; Business, Management and Accounting; Computer Science	2	2003, 2014
Journal of Applied Mathematics	Mathematics	1	2012
Journal of Applied Mathematics and Decision Sciences	Decision Sciences; Mathematics	1	2009
Journal of Banking & Finance	Economics, Econometrics and Finance	3	1985, 1997, 2003
Journal of Business Economics and Management	Business, Management and Accounting; Economics and Econometrics	1	2013
Journal of Business Ethics	Business, Management and Accounting; Economics and Econometrics; Social Sciences	1	2013
Journal of Decision Systems	Business, Management and Accounting; Computer Sciences	1	2009
Journal of Derivatives and Hedge Funds	Economics, Econometrics and Finance	1	2009
Journal of Finance	Business, Management and Accounting; Economics, Econometrics and Finance	2	1973, 1978
Journal of Financial and Quantitative Analysis	Business, Management and Accounting; Economics, Econometrics and Finance	1	1973
Journal of Investment Management	Business, Management and Accounting; Economics, Econometrics and Finance	1	2003
Journal of Multi-Criteria Decision Analysis	Business, Management and Accounting; Decision Sciences	3	1999, 2002, 2010
Journal of Portfolio Management	Business, Management and Accounting; Economics, Econometrics and Finance	3	1980, 1980, 2007
Journal of the Operational Research Society	Management Science and Operations Research; Business, Management and Accounting	7	1988, 1996, 1998, 2006, 2016, 2017
Journal of the Operations Research Society of Japan	Management Science and Operations Research; Business, Management and Accounting	1	1995
L'Actualité Economique, Revue d'Analyse Economique	Business, Management and Accounting	2	1991, 1993
Mathematical and Computer Modelling	Computer Science; Mathematics	1	1989

(*Continued*)

Table 3. (*Continued*).

Journal MP variety	Subject Area Category	Number of papers	Year
Mathematical Problems in Engineering	Mathematics; Engineering	1	2014
OMEGA	Management Science and Operations Research; Business, Management and Accounting	3	2004, 2007, 2014
Operational Research: An International Journal	Management Science and Operations Research	4	2003, 2004, 2009, 2017
Optimization	Mathematics	1	
Optimization Letters	Mathematics	1	2013
Parallel Algorithms and Applications	Computer Science	1	2000
Procedia Engineering	Engineering	1	2012
Research in International Business and Finance	Business, Management and Accounting;Economics, Econometrics and Finance	1	2016
Total		116	

and the *Financial Analysts Journal*, and one each from the *Journal of Financial and Quantitative Analysis* and the *Journal of Investing*. None, however, have been published in the *Journal of Financial Economics*, the *Review of Financial Studies*, and the *Journal of Money, Credit and Banking*, other top journals in finance.

But there is an explanation for this. Since 1952, finance can be viewed as existing in two eras. The first, for about 30 years, takes us to the early 1980s. The second is from then until now. The first can be characterised as having a high operational research/mathematical programming (OR/MP) methodological content. The second has had only an exclusively empirical content (i.e., in which econometrics is the primary tool). The transition occurred in the early 1980s when the methodological side appeared to be running out of ideas and the empirical side quickly moved in to close the gap. Moreover, at this time, most US and US-emulated PhD programmes in finance dropped what little they had in OR/MP from their curricula. By today, this has led to a depletion in the ability of the finance journals to referee papers in which OR/MP is a tool. With essentially all of the MCDA tools used in multiple criteria portfolio selection being of the OR/MP variety, and the top financial journals being in the mode of only today publishing articles of the empirical variety, one can see the challenge. This is the reason why so few MCDA portfolio papers (while 12 in total, but only four since 1997) have been able to find publication in these journals.

In addition, in their paper, Spronk et al. (2016) highlighted the growth of empirical finance over the years and they question the extent to which insights gained from descriptive finance can be used as guidelines for practical financial decisions. To illustrate their position, they referred to the preface of Fama and Miller's book, *The Theory of Finance*, where they report on how to apply financial theory to real-world decision problems:

> (…) a reflection of our belief that the potential contribution of the theory of finance to the decision-making process, although substantial, is still essentially indirect. The theory can often help expose the inconsistencies in existing procedures; it can help keep the really critical questions from getting lost in the inevitable maze of technical detail; and it can help prevent the too easy, unthinking acceptance of either the old *clichés* or new fads. But the theory of finance has not yet been brought, and perhaps never will be, to the cookbook stage. (Fama & Miller, 1972, p;. viii, taken in turn from Spronk et al., 2016)

Of all the financial journals, the one, in our opinion, appearing today to be the most receptive to MCDA portfolio papers is the *Journal of Portfolio Management* in that they appear willing to publish interesting articles no matter what the tool. Hopefully, competition will cause the others to become more open, too.

6. Distributions of papers by year and country

Since the paper by Lee and Lerro in 1973, and also by the paper by Stone (1973) later that year, papers on MCDA in security analysis and portfolio optimisation were only published on average at about one per year until the late 1990s. Then after 2000, the number of published papers addressing portfolio selection problems with MCDA approaches took a sharp increase with the trend continuing today. This is almost certainly the result of a greater awareness of the topic and of the fact that investments have certainly not gotten less complex. Figure 1 shows the publication of the 116 papers by year. However, note that the dot for 2017 in only a lower bound for that year due to the mid-2017 writing of this survey.

Table 4 displays authorship counts by country. In our counting by country, we have not taken into account the number of authors of a paper, just the number of different author countries of each publication. Spain has an authorship count of 36, the USA is in second place

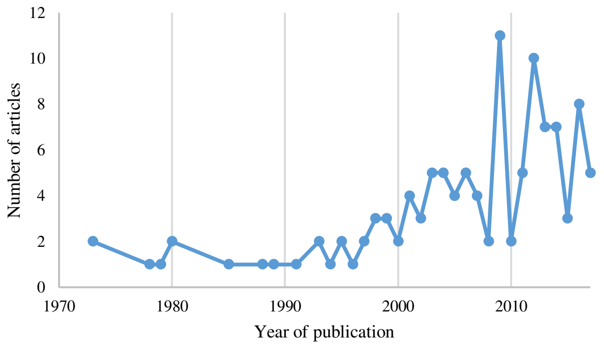

Figure 1. Distribution of papers by year.

Table 4. Authorship counts by country.

Country	Number	Country	Number	Country	Number
Spain	36	France	3	Dubai	1
USA	19	UK	3	Egypt	1
Greece	11	Belgium	2	Germany	1
Taiwan	8	Kingdom of Bahrain	2	Italy	1
Japan	8	New Zealand	2	Korea	1
Canada	7	Poland	2	Kuwait	1
Iran	6	Thailand	2	Portugal	1
Tunisia	5	Austria	1	Qatar	1
Turkey	5	Australia	1	Sweden	1
India	4	Croatia	1		
China	4	Denmark	1		

with 19, and Greece is in third with 11. After this, 28 other countries follow. With multiple criteria in portfolio selection being a difficult area and with 31 countries represented, this provides an excellent environment for the cross-fertilisation of ideas from different cultures and underscores the international recognition and importance of this growing area.

7. Criteria included

In this section, we analyse the criteria used in the security analysis/evaluation and portfolio construction/optimisation parts of the portfolio selection process. Moreover, we have performed our analysis distinguishing between mutual funds and stocks. As mutual funds are investment vehicles made up of sets of securities which can include stocks, bonds, and other assets, the criteria used in the evaluation of mutual funds can differ from those used in the evaluation of individual securities. Table 5 summarises the most popular criteria that have been used in securities' evaluation and Table 6 presents similar criterion information but at the portfolio construction/optimisation level.

Regarding securities' screening criteria (Table 5), it is evident that additional performance indicators have been used beyond risk and return. This is indicative of the complexity of the securities' screening process, as analysts and investors take into consideration various factors that can affect the prospects of the available investment options. For mutual funds, the review of the literature highlights that typical selection criteria (apart from risk and return) may well involve risk adjusted performance, expense ratios, and fund manager experience (see for example, Martel, Khoury, & M'Zali, 1991 and Saraoglu & Detzler, 2002). In the case of stock analysis criteria, the tendency is the same, formulation of the problem involves not only traditional risk and return criteria but also attributes about corporate fundamentals, including both financial and stock market criteria. Financial criteria include profitability, liquidity and operating performance ratios such as return on investment, debt/equity, sales growth, etc. Stock market criteria mostly focus on valuation ratios (price/earnings, earnings per share, book value per share), as well as on issues related to dividends and marketability. Risk is considered not only through variance, but also through measures such as skewness, and kurtosis.

It is worth noting that beyond financial and stock market indicators, asset screening often takes into account non-financial attributes. It is now widely acknowledged that not all relevant information about an investment decision can be captured with reference to financial criteria. Zopounidis and Doumpos (2013) and Steuer, Qi, and Hirschberger (2007) acknowledge the growing inclusion of non-financial criteria in recently published security evaluation and portfolio selection models. In this context, ethical, environmental, social, and governance issues have attracted considerable interest. Pérez-Gladish and M'Zali (2010), Cabello, Ruiz, Pérez-Gladish, and Méndez (2014a), Bilbao-Terol, Arenas-Parra, and Cañal (2012), Bilbao-Terol, Arenas-Parra, Cañal, and Bilbao-Terol (2013), García-Melón, Pérez-Gladish, Gómez, and Méndez (2016), Lamata, Liern, and Pérez-Gladish (2016), and Petrillo, De Felice, García-Melón, and Pérez-Gladish (2016) are some examples of recent studies that have considered such criteria in mutual funds and stock evaluation. For example, the rising popularity of ethical, environmental, social, and governance criteria for asset selection should not be solely attributed to the added value that they bring compared to traditional financial and stock market indicators. In fact, the consideration of such alternative criteria is also related to the emergence of new types of investments and strategies (e.g., socially responsible investments or SRI) which focus on sustainability and social responsibility principles. Evaluating securities in an SRI context naturally requires the examination of an enriched set of performance criteria which require complex financial/non-financial trade-offs. The review of the literature indicates that MCDA researchers are at the forefront in providing the research foundation for this growing area of interest. Ballestero, Pérez-Gladish, and García-Bernabeu (2015) provide an up-to-date review of the use of MCDA methodologies for SRI by different authors from different countries.

On the portfolio construction/optimisation side (Table 6), the review of the literature regarding relevant performance measures indicates a variety of different perspectives. First, one can note that in addition to the first two moments (mean and variance) of the return distribution, several authors have considered the next two moments (skewness and kurtosis). Examples of studies that have investigated this are Konno, Shirakawa, and Yamazaki (1993), Konno and Suzuki (1995), Briec, Kerstens, and Van de Woestyne (2013), Nguyen and Gordon-Brown (2012), Liu, Zhang, and Xu (2012), Leung, Daouk, and Chen (2001), and Prakash, Chang, and Pactwa (2003). Skewness and kurtosis provide an extended view of investment risk in that they focus on risks that arise due to asymmetric returns and heavy

Table 5. Criteria used in securities' evaluation.

Criteria	Studies	
Expected return (mean historical returns)	Albadvi et al. (2007), Boswarva and Aouni (2012), Cabello et al. (2014a), Cheung and Liao (2009), Doumpos et al. (2000), Huang et al. (2006), Khoury et al. (1993), Lamata et al. (2016)	León, Liern, Marco Pont, Segura, and Vercher (2004), Marasović and Babić (2011), Martel et al. (1988, 1991), Nguyen and Gordon-Brown (2012), Saraoglu and Detzler (2002)
Dividend yield	Doumpos et al. (2000)	
Return on equity (ROE)	Doumpos et al. (2000), Vezmelaia et al. (2015)	Xidonas, Mavrotas, et al. (2009, Xidonas, Askounis, et al., 2009)Zopounidis et al. (1999)
Return on assets (ROA)	Vezmelaia et al. (2015), Xidonas, Mavrotas, et al. (2009, Xidonas, Askounis, et al., 2009)	
Risk (variance, standard deviation)	Huang et al. (2006), Khoury et al. (1993), Lamata et al. (2016)	Martel et al. (1988, 1991), Nguyen and Gordon-Brown (2012)
Risk (Beta)	Albadvi et al. (2007), Ho et al. (2001)	Marasović and Babić (2011), Varma and Kumar (2012)
Lower semi-variance	León et al. (2004)	Marasović and Babić (2011)
Expense ratio	Saraoglu and Detzler (2002)	
Manager's tenure	Saraoglu and Detzler (2002)	
Sharpe ratio	Saraoglu and Detzler (2002)	
The maximum rate of acquisition or liquidation costs compounded by the fund	Martel et al. (1991)	
The fund's eligibility for the real effective exchange rate	Martel et al. (1991)	
Transaction costs	Khoury et al. (1993)	
Market share	Albadvi et al. (2007), Fasanghari and Montazer (2010)	Marasović and Babić (2011)
Skewness	Nguyen and Gordon-Brown (2012)	
Kurtosis	Nguyen and Gordon-Brown (2012)	
Long-term debt to equity ratio	Albadvi et al. (2007) Marasović and Babić (2011)	
Total debts to total assets ratio	Albadvi et al. (2007)	Marasović and Babić (2011)
Time interest earned	Albadvi et al. (2007)	Varma and Kumar (2012)
Total assets turnover ratio	Albadvi et al. (2007) Samaras et al. (2008)	Varma and Kumar (2012), Xidonas, Askounis, et al., 2009
Inventory turnover ratio	Albadvi et al. (2007), Xidonas, Askounis, et al. (2009)	Samaras et al. (2008)
Profit margin	Albadvi et al. (2007), Samaras et al. (2008)	Xidonas, Mavrotas, et al. (2009)
Result of audit	Albadvi et al. (2007)	Fasanghari and Montazer (2010)
Production growth	Albadvi et al. (2007)	Varma and Kumar (2012)
Sales growth	Albadvi et al. (2007)	Varma and Kumar (2012)
Price/earnings ratio (P/E)	Albadvi et al. (2007), Doumpos et al. (2000), Jog et al. (1999), Marasović and Babić (2011)	Martel et al. (1988), Varma and Kumar (2012), Vezmelaia et al. (2015), Yodmun and Witayakiattilerd (2016)
Market value	Albadvi et al. (2007), Doumpos et al. (2000)	Zopounidis et al. (1999)
Payout ratio	Albadvi et al. (2007)	
EPS coverage	Albadvi et al. (2007), Fasanghari and Montazer (2010)	Vezmelaia et al. (2015)
Liquidity	Albadvi et al. (2007), Marasović and Babić (2011)	Varma and Kumar (2012), Xidonas, Askounis, et al., 2009
Profitability variance	Albadvi et al. (2007)	
Free float of the stock	Albadvi et al. (2007)	
Capital raising within the last year	Albadvi et al. (2007)	
Price to fair value ratio	Albadvi et al. (2007)	
Gross book value per share	Doumpos et al. (2000), Varma and Kumar (2012)	Zopounidis et al. (1999)
Capitalisation ratio	Doumpos et al. (2000)	Zopounidis et al. (1999)
Marketability	Doumpos et al. (2000)	Zopounidis et al. (1999)
Financial position progress	Doumpos et al. (2000)	Zopounidis et al. (1999)
Exchange flow ratio	Doumpos et al. (2000)	Zopounidis et al. (1999)
Round lots per day	Doumpos et al. (2000)	Zopounidis et al. (1999)
Transaction value per day	Doumpos et al. (2000)	Zopounidis et al. (1999)
Equity ratio	Doumpos et al. (2000)	Zopounidis et al. (1999)

(*Continued*)

Table 5. (*Continued*).

Criteria	Studies
Structure ratio	Doumpos et al. (2000) Zopounidis et al. (1999)
Equity/ debt ratio	Doumpos et al. (2000)Samaras et al. (2008) Zopounidis et al. (1999)Xidonas, Askounis, et al., 2009
Price per share	Jog et al. (1999)
Price to cash flows ratio	Jog et al. (1999)
Price to adjusted after-tax operating earnings ratio	Jog et al. (1999)
P/B Ratio	Marasović and Babić (2011) Yodmun and Witayakiattilerd (2016)
Loans to deposit ratio	Marasović and Babić (2011) Xidonas, Askounis, et al., 2009
Net Asset Value to Enterprise Value Ratio	Marasović and Babić (2011) Samaras et al. (2008)
Economic value added	Vezmelaia et al. (2015)
Environmental, social and governance (esg) aspects	Bilbao-Terol et al. (2012, 2013), Cabello et al. (2014a), García-Melón et al. (2016) Pérez-Gladish and M'Zali (2010), Petrillo et al. (2016), Lamata et al. (2016)
Other criteria (industry evaluation, macroeconomic factors, efficiency of management, investor's preferences…)	Albadvi et al. (2007), Ho et al. (2001), Khoury et al. (1993), Marasović and Babić (2011), Martel et al. (1988) Samaras et al. (2008), Tiryaki and Ahlatcioglu (2009), Xidonas, Mavrotas, et al. (2009), Yodmun and Witayakiattilerd (2016)

tails. Other risk measures such as mean absolute deviation are perhaps more appropriate for return distributions that deviate from normality (Konno et al., 1993; Moon & Yao, 2011; Ogryczak, 2000; Tamiz, Azmi, & Jones, 2013; Xidonas, Mavrotas, Zopounidis, & Psarras, 2011).

The review of the literature indicates that systematic risk has been widely used in MCDA models for portfolio optimisation involving both funds and stocks. Some studies that have used systematic risk include Albadvi, Chaharsooghi, and Esfahanipour (2007), Ho et al. (2011), Marasović and Babić (2011), Varma and Kumar (2012), Pérez-Gladish, Jones, Tamiz, and Bilbao-Terol (2007), Abdelaziz and Masmoudi (2014), Abdelaziz, Aouni, and El Fayedh (2007), Ghahtarani and Najafi (2013), Kocadagli and Keskin (2015), Masmoudi and Abdelaziz (2017), Xidonas, Askounis, and Psarras (2009; 2011), and Amiri, Ekhtiari, and Yazdani (2011).

In addition to the above risk measures, there has been considerable recent research into tail risk measures with value at risk (VaR) and conditional value at risk (CVaR) being well-known examples. Interestingly, however, our literature review shows that only a small number of studies have considered such risk measures (Bilbao-Terol, Arenas-Parra, Cañal, & Bilbao-Terol, 2016b; Bilbao-Terol, Arenas-Parra, Cañal, & Jiménez, 2016a; Bilbao-Terol et al., 2012, 2013; Messaoudi, Aouni, & Rebai, 2017) in a MCDA portfolio construction context. Thus, it appears that multi-criteria portfolio construction models could further explore this area.

On the other hand, many studies have focused on modelling additional aspects of the portfolio construction process to address realistic issues such as:

(a) transaction costs: Yu, Lee, and Chiou (2014), Khoury, Martel, and Veilleux (1993), Xia, Wang, and Deng (2001), and Liu et al. (2012),
(b) liquidity: Albadvi et al. (2007), Marasović and Babić (2011), Varma and Kumar (2012), Steuer et al. (2007), Bouri, Martel, and Chabchoub (2002), Chen and Hung (2009), Gupta, Mehlawat, and Saxena (2008), Gupta, Mittal, and Mehlawat (2013), Arenas-Parra, Bilbao-Terol, and Rodríguez-Uria (2001), Mehlawat (2016), and Lo, Petrov, and Wierzbicki (2003),
(c) dividends: Doumpos, Zopounidis, and Pardalos (2000), Kumar, Philippatos, and Ezzell (1978), Ehrgott, Klamroth, and Schwehm (2004), Bana e Costa and Soares (2004), Lee and Lerro (1973), Xidonas, Askounis, et al. (2009), Zopounidis, Despotis, and Kamaratou (1998), Xidonas et al. (2011), and Gupta et al. (2008).

Investors and portfolio managers typically consider such issues as part of their investment strategies. Thus, incorporating these issues in extended multi-criteria portfolio construction models makes the models more

Table 6. Criteria used in the construction/optimisation of portfolios.

Criteria	Studies	
Expected return (based on mean historical return)	Abdelaziz et al. (2007), Abdelaziz and Masmoudi (2014), Alimi et al. (2012), Ammar and Khalifa (2003), Amiri et al. (2011), Arenas-Parra et al. (2001), Ballestero et al. (2009), Ballestero et al. (2012), Ballestero (1998, 2001, 2005), Ballestero and Pla-Santamaría (2003, 2004, 2005), Ballestero and García-Bernabeu (2012), Bilbao-Terol et al. (2006a, 2006b, 2006c, 2012, 2013, 2016a, 2016b), Bouri et al. (2002), Bravo et al. (2010), Briec et al. (2013), Cabello et al. (2014b), Calvo et al. (2015, 2016), Calvo et al. (2012, 2017), Chen and Huang (2009), Chow (1995), Chunhachinda et al. (1997), Davis et al. (2009), Colson and De Bruyn (1989), García et al. (2013), Ghahtarani and Najafi (2013), Gupta et al. (2008), Gupta et al. (2013), Hasuikea and Katagiri (2013, 2014), Kocadagli and Keskin (2015)	Konno et al. (1993), Konno and Suzuki (1995), Lee and Chesser (1980), Lee and Lerro (1973), León et al. (2002), Lo et al. (2003), Leung et al. (2001), Liu et al. (2012), Masmoudi and Abdelaziz (2017), Masri (2017), Mehlawat (2016), Messaoudi et al. (2017), Moon and Yao (2011), Ogryczak (2000), Pardalos et al. (1994), Pendaraki et al. (2005), Pérez-Gladish et al. (2007), Powell and Premachandra (1998), Prakash et al. (2003), Salas-Molina et al. (2017), Shing and Nagasawa(1999), Tamiz et al. (2013) Trenado et al. (2014), Utz et al. (2014), Utz, Wimmer, and Steuer (2015), Xia et al. (2001), Xidonas et al. (2011), Yu et al. (2014)
Excess return (alpha)	Wu et al. (2007)	
Increase in profits per share	Zopounidis et al. (1998)	
Return per share	Zopounidis et al. (1998)	
Capital appreciation	Abdelaziz et al. (2009)	
Capital return	Kumar and Philippatos (1979)	Xidonas, Askounis, et al., 2009
Current income	Abdelaziz et al. (2009)	
Price/earnings ratio (P/E)	Abdelaziz et al. (2009), Bana e Costa and Soares (2004), Messaoudi et al. (2017)	Xidonas, Askounis, et al., 2009, Zopounidis et al. (1998)
Market value to the book value ratio	Abdelaziz et al. (2009)	Bouri et al. (2002)
Exchange flow ratio	Abdelaziz et al. (2007)	
Discounted cash flows	Bana e Costa and Soares (2004)	
Dividend yield	Bana e Costa and Soares (2004), Ehrgott et al. (2004), Lee and Lerro (1973), Kumar et al. (1978)	Xidonas, Askounis, et al., 2009, Xidonas et al. (2011), Zopounidis et al. (1998)
Annual dividend	Gupta et al. (2008)	
Earnings per share growth	Bana e Costa and Soares (2004)	
Enterprise value (E/V)	Bana e Costa and Soares (2004)	
Liquidity (Turnover)	Arenas-Parra et al. (2001), Bouri et al. (2002), Chen and Hung (2009), Gupta et al. (2008)	Gupta et al. (2013), Lo et al. (2003), Mehlawat (2016)
Earnings' yield ratio (EYR)	Bouri et al. (2002)	Powell and Premachandra (1998)
Skewness	Briec et al. (2013), Davis et al. (2009), Konno et al. (1993)	Konno and Suzuki (1995), Leung et al. (2001), Liu et al. (2012), Prakash et al. (2003)
Initial costs	Amiri et al. (2011)	
Transaction costs	Liu et al. (2012), Xia et al. (2001)	Yu et al. (2014)
Information ratio	Wu et al. (2007)	
Marketability	Xidonas, Askounis, et al., 2009	Zopounidis et al. (1998)
Risk (variance, standard deviation)	Abdelaziz et al. (2009), Ammar and Khalifa (2003), Arenas-Parra et al. (2001), Ballestero (1998, 2001, 2005), Ballestero and Pla-Santamaría (2003, 2004, 2005), Ballestero and Romero (1996), Ballestero et al. (2009, 2012), Ballestero and García-Bernabeu (2012), Bravo et al. (2010), Briec et al. (2013), Cabello et al. (2014b), Calvo et al. (2015, 2016), Calvo et al. (2012, 2017), Chen and Huang (2009), Chow (1995), Chunhachinda et al. (1997), Davis et al. (2009), Ehrgott et al. (2004), García et al. (2013), Hasuikea and Katagiri (2013, 2014)	Kocadagli and Keskin (2015), Konno and Suzuki (1995), Lee and Lerro (1973), León et al. (2002), Leung et al. (2001), Liu et al. (2012), Lo et al. (2003), Masri (2017), Ogryczak (2000), Pardalos et al. (1994), Pendaraki et al. (2005), Powell and Premachandra (1998), Prakash et al. (2003), Salas-Molina et al. (2017), Shing and Nagasawa (1999) Utz et al. (2014, 2015)Xia et al. (2001) Xidonas, Askounis, et al., 2009, Yu et al. (2014)

(*Continued*)

Table 6. (*Continued*).

Criteria	Studies	
Risk (beta)	Abdelaziz and Masmoudi (2014), Abdelaziz et al. (2007), Amiri et al. (2011), Bilbao-Terol et al. (2006a, 2006b, 2006c), Bouri et al. (2002), Colson and De Bruyn (1989), Ghahtarani and Najafi (2013), Kocadagli and Keskin (2015)	Kumar and Philippatos (1979), Kumar et al. (1978), Lee and Chesser (1980), Masmoudi and Abdelaziz (2017), Pendaraki et al. (2005), Pérez-Gladish et al. (2007), Xidonas, Askounis, et al., 2009, Xidonas et al. (2011), Zopounidis et al. (1998)
Risk (tracking error)	Chow (1995)	Wu et al. (2007)
Risk (semi-variance)	Alimi et al. (2012), Gupta et al. (2013)	Trenado et al. (2014)
Risk (mean absolute deviation)	Konno et al. (1993), Moon and Yao (2011)	Tamiz et al. (2013)Xidonas et al. (2011)
Risk (least-absolute-value deviation)	Cooper et al. (1997)	
Risk (semi-absolute deviation)	Gupta et al. (2008)	
Risk (CVaR)	Bilbao-Terol et al. (2012, 2013, 2016a, 2016b)	Messaoudi et al. (2017)
Risk (credibilistic entropy of return)	Mehlawat (2016)	
Risk (unexplained variance)	Lee and Lerro (1973)	
Entropy (Shannon's, Yager's, Minimax) entropy	Yu et al. (2014)	
Appreciation in portfolio value	Kumar et al. (1978)	
12-month and 3-year performance	Ehrgott et al. (2004)	
Sharpe index risk-adjusted performance (indices of Sharpe, Jensen, Henriksson and Merton, Treynor and Black)	Pendaraki et al. (2005)	
Percentage change of net asset value	Pendaraki et al. (2005)	
Kurtosis	Davis et al. (2009)	
Residual risk	Kumar and Philippatos (1979) Kumar et al. (1978)	
Cash flow	Powell and Premachandra (1998)	
Costs of liquidating the portfolio	Powell and Premachandra (1998)	
Standard and poor's star rating	Ehrgott et al. (2004)	
Income return	Kumar and Philippatos (1979)	
Environmental, social, governance, and ethical aspects	Ballestero et al. (2012), Bilbao-Terol et al. (2012, 2013, 2016a, 2016b), Cabello et al. (2014b, 2015, 2016)	Powell and Premachandra (1998), Trenado et al. (2014), Utz et al. (2014, 2015)
Macroeconomic factors and other	Bana e Costa and Soares (2004), Powell and Premachandra (1998)	Tamiz et al. (2013), Xidonas et al. (2011)
Other	Ghahtarani and Najafi (2013), Powell and Premachandra (1998)	Xidonas et al. (2011)

Table 7. Special variable treatments and constraints in portfolio optimisation.

Description	Studies
Cardinality constraints	Cabello et al. (2014b), Calvo et al. (2015, 2016, 2017), Ehrgott et al. (2004), Gupta et al. (2008, 2013) Mehlawat (2016), Xidonas et al. (2011), Yu et al. (2014)
Investment threshold constraints	Abdelaziz and Masmoudi (2014), Abdelaziz et al. (2009), Amiri et al. (2011), Ammar and Khalifa (2003), Arenas-Parra et al. (2001), Ballestero (2005), Bana e Costa and Soares (2004), Bilbao-Terol et al. (2006b, 2006c), Bouri et al. (2002), Cabello et al. (2014b), Colson and De Bruyn (1989), Cooper et al. (1997), Ehrgott et al. (2004), Ghahtarani and Najafi (2013), Gupta et al. (2008, 2013) Kocadagli and Keskin (2015), Kumar and Philippatos (1979), Kumar et al. (1978), Lee and Chesser (1980), Lee and Lerro (1973), León et al. (2002), Liu et al. (2012), Masmoudi and Abdelaziz (2017), Masri (2017), Moon and Yao (2011), Pérez-Gladish et al. (2007), Trenado et al. (2014), Xidonas, Askounis, et al., 2009, Xidonas et al. (2011), Zopounidis et al. (1998)
Transaction lot constraints	Calvo et al. (2015, 2016, 2017), Mehlawat (2016), Trenado et al. (2014) Yu et al. (2014), Zopounidis et al. (1998)
Dependency constraints	Xidonas et al. (2011)
Other constraints	Amiri et al. (2011), Bana e Costa and Soares (2004), Bilbao-Terol et al. (2006a, 2012, 2006c), Cabello et al. (2014b), Colson and De Bruyn (1989), Ghahtarani and Najafi (2013), Kumar and Philippatos (1979), Kumar et al. (1978) Lee and Chesser (1980), Lee and Lerro (1973), Mehlawat (2016), Pérez-Gladish et al. (2007), Powell and Premachandra (1998), Tamiz et al. (2013)Xidonas, Askounis, et al., 2009, Xidonas et al. (2011), Zopounidis et al. (1998)

realistic. The inclusion of these realistic (financial) criteria, among others, in the portfolio optimisation process has been discussed in Kellerer, Mansini, and Speranza (2000) and, most recently, in Mansini, Ogryczak, and Speranza (2014).

Finally, as in asset screening, it is again seen that environmental, social, and governance (ESG) criteria play a frequent role on the portfolio construction side, too. Some indicative studies here include those by Powell and Premachandra (1998), Ballestero, Bravo, Pérez-Gladish, Arenas-Parra, and Pla-Santamaría (2012), Cabello, Ruiz, Pérez-Gladish, and Méndez (2014b), Calvo, Ivorra, and Liern (2015, 2016), Bilbao-Terol et al. (2012, 2013, 2016a, 2016b), Trenado, Romero, Cuadrado, and Romero (2014), and Utz, Wimmer, Hirschberger, and Steuer (2014).

With regard to methods when more than two criteria are involved, it is to be noted that the efficient frontier becomes a *surface*, thus making models with three or more criteria in the five-phase framework much more difficult to solve relative to bi-criterion models in the original four-step approach. This is because the efficient surface, which subsumes the efficient frontier, contains many more Pareto optimal solutions. For references on this, see for example, Hirschberger, Steuer, Utz, Wimmer, and Qi (2013) and Steuer et al. (2013).

8. Special variable and constraint treatments

Because Markowitz's critical line algorithm turned out to have more power than necessary to solve (1)–(4), additional sets of linear constraints can easily be incorporated into portfolio models without jeopardising appropriate efficiency results. In addition to placing upper bounds on the amounts invested in the different securities and industry and sectors constraints, transaction costs are sometimes modelled as additional linear constraints.

Furthermore, integer variables are sometimes employed, but as long as the number of integer variables is not large, the models can often be solved exactly. This is why we see in Table 7 cardinality, investment threshold, and transaction lot constraints listed. Cardinality constraints are used to control the number of securities in a portfolio. Investment threshold constraints are used so as to enforce the condition that if certain securities are to be held in a portfolio they must be held in a least some minimum amounts. Otherwise, if the number of integer variables is too large, as previously mentioned, evolutionary algorithms are customarily resorted to but this consigns one to only approximately accurate solutions.

9. Concluding remarks

In this paper, we have concentrated on the contributions of exact methods to the topic of portfolio selection possessing multiple criteria in order to provide a thorough bibliographic overview of meaningful studies in the area. In doing so we have covered the two important parts of multiple criteria portfolio selection, one being on the analysis and evaluation (i.e., asset screening) of specific securities for the creation of approved lists of securities eligible for investment, and the other being on the construction and optimization of portfolios to meet the preferences of multiple criteria decision makers when only considering securities from the approved list. From the conducted literature review, we can observe how the number of criteria considered and their variety has increased remarkably over recent years reflecting the necessity to enhance existing decision-making models with new approaches focused on individualism and realism.

Research in the area of multi-criteria portfolio management continues to be both very active and on the upswing and from what has been accomplished so far, future research is poised to take on a variety of emerging issues. Among others, they include the consideration of new risk measures, extensions of portfolio optimization to extended universes of securities (e.g., commodities, derivatives, funds of funds, and so forth), the development of powerful approaches for optimisation under uncertainty (robust optimisation), the role of non-financial dimensions (such as sustainability and social responsibility), and the validation of existing and new models on large-scale datasets from global markets.

Disclosure statement

No potential conflict of interest was reported by the authors.

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