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An invitation to portfolio decision analysis

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Abstract Portfolio Decision Analysis (PDA) – the application of decision analysis to the problem of selecting a subset or portfolio from a large set of alternatives – accounts for a significant share, perhaps the greater part, of decision analysis consulting. By construction, PDA has a sound theoretical and methodological basis, and its ability to contribute to better resource allocations decisions has been demonstrated in numerous applications. This book pulls together some of the rich and diverse efforts as a starting point for treating PDA as a promising and distinct area of study and application. In this introductory chapter, we first describe what we mean by Portfolio Decision Analysis. We then sketch the historical development of some key ideas, outline the contributions contained in the chapters and, finally, offer personal perspectives on future work in this sub-field of decision analysis that merits growing attention.

1.1 What is Portfolio Decision Analysis?

Practically all organizations and individuals have goals that they seek to attain by allocating resources to actions that consume resources. Industrial firms, for example, undertake research and development projects (R&D), expecting that these projects allow them to introduce new products that generate growing profits. Municipalities allocate public funds to initiatives that deliver social and educational services to their citizens. Regulatory bodies attempt to mitigate harmful consequences of human activity by imposing alternative policy measures which contribute to objectives such as safety and sustainability. Even many individual decisions can be viewed analogously. For instance, university students need to consider what academic courses and recreational pursuits to engage in, recognizing that time is a limited resource when aspiring to complete one's studies successfully and on schedule while having a rewarding social life.

Decision problems such as these are seemingly different. Yet from a methodological point of view, they share so many similarities that it is instructive to consider them together. Indeed, all the above examples involve one or several *decision makers* who are faced with alternative courses of *action* which, if implemented, consume *resources* and enable *consequences*. The availability of resources is typically limited by *constraints* while the desirability of consequences depends on *preferences* concerning the attainment of *multiple objectives*. Furthermore, the decision may affect several *stakeholders* who are impacted by the decision even if they are not responsible it. There can be *uncertainties* as well: for instance, at the time of decision making, it may be impossible to determine what consequences the actions will lead to or how much resources they will consume.

These, in short, are the key concepts that characterize decision contexts where the aim is to select a subset consisting of several actions with the aim of contributing to the realization of consequences that are aligned with the decision maker's preferences. They are also key parts of the following definition of Portfolio Decision Analysis:

> By Portfolio Decision Analysis (PDA) we mean a body of theory, methods, and practice which seeks to help decision makers make informed multiple selections from a discrete set of alternatives through mathematical modeling that accounts for relevant constraints, preferences, and uncertainties.

A few introductory observations about this definition are in order. To begin with, *theory* can be viewed as the foundation of PDA in that as it postulates axioms that characterize rational decision making and enable the development of functional representations for modeling such decisions. *Methods* build on theory by providing practicable approaches that are compatible with these axioms and help implement decision processes that seek to contribute to improved decision quality (see Keisler, Chapter 2). *Practice* consists of applications where these methods are deployed to address real decision problems that involve decision makers and possibly even other stakeholders (see, e.g., Salo and Hämäläinen, 2010). Thus, applications build on decision models that capture the salient problem characteristics, integrate relevant factual and subjective information, and synthesize this information into recommendations about what subset of alternatives (or *portfolio*) should be selected.

In general, PDA follows the tradition of decision analysis (and, more broadly, of operations research) in that it seeks to *improve* decision making by using mathematical models in the development of decision recommendations. In effect, the breadth of application domains where PDA has already been applied, combined with the strategic nature of many resource allocation decisions, suggest that PDA is one of the most important branches of decision analysis (see, e.g., Kleinmuntz, 2007). This notwithstanding, PDA does not seem to have received comparable attention in the literature. In part, this may be due to its many connections to other areas. For example, a considerable share of applied research is scattered across specialized journals that are not regularly read by methodologically oriented researchers or practicing decision analysts.

PDA differs somewhat from the standard decision analysis paradigm due to its focus on portfolio choice (as opposed to the choice of a single alternative from a set, such as choosing a single site to drill for oil). In this setting, it is possible to put forth analytical arguments as to why the pooling of several single choice problems into a more encompassing portfolio choice problem can be beneficial. First, the solution to the portfolio problem will be at least as good, because the combination of single choice problems, when considered together, constitutes a portfolio problem where there is a constraint to choose one alternative from each single choice problem. Thus, when considering these single choice problems together, the removal of these (possibly redundant) single choice constraints may lead to a better solution. Second, if the single choice problems are interconnected – for instance due to the consumption of shared resources or interactions among alternatives in different subsets – the portfolio frame may provide a more realistic problem representation and consequently decision recommendations that are better aligned with reality. Although these remarks do not account for concerns such as computational complexity or possible delays formulating portfolio problems, they suggest that some problems that have been addressed by looking at independent single choice sub-problems may benefit from re-formulations as portfolio problems.

As a rule, PDA problems involve more alternatives than single choice problems. From the viewpoint of problem structuring, a key question in PDA is therefore what alternatives can be meaningfully analyzed as belonging to the 'same' portfolio. While PDA methods do not impose inherent constraints on what alternatives can be analyzed together, there are nevertheless considerations which suggest that some alternatives can be more meaningfully treated as a portfolio. This is the case, for instance, when the alternatives consume resources from the same shared pool; when alternatives are of the same "size" (measured e.g. in terms of cost, or the characteristics of anticipated consequences); when the future performance of alternatives is contingent on decisions about what other alternatives are selected; or when the consideration of alternatives together as part of the same portfolio seems justified by shared responsibilities in organizational decision making.

The fact that there are more alternatives in portfolio choice suggests also that stakes may be higher than in single choice problems, as measured, for example, by the resources that are committed or by the significance of economic, environmental or societal impacts of consequences. As a result, the adoption of a systematic PDA approach may lead to particularly substantial improvements in the attainment of desired consequences. But apart from the actual decision recommendations, there are even other rationales that can be put forth in favor of PDA-assisted decision processes. For example, PDA enhances the transparency of decision making, because the structure of the decision process can be communicated to the stakeholders and the process will leave an auditable trail of the evaluation of alternatives with regard to the relevant criteria. This, in turn, is likely to enhance the efficiency of later implementation phases and the accountability of decision makers.

Overall, the aim of this book is to consolidate and strengthen PDA as a vibrant sub-discipline of decision analysis that merits the growing attention of researchers and practitioners alike. Towards this end, we offer fifteen chapters that present new theoretical and methodological advances, describe high-impact case studies, and analyze 'best practices' in resource allocation in different application domains. In this introductory chapter, we draw attention to key developments in the evolution of PDA. We then summarize the key contributions in each chapter and, finally, outline avenues for future work, convinced that there are exciting opportunities for theoretical, methodological and practical work.

1.2 Evolution of Portfolio Decision Analysis

In this Section, we discuss developments which have contributed to the emergence of PDA over the past few decades, based on our reading of the scientific literature and personal conversations with some key contributors. Our presentation is intended as neither a systemic historical account nor a comprehensive literature review but, rather, as a narrative that will give the reader a reasonable sense of how PDA has evolved. By way of its origins, PDA can be largely viewed as a subfield of decision analysis (DA). We will therefore give most of our attention to developments in DA, particularly from the viewpoint of activities in the US. However, we start by briefly discussing interfaces to neighboring fields where related quantitative methods for resource allocation have also been developed.

1.2.1 Financial portfolio optimization

As a term, “portfolio” is often associated with finance and, in particular, with optimization models that provide recommendations for making investments into market-tradable assets that are characterized by expected return and risk. The evolution of such models began with the celebrated Markowitz mean-variance model (Markowitz, 1952) and continued with the development of the Capital Asset Pricing Model (Sharpe, 1964). Already in the 1960s, optimization techniques were becoming increasingly important in forming investment portfolios that would exhibit desired risk and return characteristics.

Unlike PDA models, however, models for financial portfolio optimization typically consider tradable assets whose past market performance provides some guidance for estimating the risk-return characteristics of assets. Another difference is that the decision variables in financial optimization models are usually continuous so that assets can be purchased or sold in any given quantities. In contrast, PDA models are built for selection problems which usually involve binary choices. These differences notwithstanding, advances in financial optimization are relevant to PDA. For example, in many cases financial optimization models have spearheaded the adoption of risk measures that are applicable also in PDA (see, e.g., Artzner et al, 1999).

1.2.2 Capital budgeting models

While financial optimization deals with portfolios of tradeable assets, capital budgeting is typically concerned with intra-organizational investment, most notably the allocation of resource to real assets (Lorie and Savage, 1955; Brealey and Myers, 2004). Capital budgeting models have early antecedents in the optimization models that were formulated for resource allocation and asset deployment during the Second World War (see, e.g., Mintzberg, 1994). Related models were then adopted in the corporate world. The main responsibility would often rest with a centralized corporate finance function that would establish fixed top-down budgets for divisions or departments which, in turn, would take detailed decisions on what activities to pursue with these budgets.

Technically, some archetypal capital models can be formulated as linear programming problems (Asher, 1962), even if the explicit modeling of problem characteristics such as nonlinearities may call for more general mathematical programming approaches. Capital budgeting and its variants received plenty of attention in finance and operations research in the 1960s and 1970s (see, e.g., Weingartner, 1966, 1967). For example, program budgeting sought to elaborate what resources would be used by the elements of a large public sector program and how program objectives would be affected by these elements, in order to improve the transparency of planning processes and the efficiency of resource allocations (Haveman and Margolis, 1970). Marginal analysis, in turn, focused on the comparative analysis of marginal costs and marginal benefits as a step towards finding the best uses of resources to activities, in recognition of the broader concerns that are not necessarily under the direct control of the decision maker (Fox, 1966; see also Loch and Kavadias, 2002).

At present, formalized approaches to capital budgeting are practically pervasive in corporations and public organizations. Yet it is our impression that it is still rare to find capital budgeting models that make systematic use of all the advanced features of decision modeling – such as probabilities, multiple criteria, or dynamic modeling with real options – that belong to the modern PDA toolkit.

1.2.3 Quantitative models for project selection

Project selection was recognized in operations research as an important decision problem in operations research by the late 1950s (Mottley and Newton, 1959). Methods for this problem help determine which combinations of proposed projects or activities an organization should fund in order to maximize the attainment of its objectives (see, e.g., Heidenberger and Stummer, 1999 for a good review). Between the mid 1960s and the mid 1970s, these methods received plenty of attention in the literature. Growing demand for these methods was generated by large centralized R&D departments of major corporations where R&D managers had to decide which project proposals to fund. Helping to meet this early demand were the efforts of consulting firms such as Arthur D. Little (see Roussel et al, 1991, for a review).

By the mid-1970s, the literature on project selection methods had grown to the point where various multicriteria and multi-objective approaches (Lee and Lerro, 1974; Schwartz and Vertinzky, 1977), probabilistic approaches, and even approaches that account for project interactions were being proposed (see Aaker and Tyebjee, 1978; Heidenberger and Stummer, 1999; Henriksen and Traynor, 1999). These approaches typically lead to mathematical optimization formulations where the desired results were captured by the objective function that was to be maximized subject to budgetary and other resource constraints. The scope of these approaches was gradually extended so that projects would be assessed not only with regard to financial return but also in view of objectives such as strategic fit and innovativeness (see, e.g., Souder, 1973).

Research on project selection methods then slowed markedly in the mid-1970s. One plausible cause is that organizations become less centralized with less formal planning cycles. It has also been suggested that the methods became excessively complex and time-consuming, even to the point where their practical utility was being undermined (cf. Shane and Ulrich, 2004). Experiences from this period should serve as a reminder that while a high degree of mathematical sophistication makes it possible to consider complex project portfolios elaborated at a great level of detail, the successful uptake of these methods is still crucially dependent on securing an appropriate fit with actual organizational decision making practices.

1.2.4 Decision analysis

Although linkages to finance, capital budgeting and project selection are relevant, the origins and philosophy of PDA stem from the field of decision analysis. Prior to 1960, Ramsey (1978), de Finetti (1937, 1964), and Savage (1954) had built a mathematical theory of decision under uncertainty based on subjective probability. Edwards (1954, 1961) then outlined a research agenda for exploring the descriptive accuracy of Subjective Expected Utility theory, but there was yet no decision analysis, in the sense of a managerial technology based on these concepts. In this setting, Pratt, Raiffa, and Schlaifer (1965) made key steps towards the development of an advanced statistical decision theory with a stronger orientation towards prospective applications than the philosophical discussions and theoretic system-building of early Bayesian statisticians. Here, von Neumann-Morgenstern's utility functions (von Neumann and Morgenstern, 1944) were increasingly seen as a viable tool for helping decision makers clarify their attitudes to risk.

As an applied field, decision analysis was established in the 1960s (Raiffa and Schlaifer, 1961; Howard, 1966; Raiffa, 1968). It was quickly recognized as essential particularly in capital intensive industries in the US. For example, oil wildcatters' drilling decisions (Grayson, 1960) served as a testbed for decision tree analysis, resulting in canonical pedagogical examples of high-impact applications. By the end of the 1960s, decision analysis gained prominence in management education at leading US research universities (e.g., Raiffa, 1968). For instance, Howard began to develop a Stanford-based group which was keen on expanding the uptake of DA in addressing important decision problems (see, e.g., Howard and Matheson, 1984).

Multi-attribute utility theory (MAUT) was formulated by Keeney and Raiffa (1976) who built on the work on utility theory (e.g., Fishburn, 1964, 1970) and measurement theory (Krantz et al, 1971). MAUT and its riskless sister theory, Multi-attribute value theory (MAVT), were subsequently applied to a growing range of problems also in public policy problems where the scoring of alternatives with regard to multiple attributes contributed to more transparent and systematic decision activities. The application of DA also expanded due to the efforts that the Stanford group made by developing the DA cycle (Howard, 1968; see also Keeney 1982) in order to create an organizational decision support *process* to facilitate the analysis of decisions. Contemporaneous advances included tornado diagrams, which show the sensitivity of DA results to uncertainties, and influence diagrams, which are simple yet powerful graphical tools for representing decision models and for structuring the elicitation of probability assessments (Howard, 1988).

A more interactive approach to decision analysis, decision conferencing, evolved from consulting activities where relatively simple quantitative models were employed to facilitate interactive decision processes. For example, the firm Decisions and Designs applied decision analytic methods with a particular attention to the process of modelling aspects (see Buede, 1979). In the 1970s, this group started to work with the US Marine Corps using a PDA approach called Balanced Beam which was to last for several decades. Beginning in the late 1970s, Cam Peterson, his colleagues and later also Larry Philips began to expand their work on decision conferencing with multiple parties (Phillips and Bana e Costa, 2007).

An alternative family of methods have been developed largely by francophone researchers under the heading title "decision aid" (Roy, 1985, 1991). The general philosophy of these methods differs somewhat from the above approaches in that considerable emphasis is placed on the constructive nature of the interaction between analyst and the decision maker, as well as the social context of the decision. Although similar ideas also surface in the decision analysis tradition (Phillips, 1984), they are arguably even more prominent in the decision aid tradition, most notably in the so-called "outranking" approaches that employ different procedures in the aggregation of criterion scores. Many of the assumptions of classical decision theory – such as complete comparability and ability to fully discriminate between alternatives – are not taken for granted by proponents of outranking approaches (see, e.g., Bouyssou and Vansnick, 1986; Brans and Vincke, 1985). Overall, the theoretic and axiomatic basis of outranking approaches has a more discrete and ordinal flavor than those of value/utility-based approaches.

Another decision analytic tradition which departs from the axiomatic foundation of MAUT/MAVT theory has grown around the Analytic Hierarchy Process (AHP; see, e.g., Saaty, 2005) which, however, has been criticized for methodological shortcomings such as the possibility of rank reversals where the introduction or removal of an alternative may change the relative rankings of other alternatives (see, e.g., Salo and Hämäläinen, 1997 and references therein). Despite such shortcomings, the AHP has won popularity among practitioners, and it has been applied to various PDA problems such as the selection of R&D projects (Ruusunen and Hämäläinen, 1989).

1.2.5 From Decision Analysis to Portfolio Decision Analysis

As DA methods matured, they were increasingly applied to portfolio problems. As early as the 1960s, Friend and Jessop (1969) were experimenting with the use of formal methods in coordinating planning decisions within local government, and by the mid-to-late 1970s there was much practical work which could readily fall under our definition of PDA. Several methods for project selection, for instance, incorporated systematic quantification approaches such as project trees which resembled the more formal DA methods deployed by decision analysts.

In particular, the DA group at the Stanford Research Institute (and which later morphed into several consulting firms, most notably Strategic Decisions Group, or SDG) expanded its portfolio activities that started with multiple project applications. Specifically, several companies (for several examples, see Howard and Matheson, 1984) requested consultants to examine their entire R&D plan once they had conducted analyses of isolated R&D projects and strategic decisions. In these analyses, the cost, the probability of success (in some cases as the combined probability of clearing multiple technical hurdles), and the market value given success (based on forecasts of market share, price, etc.) were first assessed for each project using DA methods. Combining these analyses at the portfolio level offered several useful outputs. For instance, after the expected net present values (ENPV) had been were calculated for each project, the projects could be sorted in order of “bang-for-the-buck” (calculated as the expected net present value of a project divided by its cost) in order to establish the efficient frontier. For the given budget, the highest-value portfolio could then be identified as the intersection of the budget line with this frontier. This portfolio typically contained a substantially better set of projects than what the company would have selected without the analysis. These kinds of successful DA engagements were conducted at major companies such as Eastman-Kodak (Rzasa et al, 1990; Clemen and Kwit, 2001) and Du Pont (Krumm and Rolle, 1992).

Graphical structuring tools, too, have been essential in project and portfolio management. For example, while financial portfolios are often shown with plots of risk versus return for potential investments, the BCG matrix (Henderson, 1970) prompts businesses to view their sets of products holistically by classifying them into quadrants of dogs, question marks, stars and cash cows, based on the current status and potential for growth and profitability (and companies were advised to prune their businesses to achieve a healthy mix). One related result from early PDA efforts is an analogous risk-return matrix (Owen, 1984) where projects are placed into quadrants that reflect value and probability of success. When using such a matrix, decision makers, most notably portfolio managers, are encouraged to build a balanced portfolio with some “bread and butter” projects (high probability, not very high value), some “oysters” (low probability but high potential value) so that there would be a stream of “pearls” (successful projects that were revealed as oysters were developed) and to eliminate white elephants (projects with low prospects for success and low potential value).

Researchers and consultants have also been developing their dedicated decision analysis-based tools for portfolio choice problems. The DESIGN software was developed by Decisions and Designs (which later evolved into the Equity software), with a view to supporting interactive modeling in a decision conferencing setting (von Winterfeldt and Edwards, 1986, pp. 397–399). By using project-level costs and benefits as inputs, the software produced what is now regarded as a classic display showing the efficient portfolios in a cost-benefit space. According to Larry Phillips (personal communication), the original motivation for DESIGN was not portfolio choice but negotiation. In this frame, “costs” and “benefits” were viewed not as different objectives of a single decision maker, but rather as the differing, but not completely opposed, objectives of different parties.

In the late 1970s, Keefer (1978) and Keefer and Kirkwood (1978b) formulated resource allocation decisions as non-linear optimization problems where the objective function could be assessed as multi-attribute utility function. Such combinations of formal optimization and decision analytic preference elicitation called for methodological advances, including the use of mixed integer programming in solving problems with multiple decision trees containing uncertainties. Also, approaches for three point approximations were developed in response to the need to build optimization models where the probability distributions could be estimated at each point (Keefer and Bodily, 1983). In effect, these developments foreshadow current PDA efforts to combine practical methods for assessing uncertainties and for eliciting preferences when deriving inputs for optimization models.

In the 1970's, PDA approaches were applied to guide the development of major governmental project and R&D portfolios by practitioners in organizations such as Woodward Clyde, Inc (Golabi et al, 1981) and U.S. National Laboratories, (Peerenboom et al, 1989), in a line of work that continues through today (see, for instance, Chapter 14 by Parnell in this book). Decision conferencing, too, has evolved in terms of its recognition of multiple criteria and use of interactive software tools. It has increasingly won recognition as a valuable tool for portfolio problems both in the public (health, military, etc.) and private sectors (pharmaceutical). In addition, hybrid approaches have been explored by researchers such as Stewart (1991) who combines participatory DA processes with multiobjective programming.

In the 1980s and 1990s, various approaches to product portfolio management were developed, motivated by project management problems, but largely uninformed by the formal discipline of decision analysis. These approaches employ various means of scoring projects heuristically (e.g., innovativeness, risk, profitability) as a step in providing guidance to the management of project lifecycles. Clients of DA firms, internal experts applying DA, and DA consultants were organically exposed to these approaches, while specialists in these approaches were in turn exposed to DA. This has led to a mingling of ideas which is not easy to track in detail. This notwithstanding, Cooper et al (2001) provides an excellent comparison of many of these approaches which lie outside the mainstream of decision analysis.

In the 1990s, and largely, but not exclusively in the US, the portfolio approach gained prominence at several major corporations. Together with this development, decision analysis consulting grew and portfolio consultancy became a major part of its business. Portfolio projects were especially successful in the pharmaceutical industry (e.g., Sharpe and Keelin, 1998) and the oil and gas industry (e.g., Skaf 1999; Walls et al, 1995) – perhaps because these industries make large capital outlays, are exposed to uncertain returns, have clearly staged decisions and face large numbers of comparable investment opportunities with a clear separation between the financial and the operational sides of the business. Many, if not most large companies in these industries have formalized some sort of DA portfolio-planning processes. Equally important, large numbers of people from these industries have received formal DA training. Thanks to this breadth of practice, scholars engaged in consulting activities began to codify principles for high-quality R&D decision making based the use of DA methods (Matheson and Matheson, 1998).

Portfolio approaches have evolved with advances in software. For example, when spreadsheets and presentation tools became more widespread and user-friendly, it became possible to harness them in building companywide portfolio processes that were integrated with company project/finance databases. Indeed, companies such as General Motors (Kusnic and Owen, 1992; Bordley et al, 1999; Barabba et al, 2002) established DA approaches to portfolio management as part of formal planning processes in their R&D, product groups, and even business units (Bodily and Allen, 1999). When these DA groups gained expertise, they tended to develop and manage their processes with less outside help. Subsequently these practitioners have formed networks such as the Decision Analysis Affinity Group (DAAG). Various smaller consulting firms have also sprouted, some with variations of the SDG type of approach, even with a focus on project portfolio management. The resulting proliferation of decentralized activity has spawned innovations at the firm level and also conferences and books about lessons learned (e.g., Pennypacker and Retna, 2009). Thus, practitioner-level knowledge sharing proceeds apace, with some but not necessarily close connections to the scholarly research community.

In the 1990s and 2000s, there has been an expansion of multicriteria decision making approaches to portfolio problems both in public and private spheres. For example, Phillips and Bana e Costa have championed the application of PDA methods to significant resource allocation problems in the UK and Portuguese public sectors (see Phillips and Bana e Costa, 2007, for a description of their approach and experiences). There has also been a trend towards processes that seek to inform decision makers and help them to reduce the set of candidate solutions to a manageable size, partly based on the notion that a "unique" optimum solution is not necessarily best aligned with complex multi-stakeholder processes (Liesiö et al, 2007; Vilkkumaa et al, forthcoming). Advances in computer and software technology have been important drivers, too, because increasing computing power and visualization technology have permitted the near real-time presentation of what the model assumptions signify in terms of recommended portfolio decisions. Indeed, recent portfolio management systems (see, e.g., Portfolio Navigator of SmartOrg, Inc) and integrated enterprise resource management systems collate project data and offer both standard and query-based portfolio graphs and reports.

After the turn of the millennium, we have seen a proliferation of PDA approaches that build on many of the above streams. Recent advances by Gustafsson and Salo (2005), Stummer and Heidenberger (2003), Stummer et al (2009), Kavadias and Loch (2004), and Liesiö et al (2007), for instance, exemplify new approaches that combine preference assessment techniques, multi-criteria methods, decision trees, optimization algorithms and interactive software tools for engaging stakeholders in organizational decision making processes. The nature of applied work seems to be evolving as well. Some companies in the pharmaceutical industry, for instance, that have employed simpler productivity indices to rank projects are now modeling project-level interactions in more detail and using advanced structured optimization methods. PDA approaches are also finding uses in a growing range of application domains, such as the selection of nature reserves, for instance (see, e.g., Bryan 2010).

In conclusion, PDA has well-established roots that go back to the very origins of operations research. It is based on sound approaches for problem structuring, preference elicitation, assessment of alternatives, characterization of uncertainties and engagement of stakeholders. Recent advances in "hard" and "soft" methodologies, together with improved computer technology and software tools, have fostered the adoption of PDA approaches so that many organizations are now explicitly thinking in terms of portfolios. PDA methods become gained ground especially in capital intensive industries such as pharmaceuticals and energy; but they have penetrated even many other industries and public organizations where decision making activities can benefit from participatory processes (cf. Hämäläinen 2003, 2004) through which the stakeholders' expertise is systematically brought to bear on the decisions.

1.3 Contributions in this book

The fifteen chapters in this book give an overview of the range of perspectives which can be brought to bear on PDA. These chapters are structured in three Parts: Preliminaries (of which this "invitation" is the first chapter); Theory; and Applications. The chapters in Preliminaries expand on this chapter and give a stronger sense of what PDA seeks to achieve and, specifically, what PDA is in operational terms. The chapters in Theory present new theoretical advances in PDA, while the part on Applications illustrates the diversity and commonality of PDA practice across problem domains. We emphasize that there are important synergies between the three parts: the part on Theory, for example, presents advances that are relevant for future applied work while the chapters in Applications demonstrate the diversity of decision contexts where PDA can be deployed.

1.3.1 Preliminaries

In Chapter 2, Keisler tackles the critical question: What is a "good" decision – and a good decision analysis – in a resource allocation context? One perspective is provided by the celebrated decision quality chain of Matheson and Matheson (1998): Keisler argues that the dimensions of decision quality proposed by Matheson and Matheson – sound decision framing, diverse and well-specified alternatives, meaningful and accurate information, clear and operationally useful statements of value, logical synthesis, and an orientation towards implementation – provide a useful frame for elaborating the distinctive features of *portfolio* decisions. Keisler also reminds us that all modeling is a simplification of reality, and distinguishes four different levels of modeling detail in portfolio decisions. Costs and values may be observed more or accurately; projects may be more or less well-specified; multiple objectives may be taken into account completely, incompletely or not at all; and synergies between projects may be considered to a varying degree of detail. Keisler also summarizes a body of evidence, based on simulation models, which sheds light on the likely loss in value from assuming away a particular aspect of modeling complexity. Thus, his work offers new perspectives on what constitutes a suitably detailed or even "requisite" model (see also Phillips, 1984).

Chapter 3 shifts gears somewhat. Phillips provides a detailed account of a successful high-profile application of PDA to the design of a battleship for the UK's Royal Navy. Their story begins with the breakdown of the Horizon project, a three-nation collaboration to produce a new warship, and the decision by the UK to strike out on its own. Despite this inauspicious start, the author helped the Ministry of Defence to make critical design decisions to arrive at an agreed design concept in only 15 months. A critical element of the multicriteria approach was the use of "decision conferences", facilitated working modeling meetings with the representation and active engagement from key players and experts. Thanks to its level of detail, this chapter invites a careful study by all those who are interested in instructive details of "how to do it". Phillips also argues for the importance of being attentive of the social process, and of the role that PDA can play in helping members of an organization to construct preferences as a step towards agreeing on how to go forward.

1.3.2 Theory

The part on theory begins with a chapter "Valuation of Risky Projects and Other Illiquid Investments Using Portfolio Selection Models" where Gustafsson, de Reyck, Degraeve and Salo present an approach to the valuation of projects in a setting where the decision maker is able to invest in lumpy projects (which cannot necessarily be traded in the market) and financial assets (which can be traded in the market). Starting from the assumption that future uncertainties can be captured through scenario trees and that alternative actions for the investment projects can be explicated for these scenarios, their approach essentially generalizes standard financial methods for project valuation, most notably option pricing and "contingent claims analysis" (the authors call their method "contingent portfolio analysis"), resulting in an approach that is consistent with standard decision analysis approach to investment under uncertainty. Gustafsson et al also show that an important property of option pricing methodology, the equality of break-even buying and selling prices, generalizes to their environment. Overall, the approach is a significant and practically relevant extension of existing theory which benefits from the rigor of a DA framework.

In Chapter 5, Argyris, Figueira and Morton discuss multicriteria approaches. Building on the themes of Keisler, they discuss what constitutes a "good" DA process. They underscore the dangers of simply assuming, as is common in practice, that value functions over criteria are linear. While endorsing the view that analysis should be an interactive process, they point out that the term "interactive" is somewhat loose and, in fact, compatible with a range of different practices of varying degrees of interactivity. They then present two formal optimization models which can produce multicriteria non-dominated solutions based on limited preference information. They also discuss alternative uses of these models in an interactive setting.

A natural question about any problem helping technique – rarely asked and even less rarely answered – is "What does practice actually look like?" In Chapter 6, Stonebraker and Keisler provide intriguing insights into this question in the context of pharmaceutical drug development. In effect, drug development is a highly cost-intensive activity with clear-cut binary outcomes – either it leads to a marketable product or not – and thus one would expect that DA methods are particularly well-received in this environment. This is indeed the case, and the (unnamed) company in question has built up an impressive database of its decision analyses. Yet Stonebraker and Keisler's analysis shows that there is considerable variability in the structure of the underlying DA models even in the same organization. This raises the question of whether such differences are warranted while it also points back to themes in Chapter 2: How can analyses of such differences be exploited, in order to improve practice?

Applying PDA in practice is essentially a *human* endeavor. This realization – which we endorse emphatically – implies that psychological issues and organizational behavior are central. In Chapter 7, Fasolo, Morton and von Winterfeldt bring this perspective to bear on portfolio decision making. Taking their cue from Tversky's and Kahneman's (1974) celebrated work on heuristics and biases, they observe that much of decision modeling builds on normative assumptions that are made when seeking guide decision behavior. In particular, they discuss how the (often implicit) assumptions underlying this normative stance can be violated behaviorally, drawing on, first of all, individual laboratory-based research on individual decision making, and field experience of supporting organizational resource allocation decision. One of their observations is that the portfolio frame itself can serve as a debiasing device, because it forces decision makers to think of decisions more broadly.

In Chapter 8, Arévalo and Rios Insua turn their attention to the technology underpinning portfolio management in the context of innovation management. They survey web-based tools for innovation management, and outline an IT system, called SKITES, for managing a portfolio of innovations either within an organization or in a collaborative network. SKITES users may have a sponsoring or facilitative role, or they may propose or assess innovative projects. The proposed system is based around a workflow where proposal are sought, screened, evaluated and managed to delivery of promised benefits. This chapter serves to remind us of the potential of that technology can have in ensuring that the decision making process unfolds in an orderly manner, and the players involved have access to the tools they need to help them structure choice and make thoughtful decisions.

Chapter 9, the last chapter in the theory section (like Fasolo, Morton and von Winterfeldt's chapter) draws explicitly on psychological theory, and like Arévalo and Rios Insua, is concerned with the information technology which underpins PDA. Specifically, the authors Kiesling, Gettinger, Stummer and Vetschera, are interested in what might be thought of as the human-computer-interface aspects of PDA software. They report an experiment to compare how users respond to two different information displays in a multicriteria setting – a classical display, namely the parallel coordinates plot, and a more innovative "heatmap" display. Their chapter presents a compelling case that the choice of display makes a striking difference both on how users experience the system, and also on their actual behavior in exploring the solution space. They conclude, echoing a theme that arises often in this book, that the most appropriate choice of information display may depend on task and user characteristics – that there may be no all-purpose "best" solution.

1.3.3 Applications

In Chapter 10, Le Cardinal, Mousseau and Zheng present an application of an outranking method to the selection of students to an educational program. This set-up is slightly different from the typical set-up in PDA: one wants to take coordinated decisions, but the decisions are not simply yes/ no, because the students are assigned to four categories – definitely yes, possibly yes, possibly no and definitely no; moreover, the constraints are not monetary but pertain to demands such as balance of gender. This is effectively a sorting problem where the set of objects is to be partitioned into ordered classes, each with different action implications. They employ the ELECTRE TRI method which is a member of the ELECTRE family. Because the direct elicitation of preference parameters can be difficult, they allow the decision maker to provide judgments that characterize attractive solutions and place restrictions on the distribution of the items across the categories. Because these judgments are not consistent within the ELECTRE TRI modeling framework, they propose an inconsistency resolution module which can be invoked to identify constraints that the DM could relax. Importantly, this chapter reminds us that in many cases one may wish to take a coordinated system of decisions, but these decisions may be more complex (and thus, more interesting) than simply “do” or “don’t do”.

Toppila, Liesiö and Salo present in Chapter 11 a case study which describes the development of a PDA model for helping a high-technology telecommunication make investments in its standardization activities. The model explicitly recognizes the uncertainties associated with these standardization investments and admits incomplete information about model parameters. Building on these inputs, the decision model helps determine which standardization activities should be either strengthened or weakened, based on a “core index” metric which is based on the computation of all non-dominated resource allocations. Another feature of the decision model is that it specifically capture interaction terms, thus distinguishing their modeling from the model of, for example Phillips (Chapter 3) and the advice of Phillips and Bana e Costa (2007) who recommend handling interactions outside of the formal model.

In their Chapter, Montibeller and Franco discuss the implementation of PDA in local government in the UK. They emphasize that local authorities have historically tended to budget in an incremental fashion, and describe an environment in which transparency and accessibility is more important then technical sophistication. Their approach – of which they provide a number of case studies – blends ideas about structuring drawn from the British “Problem Structuring Methods” tradition, combined with the decision conferencing approach already foreshadowed in Chapter 3 Phillips. They close by presenting some ideas for the development of a standardized toolkit – in the broadest sense, comprising both software and process templates - for practitioners of PDA in this domain.

Chapter 13 by Kloeber deals with the practice of PDA in the pharmaceutical sector. He describes an industry with high costs, long development cycles, and opportunities to earn huge sums of money – or fail utterly. In such an environment, a company’s fortunes are critically dependent on the quality of decisions made about R&D investment and the management of the R&D portfolio. Based on extensive consulting experience, Kloeber describes tools for both project-level and portfolio-level analysis, and discusses the role of both probabilistic and multicriteria models.

Burk and Parnell survey PDA activity in the military area. They point out that in this decision context there is no one single dimension of value, and consequently most of the work they survey uses multicriteria methods. Specifically, they present a comprehensive, structured literature review and describe six case studies in detail using a comparative framework which in terms of its approach may be useful for other authors looking to perform a structured review of practice, Drawing on this review, they discuss different modeling choices and levels of information (gold, silver, platinum and combined) in model development. It is notable that Burk and Parnell are not bound to any particular modeling approach but, rather, report experiences from different approaches in different settings. Their chapter thus serves as a reminder of the importance of broadmindedness in modeling and the pragmatic use of whatever tools seem most appropriate for the problem at hand.

Airoldi and Morton begin with an overview of PDA practice in public sector healthcare systems, especially in settings where the implementing body is a health authority that is responsible for a geographically defined population. They draw attention to two indigenous traditions in healthcare, starting with the Generalized Cost Effectiveness (GCEA) tradition and continuing with an approach derived from Program Budgeting and Marginal Analysis which incorporates certain multicriteria ideas. By way of contrast, they then present a case study of their own, based on the prioritization of activities for the “Staying Healthy” programme of a Primary Care Trust using a decision conferencing approach that has some similarities with the work of Phillips (Chapter 3) and Montibeller and Franco (Chapter 12), but draws on ideas in health economics in scaling up benefits to the population level. Even the population aspect features significantly in Airoldi and Morton’s ideas for future work. Specifically, they describe concerns about the nature, timing and distribution of benefits and costs which are not explicitly incorporated in their process. They also speculate whether models which handle these important and decision relevant aspects could be developed without losing the accessibility which comes from the use of simpler models. The chapter therefore serves as a reminder that to be genuinely valuable and useful, PDA methods have to be adapted and contextualized to meet the specific challenges in some given domain.

1.4 Perspectives for the Future

Taken together, the above chapters highlight the diversity of contexts where PDA can be deployed. Combined with the messages in our storyline on the evolution of PDA, they also suggest prospective topics for future work. We structure our open-ended discussion of these topics under three headings which, somewhat loosely, link back to our initial categorization of theory, methods and practice. We begin with “Embedding to PDA in organizational decision making” which is central to the advancement of practice. We then proceed by addressing topics in relation to “Enhancing PDA theory, methods and tools” and “Expanding the knowledge base”.

1.4.1 Embedding PDA in Organizational Decision Making

As pointed out by the then President of INFORMS, Don N. Kleinmuntz, in a panel discussion on PDA at the EURO XXIV meeting in 2009, the real value of PDA is realized when an organization institutionalizes the use of PDA in its planning processes. There are highly encouraging examples of such institutionalizations: for instance, companies like Chevron have built strong competitive advantages by making systematic use of PDA methods (Bickel, 2010). Yet such institutionalizations are not very common and, at times, when institutionalization has taken place, the early focus on portfolio decisions may have been diluted by data management or other implementation issues.

Seen from this perspective, we need to know more about what factors contribute to successful institutionalization. Here, lessons from the broad literature on the diffusion of innovations (Rogers, 2005) can offer insights. Further guidance can be obtained from reflective studies of attempted institutionalizations, along the lines of Morton et al (2011) who have examined resource allocation decisions in two areas of the UK public sector. Furthermore, since there exists a rich knowledge base of ‘one-shot’ PDA interventions, it is of interest to study how uses of PDA can be integrated in organizational decision making processes on a more recurrent and continuous basis. Thus, topics for future activities under this broad heading include the following:

- *Transcending levels of organizational decision making:* Resource allocation decisions often involve decision makers at different levels of the organization with differentiated roles and responsibilities, which leads effectively to the question of how PDA activities at different levels can be best interlinked. For instance, PDA activities may focus on strategic and long-term perspectives that provide ‘top-down’ guidance for operational and medium-term activities (see, e.g., Brummer et al, 2008). But one can also build ‘bottom-up’ processes where individual departments first carry out their own PDA processes to generate inputs that are taken forward to higher levels of decision within corporate management teams or executive boards (see, e.g., Phillips and Bana e Costa, 2007). Such processes can be complementary, which means that the design of a process that is most appropriate for a given organizational decision making calls for careful consideration.
- *Interlinking organizations with PDA methods:* In many sectors, the boundaries between organizations and their environment are becoming more porous. For example, the competitiveness of industrial firms is increasingly dependent on how effectively they collaborate in broader innovation networks. In parallel with this development, demands for transparency and accountability in policy making have fostered the development of methods which explicitly capture the interests of different stakeholder groups. Hence, PDA methods with group decision support capabilities for inter-organizational planning seem highly promising (see, e.g., Vilkkumaa et al, forthcoming). We therefore believe that more work is needed to explore what PDA approaches suit best problem domains that involve several organizations.
- *Re-using PDA models and processes:* Deploying a similar PDA process from one year to the next may offer substantial benefits: for instance, the costs of training are likely to be lower while software tools can also be used effectively. But there may be drawbacks as well. For instance, strict adherence to a ‘standardized’ PDA process may stifle creativity or, in some settings, it can be harmful if the characteristics of the decision context change so that the initial PDA formulation is no longer valid, say, due to the emergence of additional decision criteria. As a result, there is a need to understand when PDA models can really be re-used on a recurrent basis. This stands in contrast to most reported case studies which typically assume that the PDA model is built from scratch.

- *Facilitating the diffusion of PDA models across problem domains:* Even though the specifics of PDA models vary from one planning context to another, there are nevertheless archetypal models – such as the multi-attribute capital budgeting model – which can be deployed across numerous problem contexts subject to minor variations. This suggests that when PDA models are being developed, it may be useful to extract the salient modeling features of specific applications as a step towards promoting the diffusion of PDA approaches by way of 'transplanting' models from one context to another. Yet, in such 'model transplantation', concerns of model validity merit acute attention, because a model that is valid in one problem context may not be so in another.

1.4.2 Extending PDA theory, methods and tools

Embedding PDA in organizational decision making calls for adequate theory, methods and tools. Over the years, the literature on PDA methods has grown so that there are now several tested and well-founded approaches for addressing most of the concerns that are encountered in PDA problems (including uncertainties, constraints, preferences, interactions). The relevant tool set, too, has become broader and spans tools that range from the relatively simple (e.g., scoring templates) to quite complicated (e.g., dedicated PDA tools with integrated optimization algorithms).

As an overall remit for extending PDA methods and tools, we believe that the advancement of PDA benefits from an appropriate balance of theory, methods and practice. This means, for instance, that the development of exceedingly complex mathematical PDA models whose complexity is not motivated by challenges of real problems may be counter-productive. In effect, the modest uptake of some of the most sophisticated R&D planning models can be seen as an indication of the risk of developing models that are impractical for one reason or another; hence, requisite models (Phillips, 1984) may prove more useful than the results of more onerous and comprehensive modeling efforts. There are also important tradeoffs even in the framing of PDA processes. That is, while truly comprehensive formulations make it possible to provide more 'systemic' recommendations that span more alternatives and even organizational units, such formulations can be more difficult to build, for instance due to difficulties of establishing criteria that can be meaningfully applied to a broader set of alternatives.

All in all, we believe there are many promising avenues for advancing the frontiers of theory, methods, and tools:

- *Theoretical development:* Although PDA inherits much of its theoretic axiomatic machinery from the wider field of decision analysis, interpreting that theory in terms of the particular models used in PDA still requires additional work. A recent example of such an apparent gap in theory is the baseline problem documented in Clemen and Smith (2009) and Morton (2010), where certain plausible procedures for setting the zero for value measurement can lead to rank reversals when the option set is changed. Moreover, while axiomatizations of the portfolio choice problem exist (Fishburn, 1992), these axioms seem to require strong additive separability assumptions between projects. Thus, a further direction for theoretic research would seem to investigate what sorts of relaxations of these separability assumptions might be possible (see Liesiö, 2011).
- *Advances in IT and software tools:* Progress in ICT, mathematical programming and interactive decision support tools have been essential enablers of the adoption of PDA approaches: for instance, the computing power of modern PCs makes it possible to solve large portfolio problems while rich visualization tools help communicate salient data properties and decision recommendations. Advances in ICT offer also untapped potential for approaching new kinds of problems that have not yet been addressed with PDA methods. For example, PDA methods can be deployed in collaborative innovation processes for eliciting and synthesizing information from stakeholder groups. A related use of PDA methods is participatory budget formation where stakeholders have shared interests in resource allocation decision and the priority-setting process must fulfill demanding quality standards, for instance due to accountability requirements (Rios Insua et al, 2008, Danielson et al, 2008).
- *Interfacing PDA tools with other IT systems:* Many PDA software tools are stand-alone programs (see Lourenço et al, 2008 for a review of currently available tools). Yet portfolio decisions often rely on data that may reside in other IT systems. This would suggest that a greater degree of integration with other IT systems can be helpful in designing decision processes that are linked to sources of information and, moreover, generate information that can be harnessed in other contexts. Such aspirations need to be tempered by the recognition that the development of integrated software solutions and IT systems can be costly and time-consuming. Moreover, it is possible that radical changes in organizational structures and processes lead to different requirements on decision support so that existing IT systems lose some of their relevance. These

caveats notwithstanding, the identification of viable opportunities for tool integration can expand the use of PDA tools.

- *Harnessing incomplete information:* Typically, the estimation of parameters for a PDA model requires a large number of judgments which can be time-consuming and cognitively burdensome to elicit. There exist some tools which reduce the elicitation effort by providing recommendations based on incomplete information (Liesiö et al, 2007, 2008; Argyris et al, 2011), or which help decision makers understand how sensitive the recommendations are with respect to model parameters (Lourenço and Bana e Costa, 2009). Nevertheless, there are still significant opportunities for tool development, for instance by exploring how sensitive the results are to assumptions concerning the underlying representation of value or by transferring ideas form the reasonably well-developed multicriteria context to the probabilistic context (see, e.g., Liesiö and Salo, 2008).
- *Building models for the design of PDA processes:* Most PDA models help make choices from the set of available alternatives. But analytical models can also assist in the design of PDA-assisted decision support processes. For example, by capturing the salient characteristics of the PDA problem (e.g., number of alternatives, uncertainty of model parameters), it is possible to evaluate alternative PDA process designs *ex ante* and to guide decisions about screening thresholds or strategies for acquiring information about the alternatives. Indeed, as demonstrated by Keisler (2004), the combination of simulation/optimization approaches for evaluating PDA processes holds much promise in terms of improving the appropriate use of PDA methods.

1.4.3 Expanding the PDA knowledge base

This third heading covers topics on which work is needed to improve knowledge of how successful PDA-assisted planning processes can be best enabled. These topics have a strong element of empirical research aimed at the accumulation of knowledge about the issues that are encountered when using PDA methods and tools to improve resource allocation processes:

- *Pursuing behavioral research:* Decision analysis – more than any other subfield of operations research – has maintained a close relationship with psychology and with behavioral decision theory, in particular. From the perspective of psychology, PDA problems have several specific features. First, decision makers may have to consider very large numbers of alternatives, which may pose challenges for visualization, for instance. Second, portfolio decisions are often taken in planning contexts which involve stakeholders from around the organization. These decisions are therefore social undertakings, which means that social psychological issues (such as what constitutes a persuasive argument) are important. Third, PDA problems may give rise to behavioral biases beyond those considered in the earlier literature on single choice problems. There is consequently an apparent need for studies on when such biases are likely to occur, what impacts these biases have on decision quality, and how they can be best avoided. More generally, there is a need for knowledge about how decisions are shaped by the choice of PDA methodologies and what methods can be expected to work 'best' in specific decision contexts.
- *Enabling successful facilitation:* Facilitation is often a significant part of PDA interventions, especially when the PDA activity takes place in a workshop setting or "decision conferences" (Phillips and Phillips, 1993). The existing literature on facilitation – much of which is associated with the discipline of Organizational Development – helps understand these interventions by addressing processual concerns such as the management of power, politics and personalities. In the PDA context there is an additional challenge in that modeling central becomes central in guiding content issues (Eden, 1990). There is therefore a need to better understand the role of facilitation skills in PDA (e.g. Ackermann, 1996). Such an understanding is vital because becoming an effective facilitator is not easy, and facilitation skills are not taught in most operations research/management science programs.
- *Reflective analyses of real PDA-assisted processes:* To better understand preconditions for the successful deployment of PDA methods, there is a need to build evidence from reflective analyses of real case studies. Here, relevant perspectives (see, e.g., Hämäläinen, 2004) extend well beyond the choice of PDA methods to the broader characterization of the decision context, including questions about how the PDA process is framed, what roles the participants enact and what the 'status' of the recommendations is as an input to subsequent decisions. Even though the enormous variety of decision problems and even the plurality of decision making cultures may thwart attempts at generalization, these kinds of analyses – which are likely to benefit from the use of systematic frameworks that resemble those proposed for MCDA methods (see, e.g., Montibeller, 2007) – may generate valuable insights into what methods work 'best' as a function of problem characteristics.

- *Organizational learning through evaluation:* In organizations, PDA interventions are substantial undertakings which, as a rule, should consequently be subjected to appropriate evaluations. These evaluations can serve two purposes. First, they help the organization understand what opportunities for improvement there are and how a re-designed PDA process could constitute an improvement over past practice. Second, if there is a well-established evaluation culture, consistent evaluations serve to build a database of "what works and where and when". One attendant challenge for research is to develop practical evaluation frameworks for PDA, for instance along the lines discussed by Schilling et al (2007).
- *Strengthening skill sets:* In PDA, skills for appropriate framing and scoping are pivotal because they lay the foundation for the analysis and co-determine how PDA effectively will inform organizational decision making (see, e.g., Spetzler, 2007). Furthermore, skills that pertain to modeling – such as the choice of functional representation or the specification of model parameters – are crucial, too, because even seemingly innocuous modeling assumptions (such as the choice of baselines; Clemen and Smith, 2009) may have repercussions on recommendations. As a result, those in charge of PDA processes need to master a broad range of skills, including social skills that help organizations articulate their objectives as well as technical skills that are needed to make well-founded choices among alternative approaches. This topic has broad educational ramifications.

In summary, PDA has reached its current position through an evolutionary path, enabled through the fruitful interplay of theory, methods and practice. At present, organizations are arguably faced with growing challenges in their decision making. In many business environments, for instance, firms much reach decisions more quickly in order to reap profits under accelerated product life cycles while the complexity of issues at stake may make it imperative to more experts and stakeholders. Similarly, in the public sphere legitimate demands for accountability and the efficiency of resource allocations impose ever more stringent quality requirements on decision processes. In this setting, PDA is well poised to address these kinds of challenges, thanks to the concerted efforts of researchers and practitioners who pursue opportunities for theoretical and methodogical work and, by doing so, help organizations improve their decision making.

References

Aaker DA, Tyebjee TT (1978) A model for the selection of interdependent R&D projects. IEEE Transactions on Engineering Management EM-25:30–36

Ackermann F (1996) Participants' perceptions of the role of facilitators using a GDSS. Group Decision and Negotiation 5:93-112

Argyris N, Figueira JR, Morton A (2011) A new approach for solving multi-objective binary optimisation problems, with an application to the knapsack problem. Journal of Global Optimization 49:213–235

Artzner P, Delbaen F, Eber J-M, Heath D (1999). Coherent measures of risk. Mathematical Finance 9(3):203–228

Asher DT (1962) A linear programming model for the allocation of R and D efforts. IRE Transactions on Engineering Management EM-9:154–157

Barabba V, Huber C, Cooke F, Pudar N, Smith J, Paich M (2002) A multimethod approach for creating new business models: the General Motors OnStar project. Interfaces 32(1):20–34

Bickel E (2010) Decision Analysis Practice Award. Decision Analysis Today 29(3):8-9

Bodily SE, Allen MS (1999) A dialogue process for choosing value-creating strategies. Interfaces 29(6):16–28

Bouyssou D, Vansnick J-C (1986) Noncompensatory and generalized noncompensatory preference structures. Theory and Decision 21:251–266

Bordley RF, Beltramo M, Blumenfeld D (1999) Consolidating distribution centers can reduce lost sales. International Journal of Production Economics 58(1):57–61

Brans JP, Vincke P (1985) A preference ranking organisation method: (The PROMETHEE method for multiple criteria decision-making). Management Science 31(6):647–656

Brealey RA, Myers S (2004) Principles of Corporate Finance. 7 edn. McGraw-Hill, New York, NY

Brummer V, Könnölä T, Salo A (2008) Foresight within ERA-NETs: Experiences from the preparation of an international research program. Technological Forecasting and Social Change 75(4):483–495

Bryan BA (2010) Development and application of a model for robust, cost-effective investment in natural capital and ecosystem services. Biological Conservation 143(7):1737–1750

Buede DM (1979) Decision analysis: Engineering science or clinical Art? Decisions and De-signs Inc, McLean, VA

Clemen RT, Kwit RC (2001) The value of decision analysis at Eastman Kodak company. Inter-faces 31(5):74–92.

Clemen RT, Smith JE (2009) On the choice of baselines in multiattribute portfolio analysis: A cautionary note. Decision Analysis 6(4):256–262

Cooper RJ, Edgett S, Kleinschmidt E (2001) Portfolio Management for New Products, 2nd edition. Perseus, Cambridge, MA

Danielson M, Ekenberg L, Ekengren A, Hökby T, Lidén J (2008) Decision support process for participatory democracy. Journal of Multi-Criteria Decision Analysis 15(1–2):15–30

Eden C (1990) The unfolding nature of group decision support: two dimensions of skill. In: Eden C, Radford J (eds.) Tackling strategic problems: the role of group decision support. Sage, London

Edwards W (1954) The theory of decision making. Psychological Bulletin 51(4):380–417

Edwards W (1961) Behavioral decision theory. Annual Review of Psychology 12:473–498

de Finetti B (1964) Foresight: Its Logical Laws, Its Subjective Sources (translation of the article La Prévision: ses lois logiques, ses sources subjectives, Annales de l'Institut Henri Poincaré, 1937). In: Kyburg HE, Smokler HE (eds.), Studies in Subjective Probability, Wiley, New York, NY
Fishburn PC (1964) Decision and Value Theory. John Wiley & Sons, New York, NY
Fishburn PC (1970) Utility Theory for Decision Making. John Wiley & Sons, New York, NY
Fishburn PC (1992) Utility as an additive set function. Mathematics of Operations Research 17 (4):910–920
Fox B (1966) Discrete optimization via marginal analysis. Management Science 13(3):210–216
Friend, JK and Jessop, WN (1969) Local Government and Strategic Choice. Tavistock, London
Golabi K, Kirkwood CW, Sicherman A (1981) Selecting a portfolio of solar energy projects using multiattribute preference theory. Management Science 27:174–189
Grayson CJ (1960) Decisions Under Uncertainty: Drilling Decisions by Oil and Gas Operators. Graduate School of Business, Harvard University
Gustafsson J, Salo A (2005) Contingent portfolio programming for the management of risky projects. Operations Research 53(6):946–956
Hämäläinen RP (2003) Decisionarium – aiding decisions negotiating and collecting opinions on the Web. Journal of Multi-Criteria Decision Analysis 12(2-3):101–110
Hämäläinen RP (2004) Reversing the perspective on the applications of decision analysis. Decision Analysis 1(1):26–31
Haveman RH, Margolis J (eds.) (1970) Public Expenditures and Policy Analysis. Markham, Chicago, IL
Heidenberger K, Stummer C (1999) Research and development project and resource allocation: A review of quantitative approaches. International Journal of Management Reviews 1(2):197–224
Henderson BD (1970) Perspectives on the Product Portfolio. Boston Consulting Group, Boston, MA
Henriksen A, Traynor A (1999) A practical R&D project-selection scoring tool. IEEE Transac-tions on Engineering Management 46(2):158–170
Howard RA (1966). Decision Analysis: Applied Decision Theory. Proceedings of the Fourth International Conference on Operational Research, Wiley-Interscience, 55–71
Howard RA (1968) The foundations of decision analysis. IEEE Transactions on Systems, Man, and Cybernetics SSC–4:211–219
Howard RA (1988) Decision analysis: Practice and promise. Management Science 34(6):679–695
Howard RA, Matheson JE (eds.) (1984) Readings on the Principles and Applications of Decision Analysis. Strategic Decisions Group Inc., Menlo Park, CA
Kavadias S, Loch CH (2004) Project Selection under Uncertainty: Dynamically Allocating Re-sources to Maximize Value. Kluwer Academic Publishers, Dordrecht
Keefer DL (1978) Allocation planning for R & D with uncertainty and multiple objectives. IEEE Transactions on Engineering Management EM-25:8–14
Keefer DL, Bodily SE (1983) Three-point approximations for continuous random variables. Management Science 29(5):595–603
Keefer DL, Kirkwood CW (1978) A multiobjective decision analysis: Budget planning for product engineering. Journal of the Operational Research Society 29:435–442
Keeney RL (1982) Decision analysis: An overview. Operations Research 30(5):803–838
Keeney RL, Raiffa H (1976) Decisions with Multiple Objectives: Preferences and Value Trade-Offs. John Wiley & Sons, New York, NY
Keisler J (2004) Value of information in portfolio decision analysis. Decision Analysis 1(3):177–189
Kleinmuntz DN (2007) Resource allocation decisions. In: Edwards W, Miles RF, von Winter-feldt D (eds.), Advances in Decision Analysis. Cambridge University Press, Cambridge, MA
Krantz DH, Luce DR, Suppes P, Tversky A (1971). Foundations of Measurement, Vol. I. Academic Press, New York
Krumm FV, Rolle CF (1992) Management and application of decision analysis in Du Pont. Interfaces 22(6):84–93
Kusnic MW, Owen D (1992) The unifying vision process: Value beyond traditional decision analysis in multiple-decision-maker environments. Interfaces 22(6):150–166
Lee SM, Lerro AJ (1974) Capital budgeting for multiple objectives. Financial Management 3(1):51–53
Liesiö J, Mild P, Salo A (2007) Preference programming for robust portfolio modeling and project selection. European Journal of Operational Research 181(3):1488–1505
Liesiö J, Mild P, Salo A (2008) Robust portfolio modeling with incomplete cost information and project interdependencies. European Journal of Operational Research 190(3):679–695
Liesiö J, Salo A (2008) Scenario-based portfolio selection of investment projects with incom-plete probability and utility information. Helsinki University of Technology, Systems Analysis Laboratory Research Reports, E23
Liesiö, J (2011). Measurable multiattribute value functions for project portfolio selection and resource allocation. Aalto University, Systems Analysis Laboratory, manuscript
Loch CH, Kavadias S (2002) Dynamic portfolio selection of NPD programs using marginal re-turns, Management Science 48(10):1227–1241
Lorie JH, Savage LJ (1955) Three problems in rationing capital. The Journal of Business 28(4):229–239
Lourenço JC, Bana e Costa C (2009) PROBE - A multicriteria decision support system for portfolio robustness evaluation. LSE Operational Research Group Working paper number LSEOR 09.108, Lon-don
Lourenço JC, Bana e Costa C, Morton A (2008) Software Packages for Multi-Criteria Resource Allocation. In: Proceedings of the International Management Conference, Estoril, Portugal
Markowitz HM (1952) Portfolio selection. Journal of Finance 7(1):77–91
Martino JP (1995) Research and Development Project Selection. Wiley, New York, NY
Matheson D, Matheson JE (1998) The Smart Organization: Creating Value through Strategic R&D. Harvard Business School Press, Boston, MA
Mintzberg H (1994) The Rise and Fall of Strategic Planning: Reconceiving the Roles for Planning, Plans, Planners. Prentice-Hall, Glasgow

Montibeller G (2007) Action-researching MCDA interventions. In: Shaw D (ed.), Keynote Papers, 49th British Operational Research Conference (OR 49), 4-6 Sep, University of Edinburgh. The OR Society, Birmingham

Morton A (2010) On the choice of baselines in portfolio decision analysis. LSE Management Science Group working paper, LSEOR10.128. LSE, London

Morton A, Bird D, Jones A, White M (2011) Decision conferencing for science prioritisation in the UK public sector: A dual case study. Journal of the Operational Research Society 62:50-59

Mottley CM, Newton RD (1959) The selection of projects for industrial research. Operations Research 7(6):740–751

von Neumann J, Morgenstern O (1947) Theory of Games and Economic Behavior. Princeton University Press, Princeton, NJ

Owen DL (1984) Selecting projects to obtain a balanced research portfolio. In: Howard RA, Matheson JE (eds.), Readings on the Principles and Applications of Decision Analysis. Strategic Decisions Group, Menlo Park, CA

Peerenboom JP, Buehring WA, Joseph TW (1989) Selecting a portfolio of environmental pro-grams for a synthetic fuels facility. Operations Research 37(5):689–699

Pennypacker J, Retna S (eds.) (2009) Project Portfolio Management: A View from the Trenches. Wiley, New York, NY

Phillips LD (1984) A theory of requisite decision models. Acta Psychologica 56(1-3):29–48

Phillips LD, Bana e Costa CA (2007) Transparent prioritisation, budgeting and resource allocation with multi-criteria decision analysis and decision conferencing. Annals of Operations Research 154(1):51–68

Phillips LD, Phillips MC (1993) Facilitated work groups: Theory and practice. Journal of the Operational Research Society 44(3):533-549

Pratt JW, Raiffa H, Schlaifer R (1965) Introduction to Statistical Decision Theory. McGraw-Hill, New York, NY

Raiffa H (1968) Decision Analysis. Addison-Wesley, Reading, MA

Raiffa H, Schaifer R (1961) Applied Statistical Decision Theory. Harvard Business School, Boston

Ramsey FP (1978) Truth and probability. In: Mellor DH (ed.), Foundations: Essays in Philosophy, Logic, Mathematics and Economics. Routledge & Kegan Paul, London

Rios Insua D, Kersten GE, Rios J, Grima C (2008) Towards decision support for participatory democracy. In: Burstein F, Holsapple CW (eds.), Handbook on Decision Support Systems 2. Springer, Berlin, 651–685

Rogers EM (2005) Diffusion of Innovations (5th Edition). Free Press, New York, NY

Roussel PA, Saad KN, Erickson TJ (1991) Third Generation R&D: Managing the Link to Corporate Strategy. Harvard Business School Press, Boston, MA

Roy B (1985) Méthodologie multicritère d'aide à la décision. Economica, Paris

Roy B (1991) The outranking approach and the foundations of ELECTRE methods. Theory and Decision 31:49–73

Ruusunen J, Hämäläinen RP (1989) Project selection by an integrated decision aid. In: Golden BL, Wasil EA, Harker PT (eds.), The Analytic Hierarchy Process: Applications and Studies, Springer-Verlag, 101–121

Rzasa P, Faulkner TW, Sousa NL (1990) Analyzing R&D portfolios at Eastman Kodak. Research-Technology Management 33:27–32

Saaty TL (2005) The analytic hierarchy and analytic network processes for the measurement of intangible criteria and for decision-making. In: Figueira J, Greco S, Ehrgott M (eds.), Multiple Criteria Decision Analysis: State of the Art Surveys. Kluwer Academic Publishers, Boston, 345–408

Salo A, Hämäläinen RP (1997) On the measurement of preferences in the analytic hierarchy process. Journal of Multi-Criteria Decision Analysis 6(6):309–319

Salo A, Hämäläinen RP (2010) Multicriteria decision analysis in group decision processes. In: Kilgour DM, C Eden C (eds.), Handbook of Group Decision and Negotiation, Springer, New York, 269–283

Savage LJ (1954) The Foundations of Statistics. Wiley, New York, NY

Schilling M, Oeser N, Schaub C (2007) How effective are decision analyses? Assessing decision process and group alignment effects. Decision Analysis 4(4):227–242

Schlaifer R, Raiffa H (1968) Applied Statistical Decision Theory. MIT Press, Boston, MA

Schwartz SL, Vertinsky I (1977) Multi-attribute investment decisions: A study of R&D project selection. Management Science 42(3):285–301

Shane SA, Ulrich KT (2004) Technological innovation, product development, and enterpreneurship in management science. Management Science 50(2):133–144

Sharpe WF (1964) Capital asset prices: a theory of market equilibrium under conditions of risk. Journal of Finance 19:425–442

Sharpe P, Keelin T (1998) How SmithKline Beecham makes better resource-allocation deci-sions. Harvard Business Review 76(2):45–46

Skaf MA (1999) Portfolio management in an upstream oil and gas organization. Interfaces 29(6):84–104

Souder WE (1973) Analytical effectiveness of mathematical models for R&D project selection. Management Science 19(8):907-923

Spetzler CS (2007) Building decision competency in organizations. In: Edwards W, Miles RF, von Winterfeldt D (eds), Advances in Decision Analysis. Cambridge University Press, Cambridge

Stewart TJ (1991) A multi-driteria decision support system for R&D project selection. The Journal of the Operational Research Society 42(1):17–26

Stummer C, Heidenberger K (2003) Interactive R&D portfolio analysis with project interdependencies and time profiles of multiple objectives. IEEE Transactions on Engineering Management 50:175–183

Stummer C, Kiesling E, Gutjahr WJ (2009) A multicriteria decision support systems for competence-driven project portfolio selection. International Journal of Information Technology & Decision Making 8(2):379–401

Tversky A, Kahneman D (1974) Judgment under uncertainty: Heuristics and biases. Science 185:1124–1131

Vilkkumaa E, Salo A, Liesiö J (forthcoming) Multicriteria portfolio modeling for the development of shared action agendas. Group Decision and Negotiation

Walls MR, Morahan GT, Dyer SD (1995) Decision analysis of exploration opportunities in the onshore US at Phillips petroleum company. Interfaces 25(6):39–56

Weingartner HM (1966) Capital budgeting of interrelated projects: Survey and synthesis. Management Science 12(7):485–516

Weingartner HN (1967) Mathematical Programming and the Analysis of Capital Budgeting Problems.Markham Pub. Co., Chicago, IL
von Winterfeldt D, Edwards W (1986) Decision Analysis and Behavioral Research. CUP, Cambridge