Invited Review

Real Options in Operations Research: A Review☆

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ABSTRACT

The Real Options approach to decision-making has been useful in capturing and valuing the flexibility inherent in many operating decisions that decision makers are faced with. In Operations Research (OR), a field that encompasses a plethora of problem-solving techniques for improving decision-making, we note an observable steady increase in contributions that apply the Real Options approach to model, analyze and evaluate flexible operating alternatives available to decision-makers or to optimize the operational efficiency of decision timing. We review 164 papers that appeared in five internationally-renowned OR journals in the last twelve years, cataloguing the main subject themes and contributions where the Real Options approach has been most valuable to Operations Research. We classify the reviewed papers into six main subject themes, and identify their main characteristics, the modeling approaches used, key issues and sub-categories. We further document current trends and suggest promising opportunities for future research.

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1. Introduction

'Real Options' describe corporate assets including growth opportunities viewed as options whose value depends on discretionary future investment by the firm (Myers, 1977). These corporate assets include not only tangible real assets acquired by firms through direct investment, such as plant and equipment, but also the successful outcomes of outlays in research and development (R&D), learning outcomes acquired via expenditures in training and advertising, and potential complementarities in product and service markets contingent on initial investment expenditures.

'Real Options' are contingent on *discretionary future* investment in that the magnitude, timing and schedule of investment outlays (e.g. whether lump-sum or in stages) affects the value of firm growth opportunities, such that their active management by decision-makers can be value-enhancing for the firm. Following Myers' footsteps, many researchers—exploiting concurrent developments in financial option pricing techniques—further refined and developed option-based approaches to firm and investment valuation.[1] The work of Brennan and Schwartz (1985), McDonald and Siegel (1985, 1986), Trigeorgis (1986), Pindyck (1988) and Dixit (1989), rooted in two decades of advances in option pricing theory, helped establish the foundation of what is nowadays referred to as the 'Real Options' (henceforth RO) approach to decision-making. This foundation is reviewed, synthesized and further developed by the highly-cited work of Dixit and Pindyck (1994) and Trigeorgis (1993, 1996).

As the field of Operations Research (henceforth OR) inherently relies on various problem-solving techniques for improving managerial decision-making under conditions of uncertainty, it was natural for OR scholars to adopt and seek to extend the RO approach (as early as the 1990s). Applications ranged from the valuation of flexibility inherent in production systems (see, e.g. Triantis & Hodder, 1990), the implementation of supply-chain collaborations and manufacturing joint ventures (e.g. Kogut, 1991),

[1] Articles by Samuelson (1965), Black and Scholes (1973), Merton (1973), Cox and Ross (1976), Cox, Ross and Rubinstein (1979), Harrison and Kreps (1979), Harrison and Pliska (1981, 1983), among others, have provided important developments in financial economics and financial option pricing.

capital budgeting evaluation of R&D investment projects (Pennings and Lint, 1997), and the valuation of natural resource reserves (Smith & McCardle, 1998), to name a few. More recently, we witness a steady increase in OR contributions that apply the RO approach to model, analyze and evaluate the numerous flexible alternatives that are available to decision-makers and to optimize the efficiency of managerial decision timing.

The main purpose of this paper is to provide a contemporary review of influential articles in OR journals that employ the RO approach during the last twelve years. Our main objectives are (1) to identify recent OR academic papers that employ RO concepts and modeling, and (2) establish the main subject themes (OR sub-topics) where the RO approach has been most valuable to the OR scholarly community. By reviewing and cataloguing the research contributions that we identify within each subject theme/topic, we are able to sketch their common characteristics and modeling similarities as well as propose promising paths for future research. We thus compile, manage, structure and classify a wide-ranging body of OR research within the canopy of RO.

We focus our review on papers that employ the RO approach and which appeared in five select internationally-renowned OR journals in the last twelve years. Specifically, we identify 164 RO-related papers published between 2004 and 2015 in the following OR journals: *Operations Research* (hereafter OR), *Management Science* (MS), *European Journal of Operational Research* (EJOR), *Annals of Operations Research* (ANOR), and *International Journal of Production Economics* (IJPE).[2] We propose a categorization of these 164 contributions into six main subject themes (OR sub-topics). We track the evolution of the six subject themes over time during our sample period and examine which specific themes of the RO related contributions are more covered or prevalent in these OR journals.

Alongside cataloguing the content of these 164 articles during the recent 12-year coverage period in our review (and the Supplementary material), we cite some influential work published before the starting year of our review (2004), as they help provide perspective and depth for the other reviewed articles (these are listed separately under supplementary references at the end of the paper). Beyond our comprehensive survey and convenient summary of the covered articles, this article includes a classification with six appropriate topic categories (subject themes), the single-firm versus multi-agent setting (or RO games), a modeling synthesis (in Supplementary Appendix) and directions for further research.

The article is organized as follows: Section 2 describes the approach we followed in conducting this review and presents summary statistics on the identified OR papers that employ RO. Section 3 provides a survey of the 164 papers identified in the literature, describes the six main subject themes/topics where the RO approach has been fruitfully employed in OR, discusses their evolution over time, and the common characteristics shared within each subject theme. Section 4 concludes and suggests paths for future research. The online Supplementary Appendix synthesizes the basic aspects and underlying formulations of typical RO models that are employed in the OR literature.

2. Review method and descriptive statistics

Our review approach followed three steps:

(a) Identify important recent contributions in the OR literature that employ RO concepts and modeling.

(b) Review identified contributions to ascertain the main themes and topics where the RO approach has been most applicable and valuable to OR, and

(c) Survey the research contributions within each identified main theme to ascertain their common characteristics and opportunities for future work.

In step (a), our approach was to focus on a well-specified time frame and journal universe. We restricted our review to the 2004–2015 time period and to five select internationally-renowned OR journals. We focus on the last twelve years so as to keep the review contemporary, while maintaining a time length long enough to identify recent trends in the relevant literature. Our starting year (2004) marks a decade since the influential work of Dixit and Pindyck (1994) and Trigeorgis (1993, 1996) that firmly established the RO literature. During this first decade, the contingent claims approach to the flexibility inherent in managerial decisions has been well-established as a modeling and valuation method, and our present research review is primarily interested in following on and reviewing its extended impact in OR after this first decade. We restrict the review to only these five select but influential journals in order to keep the review length manageable but with high impact content.

Operationally, we conducted step (a) as follows. For each journal within the 2004–2015 period, we performed an advanced search using the following union of keywords and conditions (i.e., all of them joined with an 'or' Boolean operator):

- '*real options*' anywhere in the text, or
- '*investment under uncertainty*' anywhere in the text, or
- '*options*' in the paper's title, abstract or keywords, or
- '*uncertainty*' in the paper's title, abstract or keywords.

The search was conducted between May and September 2015, was repeated in December 2015 for any new related published papers, and includes any accepted manuscripts not yet assigned to the journals' issues. The aforementioned search yielded results ranging from the hundreds (ANOR, IJPE, MS, OR) to the thousands (EJOR) within our time period (mainly due to the last two search criteria).[3] We manually checked all search results to finalize the identification of relevant papers reviewed in the study. We opted to be as exhaustive as possible, in that we also included (a) other literature review articles which might have a different subject focus but which discuss RO as an approach employed by researchers in that subfield (e.g., Julka, Baines, Tjahjono, Lendermann, & Vitanov, 2007), and (b) short papers that, e.g. juxtapose RO with other optimization approaches in the literature (e.g., Wallace, 2010).

Our keyword and manual search yielded a total of 164 papers that have appeared in the selected OR journals between 2004 and 2015. These are distributed as follows: 70 papers (43%) appeared in EJOR, 34 papers (21%) in IJPE, 33 papers (20%) in MS, 18 papers (11%) in ANOR, and 9 papers (5%) in OR. Related publications in EJOR are almost twice as many as those in IJPE or MS; this is natural, however, as EJOR published roughly as many papers as all other selected journals combined during the examined period.[4] In EJOR, the 70 identified contributions that employ RO concepts and modeling represent 1% of the journal's total output over our examined twelve-year period. Equally, in IJPE and ANOR they represent

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[3] These last two broad search criteria contribute about 10%-15% to the final list of identified papers.

[4] EJOR published 7552 papers between 2004 and 2015, an average of about 630 papers per year. This is almost the entire output of IJPE (3,497 papers), ANOR (1,947), MS (1,789) and OR (1,179) combined. The published paper numbers we report exclude withdrawn and retracted papers, book reviews, calls for papers, acknowledgements to reviewers, and letters from and to the editors (but include errata, corrigenda, technical notes, replies, and introductory articles to special issues).