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Tackling uncertain future scenarios with real options: A review and research framework

Research Article

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Abstract: Real options are widely applied in strategic and operational decision-making, allowing for managerial flexibility in uncertain contexts. Increased scholarly interest has led to an extensive but fragmented research landscape. We aim to measure and systematize the research field quantitatively. To achieve this goal, we conduct bibliometric performance analyses and bibliographic coupling analyses with an in-depth content review. The results of the performance analyses show an increasing interest in real options since the beginning of the 2000s and identify the most influential journals and authors. The science mappings reveal six and seven research clusters over the last two decades. Based on an in-depth analysis of their themes, we develop a research framework comprising antecedents, application areas, internal and external contingencies, and uncertainty resolution through real option valuation or reasoning. We identify several gaps in that framework, which we propose to tackle in future research.

Keywords: *Bibliometric analysis; decision processes; real options; research framework.*

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1. INTRODUCTION

Real options (RO) are widely acknowledged as an effective tool for improving flexibility and tackling managerial uncertainty. Initially introduced by Myers (1977), "real options" (RO) refers to a firm's value that can be achieved through discretionary future investments. In today's broader understanding, RO theory applies option pricing to evaluate investments in non-financial assets. Whereas traditional investment decisions based on discounted cashflow calculation only allow for an "invest or do not invest" decision (Dixitand Pindyck, 1994), real options allow to make a rather small investment (the option price) now and to postpone the final decision to later, when uncertainty decreases (Trigeorgis, 1996). This approach is particularly beneficial for highly uncertain outcomes, such as those of radical innovations (Tiberius, Schwarzer, & Roig-Dobón, 2021). For example, a car manufacturer may be unsure if the predominant electric engine technology will be based on lithium-ion batteries or hydrogen cells. Rather than fully committing to one of these options now, the carmaker may make small investments in both technologies and decide later. In this regard, real options are a means to flexibly deal with multiple future scenarios (Jashari et al., 2021; Tiberius, Siglow, and Sendra-García, 2020). Firms using RO thinking as a foresight methodology may increase their agility (Brand et al., 2021) and gain competitive advantages (Semke & Tiberius, 2020).

Practitioners recognized the importance of real options in contrast to traditional capital budgeting techniques that are not flexible enough for unexpected exogenous and endogenous developments (Trigeorgis, 1993). Hence, RO valuation is being applied to practical decision-making problems in industries, such as real estate (Yongqiang et al., 2021), information technology (Khan et al., 2013; Khan et al., 2017), or construction projects (Andalib et al., 2018; Fu & Jennen, 2009; Morreale et al., 2019).

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Over the past two decades, real options have attracted increased attention by business and management scholars, leading to a broad and somewhat fragmented literature landscape. As an analytical tool, RO thinking has not only been applied to various areas. Moreover, RO theory is an established conceptual lens to allow strategic decision-making under uncertainty (Yong Li et al., 2007). In strategy research, RO scholars have addressed the timing of market entry, models of entry, foreign direct investments, the cooperation vs. competition trade-off, or the choice of an appropriate organizational form (Trigeorgis & Reuer, 2017). Accordingly, the most prominent literature reviews on RO are concerned with certain areas of RO application, such as international business (Chi et al., 2019), operational research (Trigeorgis & Tsekrekos, 2018), metal mining projects (Savolainen, 2016), megaproject planning (Machiels et al., 2021), and electricity generation (Cesena et al., 2013). RO theory could be used to tackle current energy and environmental issues by enhancing the value of electricity generation projects (EGP). However, we still lack a comprehensive overview of all fields of study where the RO logic has been applied.

Against this background, the main purposes of this paper are to measure the performance of RO research and to systematize the field using bibliometric methods, particularly performance analyses and bibliographic coupling, relying on citations as a measure of the scientific impact. The objectives of this paper are as follows. First, we aim to evaluate the previous scientific output on RO in terms of distribution of the RO publications, research areas, most cited and prolific journals and authors as well as the most influential publications on RO, based on citation and publication numbers. Second, our goal is to identify knowledge clusters within the RO research field over the last twenty years. Third, we aim to identify possible future directions for RO research based on the results provided by the bibliometric analyses. The relevance of our research corresponds to the growing relevance of RO in business and management research and practice. Due to the broad application areas and methodological complexity, a systematic review is needed. Our findings contribute to RO research by measuring and structuring the intellectual capital in the field and identifying open research themes, which should be addressed by future research.

The results of the performance analyses show a growing number of publications since the early 2000s and identify the most influential journals and authors. The bibliographic coupling for the period of 2000-2009 has revealed six clusters, and for 2010-2019 seven research clusters have been revealed. Based on an in-depth analysis of these themes, we developed a research framework comprising antecedents, application areas, internal and external contingencies, and uncertainty resolution through RO valuation or reasoning. We identify several research gaps in that framework, which we propose to tackle in future research.

The structure of the remainder of this paper is as follows: The next section introduces the concept and past reviews on RO. The third section provides information on the conducted bibliometric analyses and data collection. The fourth section comprises graphical and tabular results of the bibliometric analyses. The fifth section discusses the results and argues on possible future avenues for RO research, followed by a conclusion.

2. BACKGROUND AND PAST REVIEWS

Real options originally referred to a firm's value that can be achieved through discretionary future investments (Myers, 1977). Today's RO approach refers to the valuation of investments in non-financial assets applying option pricing theory. In contrast to the traditional discounted cash flow approach that only selects investments with a positive net present value, the RO approach provides decision-makers with the flexibility to delay an investment while waiting for new information rather than undertaking the full investment in the present or not at all (Dixit & Pindyck, 2012). Additionally, RO analysis accounts for investment timing and operational flexibility, which makes it particularly useful for investment appraisal under uncertain conditions (Ginbo et al., 2021). Similar to a financial call option, RO gives its holder the right but not the obligation to revise a course of action in response to changed circumstances by deferring, growing, switching, or abandoning an investment (Trigeorgis, 1996). Thus, the flexibility arising from the RO adds value to an investment project.

The seminal paper by Brennan und Schwartz (1985) identified the beginning of the practical implementation of RO valuation techniques to projects characterized by high uncertainty, long time horizons, and staging of decisions, such as mining investments. Formal valuation techniques are not always applicable to investment projects, especially when the value of operating flexibility and strategic adaptability cannot be quantified, which is typically the case with R&D projects, investments in new technologies, and innovation portfolios (Gunter McGrath and

Nerkar, 2004; Kaufmann al., 2021; McGrath, 1997; Özdemir and van den Ende, 2021). Thus, scholars distinguish between the RO valuation, which applies formal models to estimate RO value, and RO reasoning, which identifies RO value conceptually, applying logic and heuristics (Trigeorgis & Reuer, 2017). Real option theory is applied to many practical decision situations in many industries, such as construction (Ribeiro et al., 2020), energy (Gupta & Mosiño, 2020), finance (Méndez-Suárez & Crespo-Tejero, 2021), healthcare (Gunter McGrath and Nerkar, 2004) or tourism (Piñeiro-Chousa et al., 2021), and many more. Also, risky endeavors, such as internationalization, can be subject to real option argumentation (Belderbos et al., 2020; Hunt et al., 2021; Ioulianou et al., 2021).

Since its inception, RO was subject to numerous publications, which in turn induced the emergence of reviews attempting to categorize the extant literature and identify research gaps. Our holistic bibliometric review complements previous review endeavors, which have become outdated or have a too narrow thematic focus. For example, Ragozzino et al. (2016) reviewed the financial economics and strategic management research dedicated to RO, discussed existing gaps between both research stems and proposed ways to converge them. Trigeorgis & Reuer (2017) conducted a comprehensive review of significant strategic management literature on RO and defined core strategy issues that should be covered within the RO theory in order to enhance its contribution to strategic management. Trigeorgis & Tsekrekos (2018) carried out an extensive review of papers on RO in operational research published in five internationally apprised operational research journals from 2004 to 2015. Some reviews focus exclusively on the RO approach within certain sectors, such as mining and energy (Fernandes et al., 2011; Martínez Ceseña et al., 2013; Savolainen, 2016). Despite extensive interest in RO and numerous structured reviews of the respective studies, no broad quantitative bibliometric analyses have been carried out yet.

3. METHODOLOGY

3.1. Bibliometric methods

Bibliometric methods apply statistical techniques to examine the structure and development of a research field (Zupic & Čater, 2015). Bibliometrics have been applied to all areas in business and management recently, such as business ethics (Rocha & Pinheiro, 2021; Verk et al., 2021), entrepreneurship (Deyanova et al., 2022; Escobar et al., 2021; Glinyanova et al., 2021; Lampe et al., 2020; Rovelli et al., 2021; Schröder et al., 2021), innovation (Sharma, 2021; Tiberius, Schwarzer, & Roig-Dobón, 2021), marketing (Lacka et al., 2020 ; Gao et al., 2021), organization (Bouckenooghe et al., 2021; Díez-Martín et al., 2021; Sharma & Lenka, 2021), strategy (Baker et al., 2020 ; Filser et al., 2021; Tiberius et al., 2020), technology management (Korte et al., 2021; Pawassar & Tiberius, 2021; Tandon et al., 2021; Zeba et al., 2021), and many more.

In particular, we conducted several performance analyses and a bibliographic coupling analysis as a specific type of a science mapping. Performance analyses assess the influence of countries, institutions, journals, or individuals based on their scientific output and received citations, whereas science mappings examine the intellectual structure of a scientific field (Noyons et al., 1999). Science mappings complement systematic literature reviews and have therefore become popular as a quantitative rather than qualitative approach to structure the body of knowledge in a field.

A series of performance analyses was carried out using BibExcel (O. Persson et al., 2009) and Excel. Fig. 1 and Fig. 2 depict the annual distribution of the publications and cited references. Further analyses have been conducted only on the primary publications. Thus, Table 1 lists the most cited journals with the number of articles they published and their h-index that captures not only the quantity of a scientific output but its significance as well (Hirsch, 2005). Similarly, Table 2 comprises the most cited authors, the number of articles they published, and their h-index. The citations count was chosen as a relevance estimator (Castillo-Vergara et al., 2018; Danvila-del-Valle et al., 2019; Vallaster et al., 2019). Table 3 contains the twenty most cited papers per year. The citations count per year was applied to offset the disadvantageous position of the more recent papers as older papers had a longer timeframe to collect citations.

Bibliographic coupling aims to find similarity patterns between publications by assessing the extent to which the reference list of one publication overlaps with the reference list of another (Kessler, 1963). This approach is suitable for examining more recent knowledge clusters within a research field (Zupic & Čater, 2015), whereas the more popular co-citation analysis focuses on the historical development of knowledge clusters (Noyons et al., 1999; Small, 1973). As we wanted to focus on the more recent developments, we chose a bibliographic coupling analysis. We used VOSviewer 1.6.15 for the construction and visualization of bibliometric networks (van Eck &

Waltman, 2010). We applied a normalization for association strength to achieve high accuracy of the network (Boyack et al., 2005; van Eck & Waltman, 2009). To offset the stronger influence of the highly cited elements of the reference lists on the construction of the network, we used fractional counting (Perianes-Rodriguez et al., 2016; van Eck & Waltman, 2014). A threshold of at least two citations per year was chosen to couple only influential publications (Zupic & Čater, 2015). As citation habits tend to change over the years, it is not recommended to perform a bibliographic coupling over periods of longer than 10 years (Glänzel & Thijs, 2012). Hence, the reduced data set was divided into two ten-year periods: Period I from 2000 to 2009 comprising 84, and Period II from 2010 to 2019 consisting of 118 publications. This enables the comparison of the subsequent periods and hence the analysis of the RO research development over time. The remaining 17 publications from 1988-1999 were therefore not part of the bibliographic coupling.

3.2. Data collection

We retrieved the publications on RO from the Web of Science (WoS) on July 17th, 2020. Searching for "real option*" in the title, yielded 1,637 publications. Publications from 2020 have been omitted from the dataset to consider contributions only from completed years. Further, the dataset was narrowed down to publications from the categories Business, Business Finance, Economics, Management, Operations Research, and Management Science. Additionally, the dataset was limited to articles and book chapters. Reviews were explicitly excluded as they contain an excessive amount of citations, which can lead to an over-aggregation of citation clusters and thus to biased results (Boyack & Klavans, 2010). Finally, the dataset was filtered by English language as it is considered to be the lingua franca of science (Vallaster et al., 2019). To focus only on high-quality research, we excluded 223 papers from journals belonging to the third and fourth quartile according to the Scimago Journal Rank (SJR) of 2019. The abstracts of the remaining publications have been manually reviewed and we removed 28 publications deviant from the topic. As a result, the final dataset comprises 510 publications.

4. RESULTS

4.1. Annual Productivity

According to the annual publications (Fig. 1), the interest in RO has increased especially since 2001. However, the number of publications is volatile.

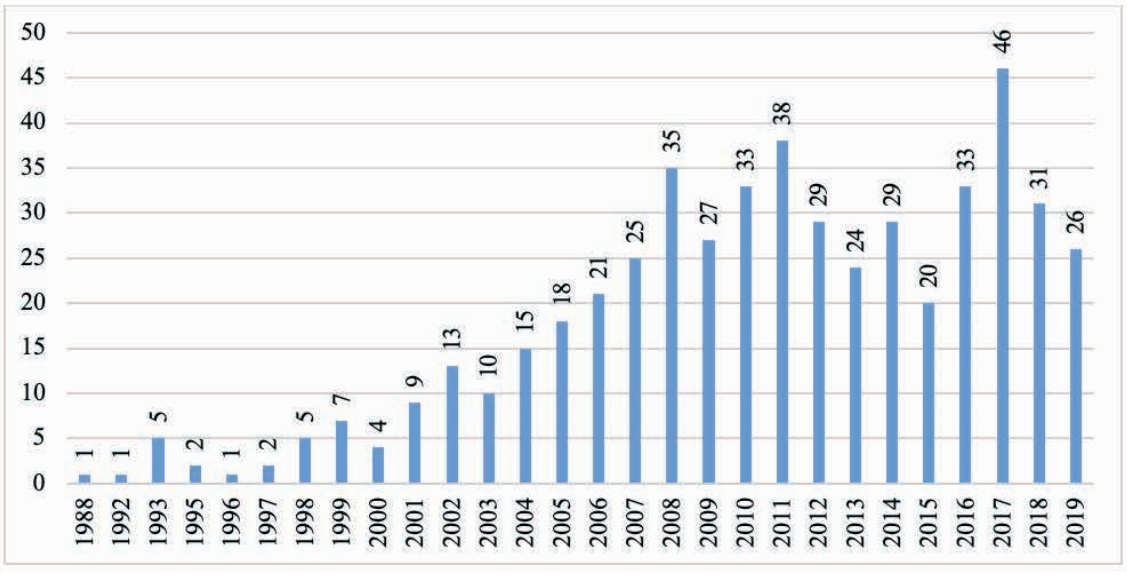

Fig. 1. Annual number of primary papers.

4.2. Journal influence

The most cited and prolific journals specialize in strategic management, followed by the journals on operational mangement and energy research (Table 1). To the less prolific but still highly cited journals belong the ones publishing finance, economics, and environmental studies.

Table 1: Most cited journals.

R	Journal Name	TC	TP	HI
1	Academy of Management Review	1,416	5	5
2	Strategic Management Journal	979	13	10
3	Energy Policy	654	22	14
4	European Journal of Operational Research	651	28	14
5	Energy Economics	637	24	13
6	Journal of Finance	592	7	6
7	Management Science	525	9	8
8	Harvard Business Review	429	3	3
9	Organization Science	422	4	4
10	Review of Financial Studies	333	6	5
11	Journal of International Business Studies	327	6	6
12	Quarterly Journal of Economics	270	1	1
13	Journal of Financial Economics	267	4	4
14	Decision Sciences	265	5	5
15	Journal of Management Information Systems	248	5	5
16	Journal of Financial and Quantitative Analysis	241	3	3
17	Information Systems Research	235	5	4
18	IEEE Transactions on Engineering Management	229	8	6
19	Journal of Environmental Economics and Management	228	3	3
20	Financial Management	216	5	4
21	Operations Research	206	5	4
22	Economic Journal	199	1	1
23	International Journal of Production Economics	198	10	8
24	Journal of Management Studies	197	3	3
25	Review of Economic Studies	193	2	2

R: rank, TC: times cited, TP: total publications, HI: h-index.

4.3. Author influence

Table 2 lists the most cited and therefore most influential authors in RO research. McGrath introduced RO thinking into strategic management. McGrath (1997) developed a conceptual framework on technology options and McGrath (1999) argued on a beneficial role of failure in entrepreneurial success. The rest of the most cited scholars are either authors or co-authors of the twenty most cited contributions per year, thus their presence among the most cited scholars is consistent. Notably, the most productive author, Trigeorgis, does not belong to the most cited ones. Notwithstanding, he is a prominent scholar in the RO research field who is known not only for his original contributions but also for the excessive literature reviews of RO studies (Trigeorgis, 1993, 1996; Trigeorgis & Reuer, 2017; Trigeorgis & Tsekrekos, 2018). That is supported by the highest h-index among RO authors.

Table 2: Most cited authors.

R	Author	TC	TP	HI
1	McGrath R	1,257	3	3
2	Folta T	443	4	3
3	Grenadier S	424	4	4
4	Benaroch M	408	4	4
5	Miller K	365	3	3
6	Smith J	356	3	3
7	Luehrman T	325	2	2
8	Adner R	315	2	2
9	Kauffman R	282	2	2
10	Trigeorgis L	280	7	6
11	Kulatilaka N	277	2	2
12	Levinthal D	275	1	1
13	Paddock J	270	1	1
14	Siegel D	270	1	1
15	Loch C	260	1	1
16	Huchzermeier A	260	1	1
17	Nerkar A	256	1	1
18	Tong T	250	3	3
19	Kogut B	243	1	1
20	Tufano P	233	2	2
21	Vassolo R	223	1	1
22	Anand J	223	1	1
23	Reuer J	215	2	2
24	Van Reenen J	199	1	1
25	Bloom N	199	1	1

R: rank, TC: times cited, TP: total publications, HI: h-index.

4.4. Most influential articles

Table 3 provides an overview of the 25 most cited articles. As older publications are privileged as they have had a longer period to be cited, we sorted the table by average citations per year. McGrath (1999) and McGrath (1997) are also the articles with the highest overall citations. In contrast, the younger article by Boomsma et al. (2012), despite having medium high overall citations, is the third most cited on an annual basis. Other highly cited papers applied RO theory to investments in renewable energy (Boomsma et al., 2012; Ritzenhofen & Spinler, 2016; Zhang, Zhou, Zhou et al., 2016), R&D projects (Gunther McGrath & Nerkar, 2004; Huchzermeier & Loch, 2001) and strategic management issues, such as alliances and strategic partnerships, international expansion and divestments (Belderbos & Zou, 2009; Brouthers et al., 2008; Folta & Miller, 2002; Vassolo et al., 2004). Interestingly, the more recent studies applying RO valuation techniques to renewable energy projects receive as much citations per year as the much older contributions covering other topics. This implies the increased interest of RO research in sustainable energy.

Table 3: Most cited articles. Source: Own elaboration.

R	Title, Author, Year	TC	TC/y
1	Falling forward: Real options reasoning and entrepreneurial failure, McGrath, 1999	583	27.8
2	A real options logic for initiating technology positioning investments, McGrath, 1997	418	18.2
3	Renewable energy investments under different support schemes: A real options approach, Boomsma, Meade, & Fleten, 2012	139	17.4
4	What is not a real option: Considering boundaries for the application of real options to business strategy, Adner & Levinthal, 2004	275	17.2
5	Real options reasoning and a new look at the R&D investment strategies of pharmaceutical firms, McGrath & Nerkar, 2004	256	16.0
6	Non-additivity in portfolios of exploration activities: A real options-based analysis of equity alliances in biotechnology, Vassolo, Anand, & Folta, 2004	223	13.9
7	Project management under risk: Using the real options approach to evaluate flexibility in R&D, Huchzermeier & Loch, 2001	260	13.7
8	Capabilities as real options, Kogut & Kulatilaka, 2001	243	12.8
9	A real options model for renewable energy investment with application to solar photovoltaic power generation in China, Zhang, Zhou, & Zhou, 2016	49	12.3
10	A real options evaluation model for the diffusion prospects of new renewable power generation technologies, Kumbaroğlu, Madlener, & Demirel, 2008	134	11.2
11	Patents, real options and firm performance, Bloom & van Reenen, 2002	199	11.1
12	The strategic exercise of options: Development cascades and overbuilding in real estate markets, Grenadier, 1996	253	10.5
13	Optimal design of feed-in-tariffs to stimulate renewable energy investments under regulatory uncertainty - A real options analysis, Ritzenhofen & Spinler, 2016	41	10.3
14	Strategic delay in a real options model of R&D competition, Weeds, 2002	182	10.1
15	Optimal feed-in tariff for solar photovoltaic power generation in China: A real options analysis, Zhang, Zhou, Zhou, & Liu, 2016	40	10.0
16	A case for using real options pricing analysis to evaluate information technology project investments, Benaroch & Kauffman, 1999	204	9.7
17	Managing information technology investment risk: A real options perspective, Benaroch, 2002	163	9.1
18	Real options in equity partnerships, Folta & Miller, 2002	163	9.1
19	Real options and foreign affiliate divestments: A portfolio perspective, Belderbos & Zou, 2009	99	9.0
20	Real options, international entry mode choice and performance, Brouthers, Brouthers, & Werner, 2008	107	8.9

R: rank, TC: times cited, TC/y: average citations per year.

4.5. Bibliographic coupling

The bibliographic coupling resulted in Network I (for Period I) comprising six (Fig. 3) and Network II (for Period II) seven clusters (Fig. 4). The clear assignment of the clusters to a particular research domain is a challenging task, as the bibliographic coupling does not guarantee a precise allocation of primary papers based solely on the jointly cited secondary papers. Thus, the name of each cluster represents not all, but the majority of the papers assigned to it.

Network I comprises the following six clusters: 1. Energy, natural resources, and environment (red), 2. Strategic Management (green), 3. Competition and Preemption (dark blue), 4. Information Technology (yellow), 5. Managerial Behavior (violet), and 6. Corporate Finance (light blue), which are described in the following.

Energy, natural resources, and environment (red): The first cluster consists of 20 articles focusing on two major subtopics: First, the valuation of policy initiatives and investment decisions, both applying ROs. For instance, some publications employ RO modeling to estimate the impact of climate change policy mechanisms on electricity investments (Szolgayova et al., 2008) and evaluate the benefits of US federal government programs on RO technologies support (Davis & Owens, 2003; Siddiqui et al., 2007). The studies related to the second subtopic incorporate the RO lens to project valuation under uncertainties. Here, Wang und Min (2006) introduce a RO model

to estimate the value of interrelated electricity projects by addressing financial risks and managerial flexibility. Another RO valuation model, presented in this cluster, deals with cost, price, and reserve volatility in mining projects (Slade, 2001).

Strategic Management (green): The green cluster contains 19 publications with the majority investigating the application of RO to international operations, such as international joint ventures (Reuer & Tong, 2005), licensing in foreign markets (Jiang et al., 2009), market entries (Brouthers et al., 2008; Li & Rugman, 2007), foreign investments (Lee & Makhija, 2009), and divestments (Belderbos & Zou, 2009; Kumar, 2005). Similar to other clusters, some authors suggest the application of the RO perspective in response to external uncertainties, especially liabilities of foreignness (Belderbos & Zou, 2009; Jiang et al., 2009) and technological uncertainty (Oriani & Sobrero, 2008; Ziedonis, 2007). Other authors propose the enhancement of the resource-based view through RO theory. For example, Kogut und Kulatilaka (2001) view the organizational capabilities as a set of ROs, whereas knowledge and technological resources are proposed to be evaluated through a RO lens (Ziedonis, 2007). Additionally, the smallest subtopics, R&D and CSR, receive more attention in recent publications and grow into separate clusters in Network II.

Competition and preemption (dark blue): This cluster comprises 17 publications dealing with the impact of competitive settings on ROs. Several studies analyze the option to delay investments in technology development and R&D projects. In particular, Weeds (2002) investigates the correlation between preemption aspirations of competitors and investment timing. Huisman und Kort (2004) address the issue of the second mover advantage waiting for the raise of new superior technology instead of current technology adoption. Furthermore, several articles combine the insights of game theory with RO logic to assist strategic planning (Smit, 2003).

Information technology (yellow): The yellow cluster, with 13 publications, provides practitioners and scholars with valuation models and conceptualization tools for IT-related investments under risky conditions. For instance, Herath und Herath (2008) propose an integrated RO valuation and post-auditing model for information security investments. Other publications apply the risk management perspective to the evaluation of RO investments in IT projects (Benaroch, 2002; Chen et al., 2009). Another subtopic relates to outsourcing decisions (Jiang et al., 2008; Su et al., 2009).

Managerial behavior (violet): This rather fragmented cluster includes the study of behavioral aspects of RO, such as attention (Barnett, 2008) and cognitive biases (Miller & zur Shapira, 2004). Other articles apply RO to the RBV (Kyläheiko et al., 2002), scenario planning (Miller & Waller, 2003), and sequential decision-making (Adner & Levinthal, 2005).

Corporate finance (light blue): The smallest cluster with only three publications addresses financial decisions in organizations. It concerns venture capital staging by ROs (Li, 2008), a dynamic model of financial structure optimization (Tserlukevich, 2008), and financial decisions in a public organization (Lambrecht & Myers, 2008).

Network II consists of the following seven clusters: 1. Energy and Environment (red), 2. Natural Resources and Corporate Finance (green), 3. Strategic Management (dark blue), 4. R&D, Innovation, and Technology (yellow), 5. Production, Manufacturing, and Supply Chain (violet), 6. Construction Projects (light blue), and 7. CSR (orange), which are described and compared to the findings from Network I in the following.

Energy and Environment (red): The largest cluster, with 35 publications, focuses on specific industries. In contrast to Network I, the influence of incentive policies grew to the biggest subtopic. Several authors reveal that policy decisions may stimulate investments regarding volume and pace. Zhang, Zhou, Zhou et al. (2016) point out that higher subsidies, the promotion of technological development, and increased market stability stimulate the investment climate. Further literature suggests the inclusion of political factors in RO models to improve their applicability to the energy sector. Subsidy levels (Boomsma et al., 2012; Zhang, Zhou, Zhou et al., 2016), price fluctuations (Lee & Shih, 2010; Monjas-Barroso & Balibrea-Iniesta, 2013; Nadarajah et al., 2017), climate policy (Sanderson et al., 2016; Torani et al., 2016), and regulatory uncertainty (Fleten et al., 2017) are mentioned. In contrast to Zhang et al.'s (2016 b) assumption of subsidy enhancing investments, Torani et al. (2016) argue that technological advancements stimulate the adoption of clean energy technologies more than political support schemas.

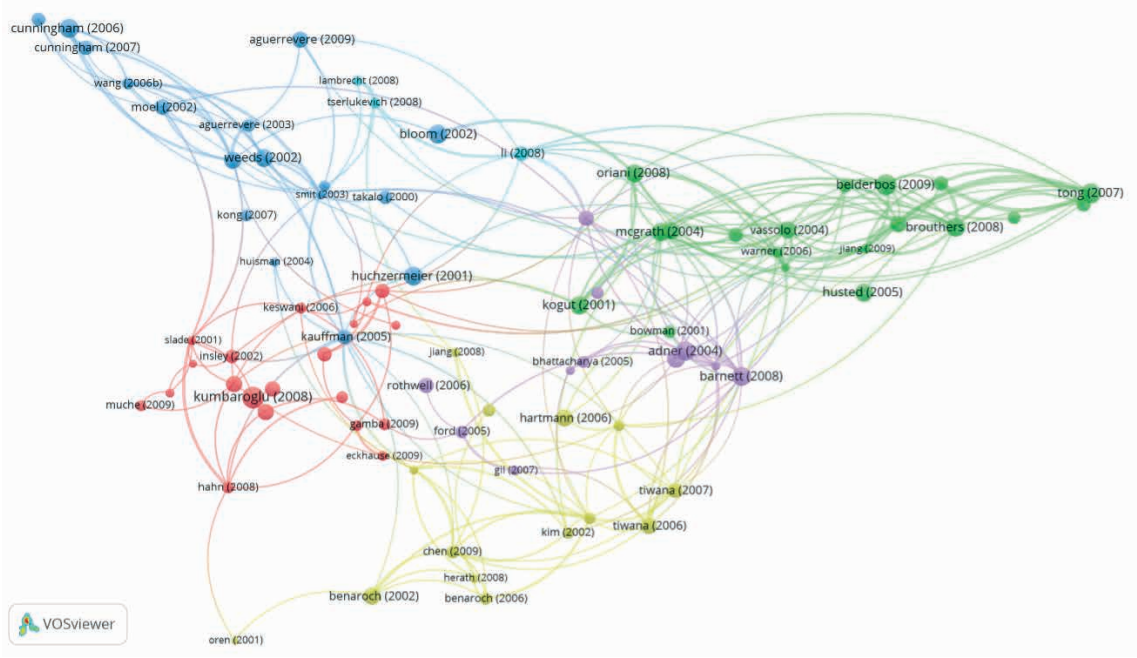

Fig. 3. Network I (bibliographic coupling, 2000-2009).

Natural Resources and Corporate Finance (green): The main focus of this cluster lies on the creation and adjustment of valuation models for RO investments. Several publications view commodity price volatility as an antecedent to RO application in mining projects (Haque et al., 2016; Siña & Guzmán, 2019; Zhang et al., 2014), offshore oil development (Guedes & Santos, 2016), oil projects (Tang et al., 2017), and maritime management (Atari et al., 2019). Additionally, the optimal timing decision is the other subtopic of the cluster. In particular, Grenadier and Malenko (2010) discuss learning effects from past events to assess the optimal investment timing. Thijssen et al. (2012) study optimal investment timing in a competitive environment. Further publications evaluate the effects of asymmetric information in RO models (Grenadier & Malenko, 2011; Kumar & Yerramilli, 2018).

Strategic Management (dark blue): Most of the 19 publications in this cluster produce mathematical models and theoretical frameworks by applying RO logic to strategic decisions. The largest subtopic relates to market entries, more specifically, the level of equity commitment (Ahammad et al., 2017; Wooster et al., 2016), the choice between green-field start-up venture and acquisition (Brouthers & Dikova, 2010), and geographic sales (Sahaym et al., 2012). Another subtopic deals with the issue of organizational learning. In particular, Driouchi und Bennett (2011) argue that managerial awareness of RO, as well as investments in RO knowledge might help firms to outperform competitors. Additionally, Leiblein et al. (2016) suggest that the application of RO to resource allocation decisions in strategic factor markets generates a competitive advantage. Furthermore, two studies compare the application of RO and other theories. Chung et al. (2013) compares divestment decisions under the RO logic. Klingebiel und Adner (2014) distinguish between the performance effect of RO and other resource allocation methods in a product innovation setting.

R&D, Innovation, and Technology (yellow): The yellow cluster enhances the understanding of the valuation possibilities of investments in R&D projects, new technology, and innovation, which are usually associated with uncertain outcomes. One subtopic deals with shortcomings of classical RO models. For example, Cassimon, Engelen et al. (2011) enhance the RO valuation model with the tools for stage-specific volatility estimation. Benaroch (2017) proposes the inclusion of proactive uncertainty-reducing mitigations in the RO valuation. Additionally, few papers employ fuzzy logic in RO valuation models (Ho & Liao, 2011; Lee & Lee, 2011; Zmeškal, 2010). Another subtopic deals with disruptive technologies, such as RFID (Dimakopoulou et al., 2014) or virtual worlds initiatives (Yang et al., 2012).

Production, Manufacturing, and Supply Chain (violet): This cluster studies the application of RO to different supply chain parties. For instance, Carbonara und Pellegrino (2018) present a model to evaluate the postponement

strategy in case of supply or demand disruptions. Cucchiella et al. (2013) use the RO approach to evaluate green investments in the supply chain concerning battery recycling. Costantino und Pellegrino (2010) investigate decision-making between single and multiple sourcing.

Construction Projects (light blue): In this cluster, with 8 publications, public/private partnerships represent the main subtopic (Gundes & Buyukyoran, 2018; Liu et al., 2014). Behavioral aspects are also discussed (Andalib et al., 2018; Morreale et al., 2019).

CSR (orange): Three of five publications in the seventh cluster deal with CSR. In particular, Cassimon et al. (2016) introduce a RO model to estimate the optimal timing for CSR investments. Lee (2019) studies the relation between CSR commitment and the RO value of the firm.

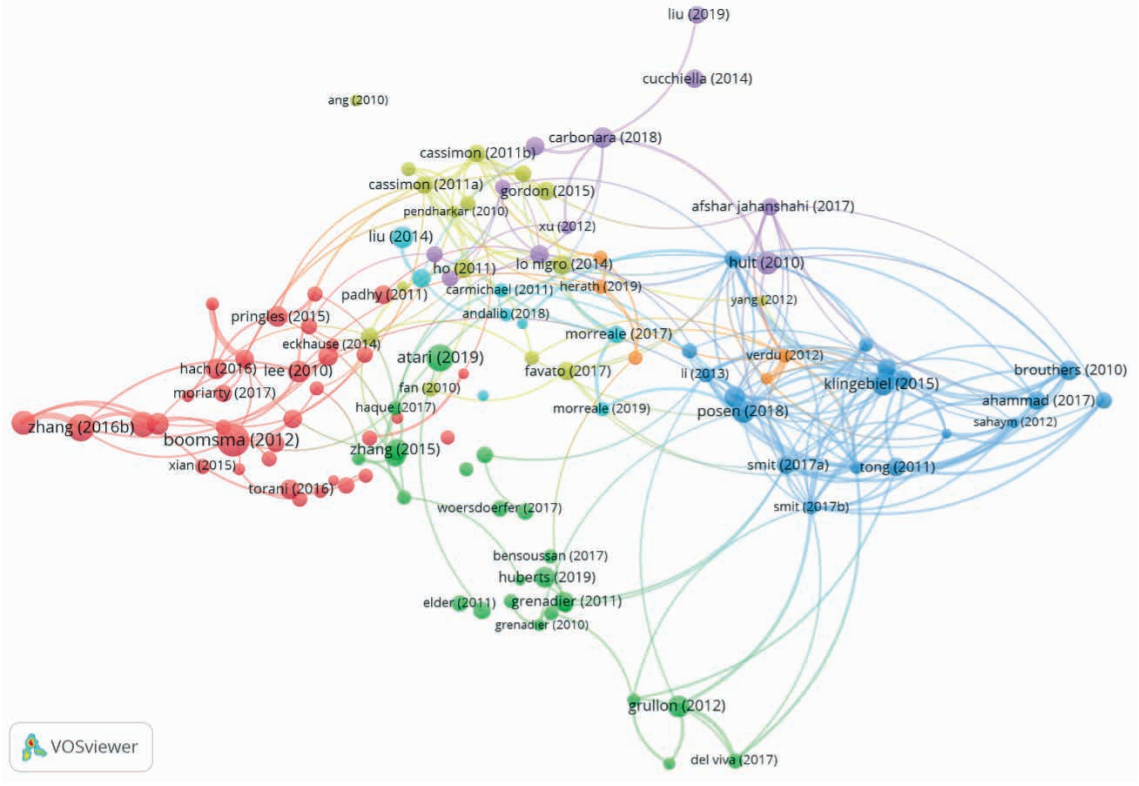

Fig. 4. Network II (bibliographic coupling, 2010-2019).

5. DISCUSSION

5.1. Evolution of RO research

Whereas the performance analyses show a high interest in RO research and give an impression over relevant journals, authors, and articles, the bibliometric coupling provides deeper insight into the structure and evolution of RO research over time. We therefore focus on these insights.

The only research stream present in both networks is RO thinking in strategic management. For all other topics, major shifts occurred. In Network I, clusters are more clearly defined, whereas in Network II some clusters overlap with each other, which implies a convergence of some RO research streams. However, traditional RO research domains, such as energy, mining industries, and corporate finance, are more clearly separated from the other clusters in Network II.

New clusters in Network II imply either the emergence of new RO themes or the increased interest in the topics underrepresented in the previous decade. For example, CSR was covered only by an paper in Network I, whereas in Network II, a whole new cluster emerged. It can be expected that this research stream will receive further attention due to the significant impact of CSR on the sustainability of business operations (Lee, 2019). “Construction

projects", the second smallest cluster of Network II, comprises papers applying the RO approach to large-scale infrastructure projects, for example in public/private partnerships or public incentives for private investments. This theme was not part of RO research in the previous decade. The same applies to supply chain management, which is covered in the fifth cluster of Network II.

Changes within clusters indicate the extension of research themes. The cluster "Information Technology" in Network I transformed into the cluster "R&D, Innovation & Technology" in Network II. Investments in IT projects play a rather subordinate role in contemporary RO research. Its focus shifted to problems such as cybersecurity (Benaroch, 2018) and to investments into R&D-heavy industries like pharmaceutics, biotech, and aerospace (Cassimon, Backer et al., 2011; Lo Nigro et al., 2014; Rodger, 2013).

Other noticeable changes occur in the first clusters of both networks that prevailingly comprise studies on the RO valuation of energy and environmental projects using formal models or simulations. However, the domain of natural resources exploration and production, formerly jointly covered with the energy sector and environmental issues, is no longer part of the first cluster in the Network II. Nevertheless, research in the second cluster comprising papers on natural resources interconnects with the first cluster. Despite the migration of this research field into the second cluster, the first cluster is the largest one in Network II. This can be explained by the amplified application of RO methods to renewable power generation technologies, like solar photovoltaic, wind energy, or bioenergy technologies (Li et al., 2015; Muñoz et al., 2011; Zhang, Zhou & Zhou, 2016). Some of these models allow for incentive policies, such as feed-in-tariffs (Boomsma et al., 2012; Ritzenhofen & Spinler, 2016; Zhang et al., 2016). Another subtopic vastly covered within the first cluster of Network II and underrepresented in Network I are infrastructure investments, such as energy storage and power transmission facilities (Chen et al., 2018; Nadarajah et al., 2015).

The Network I clusters "Corporate Finance" and "Competition & Preemption" merged into the second cluster of Network II, together with the aforementioned studies dedicated to natural resources exploration projects. Some papers on financing and investment decisions incorporate information asymmetry into RO models (Kumar & Yerramilli, 2018; Song & Yang, 2016). This is similar to the studies on RO games, which account for either complete or incomplete information (Grenadier & Malenko, 2011). The inclusion of the papers on natural resource exploration in this cluster could be partly explained by the fact that these papers consider commodity price volatility, which indicates a connection to financial markets.

Another notable observation refers to the Network I cluster "Managerial Behavior" that disappeared in Network II. Only some papers in Network II account for this topic (Andalib et al., 2018; Driouchi & Bennett, 2011).

5.2. Proposed research framework and future research

Based on the previous findings, we propose the research framework depicted in Fig. 5 as a holistic picture of the main topics discussed in RO research. The framework also allows for a detection of research gaps that need further attention and investigation.

Antecedents: At its core, RO theory deals with situations facing uncertainty. Analyzing the main antecedences allows researchers and practitioners to decide whether ROs can be applied. Prior research analyses the external uncertainties and endogenous factors essential for proper RO management. Apart from external uncertainties, current research also conveys project-specific risks. Future research is expected to further address the interdependencies between external environment and internal firm characteristics. Especially the set of unique firm resources and capabilities needed for effective RO implementation should be subject to further research. Different sources of uncertainties can be resolved with RO theory. The sources identified by prior research mainly refer to political and technological issues. Future research might include further issues.

Application areas: RO logic can be applied in areas such as capital budgeting, R&D projects, operations, strategic management, and policy evaluation. Much of the research is devoted to industry-specific applications, mostly in the energy business, mining industry, biotechnology, and cybersecurity. Future research can expand RO to other domains, as well as address new contexts for ROs and their differences. The emergence of new research clusters dedicated to construction projects and supply chains with production and manufacturing projects help support this notion. Research within such areas can be intensified in the coming years and emerge in separate research domains.

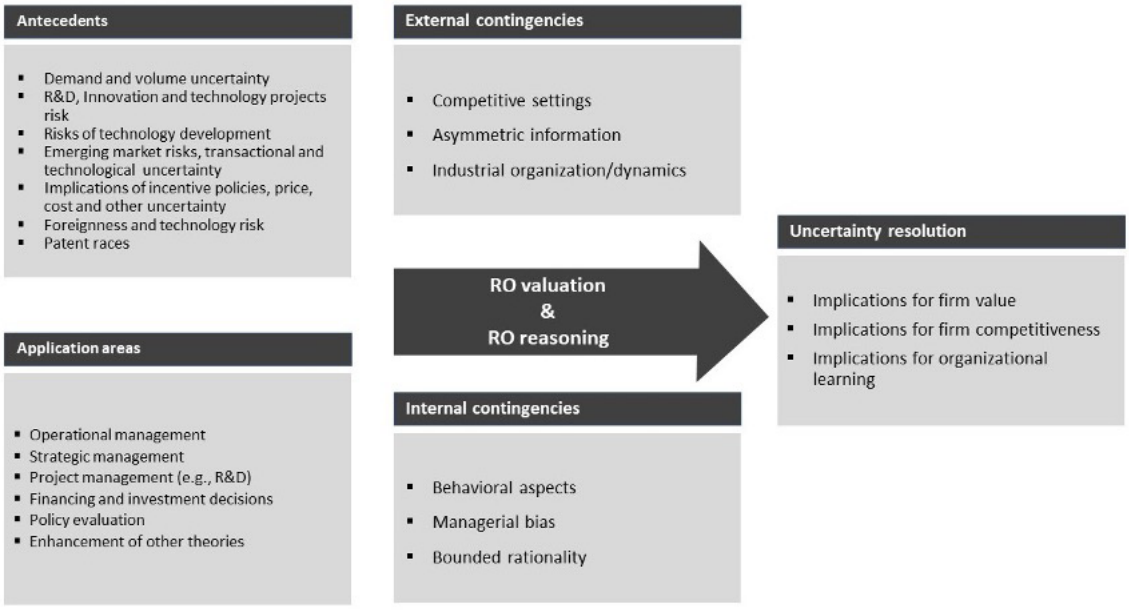

Fig. 5. RO Research Framework. Source: Own Elaboration.

The prevalence of RO research in the renewable energy and environmental context as well as the development of CSR research could indicate a long-term trend for research of sustainability issues. The findings from the performance analyses support this assumption, as the papers dedicated to investments in renewable energy belong to the twenty most cited papers per year despite their recent publication (Table 4). Papers from the research area “Environmental Science & Ecology” are currently the third most cited despite a relatively low number of total publications (Table 1).

Another perspective for RO research refers to the growing number of case studies, which implies an increase in applied studies. This is consistent with the assertion by Guedes und Santos (2016) that the RO approach cannot be generalized when it should have a value for practitioners.

RO valuation and RO reasoning: Sophisticated RO valuation models allow for decision-making. However, their complexity has already reached a level where application by practitioners is challenging. Future research might assess the applicability of valuation models in practice and strive for ways of simplification or automation. RO reasoning comprises the analytical nature of strategy, logic, or behavior. Practitioners have a more intuitive access to this. By pursuing RO reasoning, managers aim to limit risks while capturing future opportunities (Jahanshahi & Brem, 2017). Hence, future research might shift its focus to comprehensive analytical frameworks.

Internal and external boundary conditions: Boundary conditions might impact the RO process. The cluster “Management behavior” refers to the managerial biases, bounded rationality, and other behavioral aspects imposing limits on decision-making. The impact of competitive settings on the value of options imposes further limitations on RO management, particularly regarding investment timing and preemption possibilities. Accordingly, the combination of game theory and ROs can be further extended in future research. The issue of asymmetric information is spread among clusters. Future research can develop this topic in terms of exploring agency effects on RO decision-making.

Managing uncertainty: The goal of ROs is to deal with uncertainty that leads to higher value. Further research in this regard can provide insights into received value, as well as learning and competitive effects. Other topics for future research might be the value of gained experience during RO applications. Overall, the organizational effects of RO projects can be compared to other flexibility approaches. Due to the industry-specific focus of current research, more general findings on the theoretical level might increase the RO logic application in projects.

6. CONCLUSION

The purpose of this paper was to provide a holistic review on RO research in business and management. Against this background, we contribute to the extant body of RO literature by mapping previous RO literature, providing a comprehensive and systematic overview of RO research, and outlining future research avenues.

The number of publications on RO has been (unsteadily) growing from the beginning of the millennium. RO research is mostly subject to strategic management, operations, and energy research. This corresponds with the high number of citations by journals in these fields. The results of the bibliographic coupling depict the development of the RO research over two decades. A clear distinction of RO publications between operations and strategy is apparent. Our proposed research framework identified the most relevant themes regarding antecedents, application areas, external and internal contingencies, and ways to solve the uncertainty problem by RO valuation and RO reasoning (Fig. 5).

It can be expected that RO research will increasingly expand into other areas and will not focus on finding a universal one-fits-all solution. We argue that empirical settings might bring fruitful insights, whereas more differentiated approaches have to be developed to make RO application more efficient. As a tool for tackling uncertainty, RO have been applied to salient issues, such as sustainability, CSR, and renewable energy. New rising topics are likely to be addressed in future RO literature. In particular, we call upon future research to consider RO theory as an analytical tool for dealing with growing political and/or epidemiological turbulences impacting firms as well as interdependencies between internal and external uncertainties. To improve the practicability of RO application, complex RO valuation models can be simplified for their usage in managerial practice, especially making the models accessible for small and middle-sized firms. Additionally, a combination of ROs and other theories may be an interesting area for exploration. We suggest that future research should explore the following research questions (Table 4).

Table 4: Proposed future research themes.

What are the independencies between internal and external uncertainties as antecedents of the application of RO theory?
How can RO theory be applied to sustainability issues (such as renewable energy)?
What are the differences between various RO application areas?
How can RO valuation models be simplified for an easier application in managerial practice?
What are the opportunities to combine RO with other theories (such as game theory)?

Our study is subject to several limitations. First, the database choice limits the dataset. Future studies could consider additional databases such as Scopus, which has a broader scope of journals. However, as the Web of Science covers journals with an Impact Factor and it is sufficient to cover the most relevant journals, we believe that our choice is appropriate. Second, the selection criteria, subsequent manual selection of publications and further data clearing could have resulted in somewhat biased research outcomes. Therefore, we encourage future researchers to use a less restrictive narrowing down of the initial dataset. Third, bibliographic coupling may not always assign similar papers to the same cluster but to the ones developing competing perspectives. As a consequence, co-citation analyses and systematic literature reviews should be considered for future research to complement our findings. Fourth, the identification and interpretation of common research topics of the clusters are subjective. Thus, a combination of a quantitative bibliometric study and a qualitative literature review could be applied in the future (Vallaster et al., 2019). Fifth, bibliometric analyses reflect the current state of science and thus have to be repeated regularly, which we encourage future research to do in the near future.

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