THE RESISTIBLE RISE OF BAYESIAN THINKING IN MANAGEMENT: HISTORICAL LESSONS FROM DECISION ANALYSIS

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Abstract

This paper draws from a case study of Decision Analysis – a discipline rooted in Bayesianism aimed at supporting managerial decision making – to inform the current discussion on the adoption of Bayesian modes of thinking in management research and practice. Relying on concepts from the Science, Technology and Society field of study, and Actor-Network Theory, we approach the production of scientific knowledge as a cultural, practical and material affair. Specifically, we analyze the activities deployed by decision analysts to overcome the challenges of making a discipline built on Bayes' legacy scientifically acceptable, managerially relevant, and long lasting. As a novel contribution to the discussion on the 'Bayesian revolution', our study goes beyond institutional accounts of the legitimation of Bayesianism to highlight the role of politics and material artifacts in past and current attempts at importing Bayesianism. Our study also shows the importance of historical continuity in the promotion of Bayesian methods in management.

Key words: Actor-network theory – Bayes – Boundary objects – Boundary organizations – Decision theory – History of management science – Translation.

THE RESISTIBLE RISE OF BAYESIAN THINKING IN MANAGEMENT: HISTORICAL LESSONS FROM DECISION ANALYSIS

The current call to 'go Bayes' in management research (Kruschke, Aguinis, & Joo, 2012; Zyphur & Oswald, in press), and to reap the benefits of the Bayesian revolution currently underway in statistics (Efron, 2005,) may give management scholars familiar with decision making research a sense of déjà vu. In the 1960s, a group of US-based scholars offered to build on a Bayesian revival in statistics to develop a Bayesian approach to managerial decision-making. Despite noticeable achievements, such as the creation of a new theory of choice, called 'Bayesian Decision Theory' or 'Rational Choice Theory' (Savage, 1972 [1954]), and a new applied discipline known as 'Decision Analysis' (Howard, 1966; Raiffa, 1968), this early Bayesian research program has now declined, as illustrated by Figure 1 that reports the use of expressions related to 'Decision Theory' and 'Decision Analysis' in a vast number of published books since 1940.

INSERT FIGURE 1 ABOUT HERE

The trajectory of Decision Analysis over the last 50 years suggests that there is more to the current adoption of Bayes' ideas in management than discussions of their advantages over methods for testing models, such as the Null Hypothesis Significant Testing (NHST), developed by 'frequentist' statisticians (Zyphur & Oswald, in press). As shown by McKee and Miller (in press) and Orlitzky (2012), adopting Bayesianism may involve deeper institutional changes in academia. But the case of Decision Analysis is also a useful reminder that Bayes' ideas and their practical applications have been forgotten and rediscovered several times over the last two centuries (McGrayne, 2012). The ups and downs of academic interest in these ideas suggests it is necessary to reconsider the idea of a linear advance of science, and to assume instead that the production of scientific knowledge is a cultural, practical and material affair (Fleck, 1979 [1935]; Kuhn, 1962; Law, 2008b).

This paper builds on that assumption to look more closely at the activities that are at stake in promoting Bayesian ideas in management research. Our analysis is informed by insights from the field of Science, Technology and Society (STS), which has investigated how scientists 'make' science, and has developed a rich repertoire of concepts useful in understanding the creation and emergence of scientific disciplines (Law, 2008b; Zammito, 2004). Within STS studies, Actor-Network Theory (ANT) (Callon, 1986; Callon & Latour, 1981; Latour, 1986, 2005; Law & Hassard, 2005 [1999]) is one pathway for exploring how scientific theories and methods are constructed and adopted. ANT studies suggest that a 'good' theory or method does not diffuse by itself. They show that the adoption of a new theory (e.g., NHST) in academic circles and beyond involves continuous activities in order to align multiple actors' interests (Akrich, Callon, & Latour, 2002 [1988]; Callon, 1986) and to assemble material devices (Latour, 1987; Latour & Woolgar, 1986 [1979]).

Drawing on the historical case of Bayesian Decision Theory (Savage, 1972 [1954]) and its applied version, Decision Analysis (Howard, 1966; Raiffa, 1968), we investigate the activities involved in the import of Bayesianism in management research. We combine archival material with 32 interviews to analyze the establishment, in the Operations Research and Management Science (OR&MS) community, of a discipline rooted in Bayes' ideas. Our findings go beyond an institutional approach to the legitimation of Bayesian methods (McKee & Miller, in press; Orlitzky, 2012) to highlight the multiple activities in which Bayesians scholars have engaged to construct the scientific and practical relevance of their discipline. In particular, our study shows how some material and organizational elements have facilitated the adoption of Bayesianism in management. From this analysis, we derive lessons for the (re)current project to 'go Bayes' in management research. As a whole, our study shows the value of STS and ANT concepts to analyze the social and material practices that underlie any type of organizational and management research.

Our paper is organized as follows. We first set the stage for our analysis by relating the historical background against which Decision Analysis emerged. We then present the core assumptions and concepts from STS and ANT that we rely on in our case study. The following section presents our approach to gathering and analyzing data, and finally we describe our findings and discuss their implications.

HISTORICAL BACKGROUND: THE UPS AND DOWNS OF BAYESIANISM

The Resistible Rise of Bayes' Rule

Our current knowledge of what became 'Bayes' rule' comes from the posthumous publication in 1763 of the Reverend Thomas Bayes' manuscript by his friend Richard Price, who chose to publish it for theological reasons – to him it provided a proof of the existence of God (Bellhouse, 2004; Stigler, 2013).[1] In this essay, Bayes explains how knowledge should change to account for new evidence and offers a method for evaluating *inverse probability*. In more modern statistical parlance, Bayes proposed a rule to update the 'prior' probability (or belief) assigned to a hypothesis in light of new evidence, and to compute the 'posterior' probability. Bayes' ideas were refined by Pierre Simon de Laplace who used modern notations (Zabell, 1989). Besides providing a rule to revise probabilities, Bayes added a note stating that, under conditions of ignorance about the prior probability distribution, it is reasonable to assume that every possible a priori event (or hypothesis) should be given equal probability. For instance, in a binomial case, it is reasonable to assume odds of 50-50 under conditions of complete uncertainty. Bayes' equal prior assumption has generated (and still generates) much passionate debates among statisticians, as it means that when we do not know the probability of events, we should give the same probability to every possible event.

Bayes' rule was widely taught throughout the 18th and 19th centuries, and used by mathematicians to solve a number of problems (Edwards, 2004; Fienberg, 2006). However, the fact that Bayes' method was dominant in those centuries does not mean that contemporary mathematicians were 'Bayesian' in the sense that they all adhered to a 'subjective' interpretation of probability. In fact, the two interpretations of probability, according to which a probability either represents a "certain measure of our knowledge" or measures "…the possibility of things independently of our knowledge", had yet to be fully spelt out at that time (Daston, 1994: 331; Hacking, 1975). In the late 19th century, however, the diverse arguments that mathematicians used to discuss the nature of probability converged to distinguish a 'subjective' from an 'objective' meaning of probability. These labels had important implications, as they reflected a nascent opposition in scientific circles between the "world of things" – wherein reality and truth lie – and the "world of the mind", the realm of subjectivity and non-scientific knowledge (Daston, 1994: 341). So the word 'subjectivity' gained negative connotations in this period, as it designated the exact opposite of what philosophers such as Comte sought: "a capricious, arbitrary quality of the mind, responsible for not only inter- but also intra-individual differences" (Daston, 1994: 342).

In the early 20th century, as a new statistical paradigm emerged – the frequentist approach – the two faces of probability diverged (Hacking, 1975). Frequentists, such as Pearson, Fisher and Neyman who laid the foundations of modern statistics (e.g., NHST), explicitly redefined probability as an 'objective' number, i.e., the limit of the relative frequency of an event that can be observed in a large number of trials. They also tended to conflate the 'subjective' meaning of probability, according to which a probability is a number that captures a 'subjective' degree of belief, to Bayesianism, and campaigned fiercely against Bayes' assumption of equal prior (Edwards, 2004; Fienberg, 2006). Fischer (1925), in particular, affirmed his conviction that "the theory of inverse probability is founded upon an error, and must be wholly rejected" (as quoted by Bellhouse, 2004: 36), while Neyman proclaimed Bayes' equal prior assumption to be "illegitimate" (Perks, 1947: 286). After the Second World War, Bayes' ideas were virtually banned from most statistical departments, which were by then generally run by frequentists. This ban seems paradoxical, given that Bayes' rule had proved it usefulness during the Second World War by helping US Operational Researchers to detect U-boats and Alan Turing to crack the Enigma code. But, as these applications were classified secrets, after the war Bayes' rule was "buried again" (McGrayne, 2012: 61-86).

The Challenges of Importing Bayesianism into Management in the 1950s and 1960s

It was into this context that a neo-Bayesian movement (Lindley, 1953, 1957; Raiffa & Schlaifer, 1961; Savage, 1972 [1954]; Schlaifer, 1959) re-emerged in statistics in the 1950s (Fienberg, 2006), stimulated by the works of Ramsey and de Finetti among others (De Finetti, 1989 [1931]; Ramsey, 1931). But promoting Bayesian ideas in management research was problematic at the time for three main reasons. First, Bayesians were a minority, and frequentists still regarded the assumption about the prior probability distribution as a grave threat to science (McGrayne, 2012), so relying on it could only harm, if not undermine, the academic legitimacy of the promoters of Bayes' ideas in management.

Second, early Bayesian scholars (such as Jimmy Savage) were unwilling to apply their theory to any kind of practical problems. As John W. Pratt later recalled, in the 1950s Bayesian and frequentist statisticians kept publishing "too many minor advances extracted from real or mythical problems, sanitized, rigorized, polished, and presented in pristine mathematical form and multiple forums" (McGrayne, 2012: 139). In addition, earlier applications of Bayes' rule to solve practical problems had either been forgotten or were still classified secrets, and Bayes' abstract principles had to demonstrate their usefulness for practitioners in a context in which computers were almost non-existent.

Third, the multiple ups and downs of Bayes' rule since its publication in 1763 suggested that one could not safely bet on the future of a field built on principles that had been subjected to such intense controversies, and which had, at times, totally faded from academic sight. The difficulties of bringing Bayes' ideas into management research and practice suggest that persistence would be crucial to any attempt at importing them into academia.

In light of the eventful history of Bayes' rule, it appears that, to analyze how management scholars have addressed this triple challenge of making Bayes' ideas scientifically acceptable, practically relevant and persistently used, we should reconsider the idea of the linear progress of science, and focus instead on the making of science. STS and ANT studies provide useful concepts and assumptions with which to conduct such an inquiry.

CONCEPTUAL BACKGROUND

A Science, Technology and Society Analysis of Bayesian Decision Theory

After the Second World War and the experience of the nuclear bomb, intellectuals came to consider that the links between science and technology were both indissoluble and ethically questionable (Law, 2008b). It was in this context that scholars from various disciplines, such as the history of science, the philosophy of science and cultural sociology, became interested in the science-technology nexus, giving rise in the 1960s to what is known today as the STS field of study (Zammito, 2004). Being interdisciplinary in nature, the STS field draws on a wide range of intellectual resources, but Kuhn's (1962) book, *The Structure of Scientific Revolution*, acted as a catalyst for its development (Law, 2008b). Like Kuhn, STS scholars comprehend science as a cultural activity associated with specific practices, rather than as a set of cognitive activities solely focused on theory or hypotheses testing. In line with Kuhn, STS scholars also rely on case studies to analyze the making of science (Law, 2008b). We introduce below some of the distinctive assumptions that STS scholars have developed to analyze the links between science, technology and society. Knowledge of these assumptions is needed to understand our analysis of how Bayesianism was introduced into management.

Bloor's Principle of Symmetry. David Bloor work is central to STS studies: a sociologist of science, he challenged the assumption that "true (or rational) beliefs are to be explained by reference to reality, while false (or irrational) beliefs are explained by reference to the distorting influence of society" (Bloor, 1999: 84). Instead, Bloor (1976) advanced the "principle of symmetry" according to which sociologists should apply the *same* explanatory principle – a sociological explanation – to both theories' failures *and* successes. In essence, he contends that scientific activities can be subjected to sociological enquiry, and invites sociologists to study *how* scientific knowledge comes to be accepted as true, or rejected as false. So this assumption reverses the accepted relation between truth and causality: instead of assuming that a scientific theory is accepted *because* it is 'true' (or not yet 'rejected'), Bloor suggests that a scientific theory becomes 'true' *when* (or *because*) it is accepted.

In concrete terms, suppose the current project of 'going Bayes' in management succeeds, STS scholars would argue that this success results not so much from the capacity of Bayesian methods "to estimate models when traditional estimations fails" (Zyphur & Oswald, in press) as from the continuous activities – such as special issues on Bayesian statistics in leading journals or the organization of symposia at conferences – that Bayesian scholars operating in management research had deployed to enlist their colleagues' support for their project. Similarly, STS scholars would explain the dominance of NHST in management as resulting from social (e.g., ingrained habits), material (e.g., availability of software packages) and political (e.g., gate keeping) practices rather than from its 'scientific value'.

The Generalized Principle of Symmetry. Callon and Latour, two sociologists who have contributed to the development of Actor-Network Theory, expanded Bloor's program of research by introducing the "generalized principle of symmetry" (Latour, 1993 [1991]: 94-

97). For them, Bloor's principle of symmetry is not enough, as it assumes that 'the social' pre-exists and can account for scientific activities and technologies. Sociologists of science relying on Bloor's principle typically hold that science and technology are 'socially constructed' and that 'social' factors shape technologies. Against this assumption, Callon and Latour (1981) argued that both social and technical elements should be explained simultaneously: in effect, they 'symmetrized' the social and the technical factors by asserting that these factors co-produce themselves. For scholars who adopt the generalized principle of symmetry, what matters is to understand how *both* human (e.g., social factors) *and* non-human entities (e.g., material objects) are assembled together to form an 'actor-network'. This generalized principle of symmetry was the starting point for the development of Actor-Network Theory (Callon & Latour, 1981; Latour, 2005; Orlikowski, 2007).

Relational Materiality. Actor-Network Theory is one pathway to study innovation and knowledge creation processes in science and technology. Despite its name, ANT has almost nothing to do with social network theory as developed by Burt (1995) or Granovetter (1985), nor is it a unified theory (Latour, 2005; Law, 2008b). Rather, the ANT acronym is an umbrella for sociological works that share a *relational materiality assumption* according to which "entities achieve their form as a consequence of the *relations* in which they are located" (Law, 1999: 4, *emphasis ours*). This assumption, which extends insights from semiotics (i.e., the study of sign and symbols and their use; cf. Greimas & Courtés, 1982 [1979]) to all sorts of non-semiotic entities, means that entities do not have pre-existing properties but that their properties are produced *in* and *by* their *relations* with one another (Law, 1999, 2008a). An important implication of this assumption is the need to consider non-human entities when analyzing social situations (Latour, 2005; Law, 2008b).

Accordingly, ANT scholars do *not* ask 'why things happen' but rather 'how do things arrange themselves', and "*how* the materials of the world (social, technical, documentary, natural, human, animal) get themselves done in particular locations [at a given point in time] in all their heterogeneity" (Law, 2008b: 632). So ANT scholars aim to follow how scientific facts, concepts and theories emerge from a construction process that consists of the 'assembling' and 'disassembling' a set of heterogeneous elements referred to as an 'actor-network' (Alcadipani & Hassard, 2010; Callon & Latour, 1981; Latour, 2005). For instance, an ANT account of the construction of probability theory would show how such a theory came to exist in the 17th century thanks to material devices such as 'honest' six-faced dices (David, 1955), the social practice of gambling in the French court society and in England, and the epistolary relationships between mathematicians (Fermat, Laplace, Pascal) and noblemen (the Chevalier de Moivre, the 2nd Earl Stanhope) interested in solving problems of chance (Bellhouse & Genest, 2007). Building on these elements, ANT scholars would explain that a complex set of relations between human beings interested in games of chance, material artifacts (e.g., dices, playing cards) and a set of socially situated practices (e.g., gambling) together 'brought into being' the concept of probability.

A Tool-Kit for Studying the Assembling of Decision Analysis

Five concepts are relevant for investigating how Bayesian Decision Theory and its applied version – Decision Analysis – were brought into being: namely translation, trial of strength, black box, boundary object and boundary organization. We introduce each of them in turn.

Translation. Callon and Latour (1981) do not use the word translation in its linguistic sense, but to describe the activities by which the interests of human and non-human entities are actively redefined in order to be aligned with each other, and hence make the assembling of an actor-network possible.

> [By] translation, we understand all the negotiations, intrigues, calculations, acts of persuasion and violence, thanks to which an actor or force takes, or causes to be conferred on itself, authority to speak or act on behalf of another actor or force. (…)

> Whenever an actor speaks of 'us', s/he is translating other actors into a single will, of which s/he becomes the spokesman. (Callon & Latour, 1981: 279)

The process of translation involves actors promoting a project (e.g., the diffusions of Bayes' ideas in management science) 'enrolling' various entities (e.g., reviewers, software producers) and 'aligning' their interests by providing them with a social role or identity and a framing of a problem (e.g., presenting 'Bayesian estimation' as a relevant solution to the problem of inference). If the entities accept these definitions of their interests, roles and problems, they become 'allies' (e.g., 'Bayesian management scholars'), and the project becomes an "obligatory passage point" that channels all the interests in one direction and through which all actors must pass (Callon, 1986). The scientific entrepreneurs can therefore 'speak in the name' of their allies and an actor-network made of these human and non-human entities can be 'assembled'. Hence, translation is an inherently political process, as "to speak for others is first to silence those in whose name we speak" (Callon, 1986: 216) and its results are "situation[s] in which certain entities control others" (Callon, 1986: 224).[2]

However, maintaining an 'assemblage' necessitates continuous work to align the interests of all the actor-network's entities. Translation is a never ending endeavor, as the alliances that form an actor-network can be fragile, and their reconsideration may lead to it being disassembled. Callon (1986) famously illustrated this feature of translation in a study that showed how a group of marine scientists helped French fishermen fight against the decline in the population of scallops in St Brieuc Bay. The researchers' program consisted of importing techniques that had proved successful in Japan. It also involved redefining the roles and goals of various entities involved in the project – such as the scallops, the fishermen and the researchers – in order to align them. After multiple, difficult negotiations, all entities accepted the redefinitions of roles and goals, an actor-network assembled, and the population of scallops stopped declining. However, after a while, the actor-network disassembled, as the fishermen questioned the redefinition of roles and the scallops changed their behaviors. This fragmentation of their alliances prevented the restocking of scallops. The concept of translation allows describing such activities whereby academics such as Bayesian scholars form alliances with human and non-human entities to advance their projects.

Trials of Strength is another ANT concept that can help describe how new scientific paradigms are enacted: the notion refers to situations where scientists aim to convince their peers that their project is scientifically valid and useful (Latour, 1987; Yonay, 1994). Such situations are usually characterized by intense debates during which a research paradigm's key assumptions are challenged and have to be defended. The debate between Harold Jeffreys, an early Bayesian promoter, and the frequentist Ronald A. Fisher in the 1930s and 1940s was a notable trial of strength in the history of statistics. The authors contested with each other in a succession of articles, comments and rejoinders in the Royal Society's *Proceedings* that lasted for two years, up to the point where its editors had to stop them (McGrayne, 2012: 53-58). Jeffreys subsequently wrote a landmark book, *The Theory of Probability*, in which he explained how to apply Bayes to the analysis of scientific problems. Fisher replied, saying that Jeffreys had made "a logical mistake in the first page which invalidates all the 395 formulae of his book" (Box, 1978: 441). Although this debate ended inconclusively, Fisher's domination was ultimately consolidated, in part due to the fact that, at that time, physicists developing quantum mechanics were using frequencies in their experimental works, and hence gave academic credibility to the frequentist theory of probability (McGrayne, 2012). This suggests that the ability to link a research program (e.g., frequentism) to an established or prestigious field of study (e.g., physics) can be an important resource during a trial of strength.

Black boxes. For ANT scholars, the term 'black box' does not refer to the unknown psychological processes that may cause of phenomenon. This notion refers to a scientific theory, or a set of methods, that has become well accepted by the scientific community, to the point where it is no longer questioned (Callon & Latour, 1981). This concept reveals:

> …the way scientific and technical work is made invisible by its own success. When a machine runs efficiently, when a matter of fact is settled, one need focus only on its inputs and outputs and not on its internal complexity. Thus, paradoxically, the more science and technology succeed the more opaque and obscure they become. (Latour, 1999: 304)

Thus, theories that have won 'trials of strength' are likely to become 'black boxes' (Latour, 1987; Yonay, 1994). Bayes' rule, for instance, was a black box throughout the 19th century, when it was used without being questioned by many mathematicians. However, black boxes are never fully closed, and may be re-opened (Callon & Latour, 1981), as in the case of Bayes' rule, when Fisher (1915) challenged the validity of Bayes' assumption about the 'prior probability distribution', opening a debate between Bayesian and frequentist statisticians that is still ongoing (Edwards, 1954, 2004; Zyphur & Oswald, in press).

Boundary Objects. What makes a material device a 'boundary object' is *its use* by groups of people operating in different social worlds in order to undertake some common activity (Star & Griesemer, 1989). Star and Griesemer (1989) showed, for instance, that the creation of Berkeley's Museum of Vertebrate Zoology involved developing 'repositories' that were used collectively by many actors from different social worlds (e.g., scientists, amateurs, trappers who helped collect animals) to develop collections of species with the aim of 'conserving California and its nature'. These repositories operated as "boundary objects" (p. 393), because they helped enroll actors with highly diverse ranges of practices, motivations and viewpoints, and contributed to aligning their interests. In short, they supported the work of translation that was needed to create the Museum. Generally, material devices which facilitate translations between actors' viewpoints or interests and which act as interfaces between heterogeneous social worlds can be described as boundary objects (Lamont & Molnár, 2002). Boundary objects are important for our inquiry, as they help analyze how

Bayesian scholars concretized and stabilized their actor-network by facilitating the coordination between the human and non-human entities that were part of it.

Boundary Organizations. STS scholars have recently extended the concept of boundary object to organizations, after they observed that entire organizations may serve as boundary objects in some cases (Guston, 2001). A boundary organization is an organization which facilitates the collaboration of actors belonging to distinct social worlds such as scientists and politicians, by providing those actors with the right set of incentives (Guston, 2001). For Miller (2001), the UN Intergovernmental Panel on Climate Change acts as a boundary organization because it "…meditate(s) between the institutions of 'science' and the institutions of 'politics' (…)" (p. 482) and provides incentives that facilitate effective communication between actors located in different social worlds. Another important property of boundary organizations is that they are more stable than boundary objects, and so can stabilize ongoing collaborations between scientific and non-scientific actors (Miller, 2001).

Organizations located at the boundaries between science and non-science social worlds can be especially useful in for developing a new scientific paradigm, as such projects usually involve assembling an increasing number of heterogeneous entities, which results in scaling-up the actor-network. For instance, advancing Bayes' ideas in management research may entail obtaining research grants from government bodies, as well as securing the involvement of organizations, so that their employees accept participating in surveys or experiments. Such collaborations might be difficult to enact, as each actor has its own interests and motivations (Bartunek & Rynes, in press). The creation of organizations that provide appropriate incentives to individuals involved in different systems of accountability (e.g., sales for managers, publications for scholars) can help overcome these tensions.

As a whole, works from the STS and ANT fields analyze scientific discipline-building as a cultural, political, and material process, and provide a rich vocabulary to describe the activities underlying the making of any discipline. Such works consider scientists as being engaged in the continuous assembling of relations between heterogeneous entities, and pay special attention to how they stimulate the interests of these entities to enroll them in their actor-network. This continuous process of *translation* may involve building *black boxes* that facilitate the acceptance of theories and methods; engaging in *trials of strength* to defend the value of a given research program; assembling *boundary objects* which help entities from heterogeneous social worlds to cooperate together; and sometimes also mobilizing *boundary organizations* that can align diverse participants' interests, and help grow and stabilize the actor-network. Accordingly, to 'go Bayes' – to establish a new Bayesian discipline in management science – means constructing, developing and consolidating an actor-network composed of an heterogeneous set of actors and objects that cut across diverse social worlds.

METHODS AND DATA

Following the STS and ANT methodological tradition (Law, 2008b), we draw from a case study, the rise of Decision Analysis from the 1950s, to investigate the activities engaged in by some scholars in attempting to import Bayes' ideas into management research and practice.

Data Collection

To reflect our interest for historical analysis (Rowlinson, Hassard, & Decker, 2014), we collected historical data on the Decision Analysis field. We collected a set of documents from the leading professional association in the field – the Decision Analysis Society (DAS) from the Institute for Operations Research and the Management Sciences (INFORMS). We accessed past issues of *Decision Analysis Today: The Newsletter of the INFORMS DAS* for the period 1992-2009. We also consulted other secondary data, including historical works on Bayes' rule (Bellhouse, 2004; Fienberg, 2006, 2008; McGrayne, 2012), personal accounts of decision analysts (Howard, 1980, 2007; Raiffa, 2002, 2006), two survey papers on Decision

Analysis applications (Corner & Kirkwood, 1991; Keefer, Kirkwood, & Corner, 2004), as well as one doctoral dissertation focused on decision analysts' interventions in organizations (Bond, 1999). These documents were all useful in capturing the reflections of decision analysts on their practice and on the development of the discipline.

We combined these archival data with 32 research interviews with decision analysts, both academics and practitioners. Because we were interested in the discipline's historical development, we sampled actors who had been active in the Decision Analysis field at different periods of its development, which led us to contact such 'historical' figures as Ralf Brown, Ralph Keeney, John Pratt, Howard Raiffa, and Bernard Roy, as well as individuals still active in the academic or practitioner communities (e.g., Bruce Judd, Philip Beccue), as Table 1 shows. Our semi-structured interviews lasted between 37 and 143 minutes, and all were tape-recorded and transcribed. We asked the participants to introduce themselves to gather information about their background, to comment on the success of Decision Analysis, and to recount examples of applications of Decision Analysis in which they played a role. This material allowed us to obtain insiders' views on the construction of Decision Analysis as an academic discipline and a practice, and to identify the areas of resistance to their project.

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Data Analysis

To investigate the translation efforts underlying the development of Decision Analysis over a 50-year period, we combined qualitative (Guba & Lincoln, 1994; Yin, 2009) and longitudinal data analysis methods (Langley, 1999), and followed a three-stage data analysis process. The first stage followed an historical approach, using a 'narrative' strategy (Langley, 1999), to reconstruct a comprehensive story of the Decision Analysis discipline, and clarify its development stages. We built a chronology an isolated the key phases of Decision

Analysis development. We then combined this chronology with our interviews data and the longitudinal secondary data to set out a narrative of the history of the discipline.

Second, relying on concepts from ANT and STS, we searched our historical account to identify episodes of translation during which decision analysts had faced various forms of resistance. We looked for trials of strength by identifying occasions when the work of translating Bayesian Decision Theory axioms into stabilized forms of knowledge or tools was challenged. We also focused on material devices used in the translation process, aiming to uncover the roles played by black boxes, boundary objects and boundary organizations in constituting Decision Analysis.

Third and finally, we used our interviews and secondary data to analyze how decision analysts, through their translation work, have faced the three aforementioned challenges of making Bayes legacy *scientifically acceptable*, *practically relevant* and *persistently used in academia and managerial practice* since the 1950s. We organize our findings to explain how these early Bayesians scholars endeavored to maintain, expand and consolidate the actor-network in order to address these three challenges.

BRINGING BAYESIANISM INTO MANAGEMENT RESEARCH

Disciplining Bayesianism to Make it 'Scientifically Acceptable'

Disciplining Subjective Probability. Despite the prevalence of frequentist ideas, some influential statisticians in the mid-1950s, such as Savage, remained deeply convinced of the value of the Bayesianism, and provided the foundations of a new theory of decision making based on Bayes' ideas and the concept of subjective probability (Pratt, Raiffa, & Schlaifer, 1964; Raiffa & Schlaifer, 1961; Savage, 1972 [1954]; Schlaifer, 1959). Establishing a subjectivist Bayesian approach to decision-making proved challenging and led to a trial of strength, as most contemporary statisticians were "violently opposed to using judgmental probabilities" (Raiffa, 2002: 181).

The fact that Bayesianism, especially in its subjective variant, was seen as a threat to sound scientific knowledge is clear in most writings of those mathematicians opposed to it. For Howson and Urbach (1989), "[t]he sharpest and most persistent objection to the Bayesian approach has been that it treats certain subjective factors as relevant to the scientific appraisal of theories" (p. 11). The prevalence of this vision of science early in the 20th century might explain why leading subjectivist figures – such as Ramsey and de Finetti – offered *operational* definitions of the concept of subjective probability that linked the concept to a simple measure: the betting quotient. For de Finetti, a probability was "derived as the ratio between the sum of money an individual would be ready to bet on the occurrence of a certain event in exchange for a given prize and the prize itself" (Feduzi, Runde, & Zappia, 2014: 3). Thus, quite ironically, while de Finetti is known for the claim that "probability does not exist" (1974: x) – by which he meant that it only exists subjectively, in the minds of individuals – much of his work has been dedicated to bring this entity into being, to turn it into a measurable, scientific concept – in short to 'discipline' it.

Besides establishing the concept of subjective probability as measurable, a broader challenge was to provide it with sound statistical foundations. It was Savage who performed this work, by establishing the axiomatic basis of the new Bayesian theory of decision under uncertainty in his 1954 book *The Foundations of Statistics*. The fact that he provided a "non-frequentist alternative to the Kolmogorov axioms" (Fienberg, 2006: 11) illustrates the subtlety of the translation work Savage performed: rather than fighting against the "widely accepted axiomatic concept" (Savage, 1972 [1954]: 3) of probability that Kolmogorov had established, he showed that subjective probabilities share the same mathematical properties as objective probabilities. In providing an axiomatic structure to Bayes' ideas, he spared potential allies who might find the subjectivist notion of probability useful, yet would not be prepared to give up on Kolmogorov's (1933 [1950]) mathematical foundations. This move consolidated Bayesianists' position in the on-going trial of strength against frequentist statisticians, as they could rely on the same 'black box' of Kolmogorov's axioms.

Converting to Bayesianism. Adopting the subjective meaning of probability often represented a difficult move, even for those who became the most active spokespersons for Bayes' ideas (e.g., Savage, Lindley…), as it usually marks a profound change in their beliefs about inference, and more generally about the sources of knowledge (McGrayne, 2012; O'Hagan, 2013). For instance, Savage recalls that it took him "a year or two to make the transition…" and to fully recognize the value of the Bayesian approach (Fienberg, 2006: 19). In the second edition of his book, he even employs a religious term, saying that he became Bayesian after "he lost faith in the devices of the frequentistic schools…" (Savage, 1972 [1954]: iv). In the same vein, Raiffa explains that becoming a Bayesian was a "religious-like conversion", and that after he 'converted' to Bayesianism, he became a proselytizer:

> [I] too got religion and gained the necessary conviction that the subjectivist school was the right school – certainly for business decisions – and [I] came out of the closet and began preaching the gospel according to Bayes' disciples. It was now 1958, and we [Raiffa and Schlaifer] were convinced that our mission was to spread the gospel. (Raiffa, 2002: 180)

This religious vocabulary suggests that accepting the subjective concept of probability has strong implications, at the philosophical, and even at the metaphysical levels (Ellis, 1842). The move involves reconsidering the ontological status of the notion of probability that is, the very meaning of *what* a probability *is* (Hacking, 1975). Accepting the concept of subjective probability equates to accepting a different definition of what reality is, a process that resembles a conversion to a new religious cult, and is likely to create phases of 'cognitive dissonance', as converts have to forgo their previous firmly-held beliefs about the nature of reality (Festinger, Riecken, & Schachter, 1956). The difficulty involved in such changes may explain the slowness of the first Bayesian leaders' conversions, the resistance frequentist statisticians mounted against the notion of subjective probability, and the fact that converting actors ignorant of frequentism proved to be easier than converting hard-core frequentists.

Moving from Decision Theory to Decision Analysis. Although Decision Theory emerged between the mid-1950s and early 1960s, it was not until the late 1960s that an academic discipline was established in the management science community, thanks to the progressive enrollment of academics located beyond the statistical departments where the opposition against Bayesianism was fiercest. In fact, many of the first teaching programs incorporating Bayesian Decision Theory were developed in business schools where Decision Analysis leaders (such as Raiffa) met student audiences less reluctant to adopt a decision making approach associated with subjective probabilities, which encouraged them to further develop the Bayesian theory of choice. For instance, Raiffa mentioned in his interview that the subjective interpretation of probability seemed more natural to his Harvard Business School students than to those in Columbia University's Department of Statistics, his former base. The Bayesian theory of choice fitted better with business students' forward-looking approach to decision-making, and their conception of business environments as associated with uncertainty, and the presence of both threats and opportunities. Thus, at a time shaped by Gordon and Howell's (1959) report, business schools offered a context that welcomed the newly founded discipline, which – despite its subjectivist flavor – was nonetheless based on sound statistical foundations (Savage, 1972 [1954]). The Bayesian actor-network also extended to schools of economics – Savage's theory forms one of the foundations of contemporary economics – and, in schools of psychology, where some scholars, such as Edwards actively promoted Bayesianism (Edwards, 1954; Phillips & von Winterfelt, 2007).

Inevitably, the extension of the Bayesian actor-network required further translation work, as was evidenced by its change of name, from Decision Theory to 'Decision Analysis', which is defined as 'applied' Decision Theory. This label, attributed to Howard (1966), was quickly adopted by Raiffa in his 1968 book, and had become the accepted name for the field by the late 1960s (Raiffa, 2002: 182).

The translation work undertaken by Raiffa and his colleagues at Harvard University, and by Howard at the Stanford University School of Engineering was exemplary. Raiffa promoted an applied version of Bayesian Decision Theory directed primarily at managers by writing influential books (Raiffa, 1968), by organizing research seminars – such as the 'Decision under Uncertainty' seminar series (with help from Pratt), which ran from 1961 to 1964 – and by developing new courses where he could teach the pillars of the emerging discipline (Raiffa, 2006). At the same time, at Stanford University, Howard was actively enrolling scientists working in the field of systems science and cybernetics, as shown by the series of papers he published between 1965 and 1970 (Howard, 1965, 1968, 1970). Not only did Howard propose the new 'Decision Analysis' label for the emerging discipline to better reflect its applied nature and so appeal to engineers, he also combined Decision Theory with system analysis so as to enable Decision Theory to deal with large-scale problems. Finally, he captured the interest of engineers by showing how existing decision methods failed to consider a whole class of problems that were becoming prevalent in firms (Howard, 1968).

Despite the reluctance of their colleagues operating in related fields, decision analysts' efforts to mobilize a Bayesian approach to decision making in academia were fruitful, and resulted in the emergence of a Bayesian actor-network, as evidenced by the development of new academic curricula offering courses in Decision Analysis in US Universities in the 1960s and 1970s (McGrayne, 2012). Thus "Decision Analysis became part of the core curriculum for the Master's Degree in Public Policy" at the Kennedy School of Government formed in 1966 (Raiffa, 2002: 43), and at the same period, the Kellogg School of Management's MBA introduced a Decision Analysis program. The growth of this Bayesian actor-network was also evident in the fact that the management science community officially welcomed Decision Analysis in the early 1970s:

> When *Management Science* first created departments in 1969, there was a decision theory department with H.O. Hartley serving as department editor. In March 1970, the name of the department was changed to 'Decision Analysis', reflecting the new terminology advocated by Howard (1966; 1968) and Raiffa (1968). (Smith & von Winterfeldt, 2004: 563-564)

By 1980, the Bayesian actor-network included more and more entities: new academic associations were created (e.g., the Decision Analysis Special Interest Group of INFORMS) and more Decision Analysis papers were published. Figure 2 shows how the number of Decision Analysis publications in major OR&MS outlets increased between 1955 and 1985, showing the growing interest in Decision Analysis over this period.

INSERT FIGURE 2 ABOUT HERE

Managerializing Decision Analysis to Enroll Practitioners

Enrolling practitioners was a major element in the trials of strength in which Bayesian scholars opposed frequentists, which some Decision Theory leaders saw as necessary to convince reluctant academics of its 'practical' value (Raiffa, 2006; Pratt, interview).

> Even statisticians who were on our side in the philosophical debates about the foundations, were skeptical about implementing it. They felt: (1) the subjective (Bayesian) approach is all too complicated, and (2) real experts won't cooperate by giving judgmental information. (Raiffa, 2002: 179-180)

Besides this aspect, enrolling practitioners was also a genuine motivation for most decision analysts, who had become convinced of the value of a Bayesian approach to decision-making in their interactions with practitioners. After all, managers often need to make decisions without sample data – for instance, when launching radically new products: frequentist methods of inference based on the repetition of standardized phenomena were of little help in such contexts.

> I had time to study case after case in the MBA repertoire of cases, and it was crystal clear that managers galore needed some systematic way of thinking about their decision problems, which were overwhelmingly concerned with uncertainties that needed the judgmental inputs of managers. The [frequentist] statistical paradigm was out of kilter, was hobbling. A typical business decision problem might involve several uncertainties, and some of them required the judgments of production managers or marketing

> specialists or financial experts with no possibility of accumulating sampled evidence. To force those problems into a statistical decision format was too cumbersome. (Raiffa, 2002: 181)

As early as 1962, Raiffa and Schlaifer interacted with Dupont executives with the aim of capturing their expert judgments (McGrayne, 2012: 150; Raiffa, interview). In the same vein, Howard (2007) recalls the idea of developing an applied version of Bayesian Decision Theory occurred during a course at a General Electric nuclear power station, when an engineer following the course outlined a problem and asked him "if what [they] were discussing in class could help solve [it]" (p. 37). Howard offered to help, and they worked on the problem together for 8 months. Rex Brown told us in his interview that his first attempts to apply Bayesian Decision Theory in real business contexts emerged from the personal connections with practitioners that he developed through his teaching activities.

In order to demonstrate the practical value of a Bayesian approach to decision making, decision analysts tried to enroll practitioners of all kind – energy company engineers, medical doctors, military engineers, top managers, and R&D and asset managers. Concretely, they embarked on a work of translation, which consisted in turning Decision Theory's axioms into tools that practitioners could use in their daily practice. But this task was not straightforward, and decision analysts had to rely on a variety of tactics to enroll managers.

Selling Decision Analysis to Managers. Crossing the boundary between academia and practice usually involves knowledge transfer activities, such as publishing in outlets positioned at the interface between these two communities (Rynes, Giluk, & Brown, 2007). Conscious of the importance of this type of activity for the success of their project, decision analysts published in managerially oriented journals: for instance, Ulvila and Brown (1982) tried to enroll new practitioners by providing them with all sorts of arguments about the value of Decision Analysis in a paper they published in *Harvard Business Review*. They explained that decision analysts had refined their art in order to be "more flexible and modest in how to make the[ir] basic decision theory formulation[s] useful to managers" (p. 130). They also suggested that decision analysts were now able to conduct analysis more quickly than in the 1970s, and that the process was less disruptive and more personalized than before. Ultimately, the authors claimed that Decision Analysis had become "an accepted part of the staff services that major corporations draw on routinely, much as they do industrial psychology, cost analysis, marketing research, and economic analysis" (p. 130) in many organizations, and provided a series of illustrations. All these arguments were designed to help enroll new companies in the Decision Analysis project.

Even when promoting Bayesianism in academia, decision analysts made sure that their newly created journals – such as *Decision Sciences* (1970) or *Omega* (1973) – welcomed short cases reporting experiences of implementing Decision Analysis in organizations. This keenness to engage with practitioners took a step forward with the creation in 1971 of a new journal, *Interfaces*, which intent was "…to be informative, easy to read, brisk (for busy managers), topical, relevant, and professional" (Norden, 1970: 1). This journal, which Dyer claimed in interview had played a crucial role in exposing practitioners to Decision Analysis, included a 'Practice Abstracts' section, which carried descriptions of real Decision Analysis applications, aimed at turning practitioners into allies to increase the viability of their project:

> Basically the idea was to try to get people from industry and government and so forth … who had no incentives to publish like academics do (…) to write up just short descriptions with considerable help from me, (…) to persuade them to write up brief non-technical descriptions of their projects. (…) there's always been too much of a gap I think between practitioners and theory. And this is one of many, many attempts by the organizations involved to foster more dialogue between the two. (Keefer, interview)

Materializing Decision Analysis Concepts. Collaboration between scientists and non-scientists often involves relying on material artifacts (Star & Griesemer, 1989). In our study, material devices are all the more important, as Decision Theory's core entities – such as expected utility or subjective probabilities – do not 'exist' as such 'out there' and have to be assembled through translation work.

When Raiffa decided to go into the field to collect judgments from business experts, he quickly realized that becoming "expert in the art of soliciting judgmental information" was a challenging task. He had to learn gradually "how to ask for the input data [I] needed by the proper framing of questions. … [how] not to ask questions one way or another way, but to ask both ways and confront resulting incoherencies in an open manner" (Raiffa, 2002: 180-181). As this discipline evolved, the tacit knowledge that emerged from interactions with practitioners became more explicit, and so could be materialized into elicitation protocols (e.g., the Stanford/SRI assessment protocol), and into decision tools (e.g., decision trees, influence diagrams, beliefs networks) that were subsequently broadcast via academic papers (Spetzler & Stael Von Holstein, 1975), consultancy reports (Howard & Matheson, 1984), and books (Clemen & Reilly, 2001; Edwards, Miles, & von Winterfeldt, 2007).

However, the enrollment of various types of practitioners from heterogeneous social worlds (e.g. energy, health sectors) required decision analysts to continue the translation of Bayes' ideas through the "engineering" of Decision Theory (Cabantous & Gond, 2011: 580).

Mobilizing Decision Tools as Boundary Objects. Research on decision analysts' practices reveals how some decision tools were assembled and operated as boundary objects (Cabantous, Gond, & Johnson-Cramer, 2010). Decision trees – one of the best-known Decision Analysis tools – illustrate well the idea that decision tools are a means of translation between decision analysts and practitioners. Raiffa explains how he created decision trees to help his Harvard MBA students to understand Decision Theory principles:

> Most students at the B-School had difficulty with mathematical abstractions (…) so I began using decision tree diagrams that depicted the sequential nature of decision problems faced by business managers. … I never made any claim about being the inventor of the decision tree but I could not begin to discuss decision making without growing a tree and I began to be known as Mr. Decision Tree. (Raiffa, 2006: 33)

In managerial contexts, decision trees were shown to be marvelous tools to overcome the differences between decision theorists and managers looking at the same problems. Their flexibility allowed them to solve real problems together, while talking their own language:

> Well I don't think they [managers] associate utility functions with decision problems. That's far removed from their thoughts. I find it quite easy to get them to start talking about the decision problems they have and then you start saying to them 'Well, one way of looking at this is through the vehicle of the decision tree; let's try and draw an initial decision tree for this problem.' But if I started saying to them 'What's your utility function?' they'd go nuts… They simply think about the nature of the problem or problems they have, whether it's a new product launch or whether it's a major strategic investment. (Thomas, interview)

In practice, decision trees translate Decision Theory principles into a vocabulary accessible to managers and simplify calculations, as the parameters can be usually obtained easily by flipping the tree (i.e., applying Bayes' rule to calculate the value of probabilities in the tree):

> The worst thing you can do is to use the Bayes theorem. It's too complicated. Just use common sense and play around with things, then it was pretty easy. We had people doing complicated things that could have been done by Bayes, but we didn't do it by Bayes. We did it by tree-flipping. (interview with Raiffa reported in McGrayne, 2012: 149)

Because they respect the integrity and rigor of Decision Theory, but are nonetheless usable by decision makers (i.e., they are figures that they can handle easily), decision trees can work as boundary objects, aligning the interests of decision makers in search of a quick solution to their problems with academics' willingness to respect the integrity of Bayes' ideas. Our data suggest that other decision tools were also used as boundary objects, as David Matheson, a former principal at Strategic Decisions Group (SDG), suggests:

> So for example, I got a lot of traction [from] tornado diagrams; they're simple, they're easy to understand, people can deal with them very quickly and they understand how that can be a solution to their problem. So there's a whole lot of questions behind that, but those are for people who are already committed and they do come up. So how does this actually work, what's really going on here? Then, all the Decision Analysis stuff comes out, but it's not until they need to really understand it that it comes out. They don't care; they care about the result. (Matheson, interview)

All these examples suggest that tools developed by decision analysts to interact with practitioners were actively used as boundary objects. They were general and abstract enough to circulate across organizations (in classrooms, business meetings, or consulting missions), but could still be tailored to local managerial needs. Their flexibility allowed their adaption to local contexts – for instance by incorporating organizational experts' judgments as parameters – while their structure ensured they still respected Decision Theory axioms.

On the one hand, these Decision Analysis tools act as black boxes, hiding the complexity of the theory's axioms behind a material interface that is ergonomic. Thanks to these objects, decision makers and managers can rely on Decision Theory's insights while making their decisions without even realizing it. On the other, mobilized as boundary objects, decision tools materialize the links between decision-making practice and Decision Theory's axioms, and hence turn Decision Theory into a set of practices accessible to business actors.

Managing Tensions to Stabilize the Bayesian Actor-Network

Constituting an actor-network is a never-ending process, which requires the continuous involvement of all its entities (Callon, 1986). The fact that, by the end of the 1970s, decision analysts had enrolled a highly heterogeneous set of human actors (management scholars, psychologists, and all kinds of practitioners) and of non-human entities (e.g., decision tools) did not necessarily mean the Bayesian actor-network would last long. How did decision analysts ensure the continued alignment of these heterogeneous entities' interests?

Selectively Excluding and Including Actors. Despite the consolidation of the Bayesian actor-network in various academic spheres (economics, psychology, and management) in the 1970s, decision analysts continuously had to defend their approach to making decisions, which involved winning new trials of strength with fresh opponents. For instance, as Decision Analysis developed, new decision theories arose (e.g., the 'fuzzy' approach to decision making), some of which the self-proclaimed 'official' translators of Bayes' ideas perceived as illegitimate. The debate published in *Interfaces* in 1992 illustrates of the kind of battle decision analysts had to win (Howard, 1992a). As part of this trial of strength, Howard delineated the boundaries of Decision Analysis, famously excluding some approaches he classified as "heathens, heretics, or cults", and contrasting them to the "true" Bayesian approach to decision making he had co-developed with his colleagues, which he now called the "old-time religion" (Howard, 1992b).

> Yet, there are dissenters. To use a religious metaphor, heathens are those who pursue decision-aiding procedures that have different underlying philosophies. Heretics follow the general ideas of Decision Analysis but wish to change some underpinnings in a ruinous desire to achieve greater consistency with certain experiments involving unaided decision makers. Cults are composed of those who superficially follow the paradigm, but are willing to bend their practice in ways that allow the decision maker to avoid the dictates of logic while appearing to have done a Decision Analysis. (Howard, 1992a: 15)

Some proponents of alternative decision-making methods that the custodians of Bayes' ideas in management research judged illegitimate tried to benefit from the growing power and reputation of Decision Analysis in business and industrial circles. But at the same time, other actors who were central Bayesian actor-network entities threatened to quit the Decision Analysis community. For instance, in the mid-1990s, some practitioner-oriented members of the Decision Analysis Society of INFORMS felt that the association was in danger of becoming too academic, and challenged its legitimacy to speak on behalf of practitioners:

> Some of the non-academic members of the Special Interest Group have expressed concern[s] to me about its heavily academic flavor; they feel that their problems aren't getting enough attention. It is too soon to know what actions are appropriate, [but] it's a good bet that the complaint is justified. We should do something about it, if we can find something sensible to do. (DAS newsletter, August 1994, Edwards' Presidential address)

Eventually, some of them created the Decision Analysis Affinity Group (DAAG). While they clearly remained attached to Bayesianism, their desire for an arena where they could "share, between practitioners only – academics and consultants are not allowed unless invited by the Chairman – Decision Analysis practice and experience" (DAAG, 2011) illustrated the fragility of the actor-network. The creation of the DAAG showed the difficulty of maintaining lasting relationships with diverse actors.

Relying on Boundary Organizations to Manage Tensions. To understand how decision analysts managed to overcome the tensions that arose among the heterogeneous actors they had enrolled (e.g., scholars based in engineering and business schools, Bayesian statisticians, PhD students, practitioners), it is important to look at the role of organizations located at the interface between the different groups involved in the Decision Analysis field, and which decision analysts had created to sustain their project. The group that Howard and Matheson created at the Stanford Research Institute (SRI) in the mid-1960s illustrates how such organizations acted as boundary organizations, and helped stabilized the Bayesian actor-network by incentivizing academics and practitioners to work together. As Spetzler explains, this group ensured continuous and large-scale engagement with real decision problems so as to advance Decision Analysis practice:

> I think of Ron Howard as one of those people that's on the academic side and has always considered it to be a practical engineering profession. So he wants the profession to serve in a sense the practice of Decision Analysis. (…) you can see this with the start of the Stanford Research Institute group, we kind of created this thing so we could practice it because we knew that we couldn't advance the state of the art without actually trying to solve big decision problems. (Spetzler, interview)

The location of this group at the SRI helped align academics' and practitioners' objectives, and demonstrated the relevance and legitimacy of Decision Analysis. In the 1970s and early 1980s, the idea of establishing university/industry partnerships gained currency in the US (Shapin, 2008). One notable characteristic of the SRI is that it invited its academic members to engage actively with practice: for instance, in order to foster relations with practitioners, the group's founders created a joint PhD program with the University's Engineering Economic Systems Department that required PhD students to do one-year internships working in corporations:

> …most of the PhD interns in Decision Analysis, the best ones, would come to Stanford Research Institute or later [onto the] Strategic Decisions Group…. This whole constant flow of very bright PhD people that actually did their dissertations on topics that were practical and of great value because they'd practiced for a year, really advanced the state of the art. (Spetzler, interview)

This program helped overcome conflicts of motivations between academics and practitioners, by creating incentives for both sides to collaborate on specific projects. For instance, Carl Spetzler (an alumnus of this PhD program) developed the 'SRI protocol' for encoding expert judgments on probability during his internship at Standard Oil of Indiana (now Amoco). This protocol became part of the SDG consultants' practice, and was also published in *Management Science* (Spetzler & Stael Von Holstein, 1975). So this PhD program acted as a boundary organization, in allowing practitioners seeking smart solutions to concrete problems to collaborate with PhD students in quest of real data to further their theoretical studies.

In a similar vein, consultancy firms created by decision analysts contributed to stabilizing the Bayesian actor-network by ensuring that the interests of diverse actors were aligned. Many of these consultancy firms, which blossomed in the late 1970s and 1980s, were either spin-offs from research centers or were created by former students of leading decision analysts from Stanford and Harvard. Most of their consultants maintained their relationships with researchers. For instance, the SDG emerged from the SRI, as Spetzler recalled: "in 1980, after 12 years at SRI, (…) I attracted the remaining leaders of the [SRI] Decision Analysis group to join me and… [start] Strategic Decisions Group" (interview).

These consultancy firms helped stabilize the Bayesian actor-network by codifying the tacit knowledge co-created by decision analysts and all kinds of practitioners during their interactions to solve concrete problems. They helped make such knowledge explicit (Nonaka & Takeuchi, 1995), notably through book publication: the SRI published two books in 1968 that were "best sellers in their time" (Abbas, 2004), while the SDG published a report in 1984 codifying its practice (Howard & Matheson, 1984) that became a reference source for decision analysts. More important for the durability of the Bayesian actor-network, successful consultancy firms were the tangible proof that Bayesian ideas were useful to a large number of practitioners, such as medical doctors, energy engineers, and managers, who were ready to spend significant sums of money to benefit from Decision Analysis' insights.

So, throughout its history, the Decision Analysis community has assembled a variety of organizations at the interfaces of various social worlds that were ideal candidates to play the roles of boundary organizations which, in fact, some of them did. In particular, our findings highlight the importance of PhD programs, consultancy firms, and societies of academics and professionals in maintaining the Bayesian actor-network. These organizations provided actors with incentives to collaborate, demonstrated the practical relevance of Bayesian decision-making, and helped support the constant assembling of objects that functioned as boundary objects, such as software packages including Decision Analysis modules.

However, living at the boundaries between science and industry raised moral and political concerns, as scientists and entrepreneurs have long been conceptualized as having antipathetic identities (Shapin, 2008). Our interviews suggest that boundary organizations also played important roles here, helping decision analysts to develop hybrid identities at the interface between the academic and practice worlds, establishing them as obligatory 'passage points' between Decision Theory and decision making practice. Tellingly, an analysis of the resumes of the scholars we interviewed suggests their careers have generally spanned both worlds, and their interviews suggest that boundary organizations enabled the hybridization of their academic and practical activities. So boundary organizations facilitated the integration of Bayesian ideas into both academia and practice, sustaining the actor-network that bridges Bayesian Decision Theory and managerial decision-making practice.

Epilogue: Decision Analysis – a Half-Success?

Thus, in the space of 50 years, a group of scholars and practitioners assembled a forum where Bayesian ideas could be discussed and applied to real decision problems. Decision Analysis is used in many organizations in particular in the environmental, oil and gas, clinical, military and R&D sectors (Clemen & Kwit, 2001; Edwards et al., 2007); and is taught in many universities (Keeney, See, & von Winterfeldt, 2006).

However, as Figure 2 shows, the number of Decision Analysis publications in major OR&MS journals has declined since the mid-1980s. Generally, the discipline of Decision

Analysis, as ultimately constituted, is not as strong as the early proponents of Bayesianism in management science hoped: many of our interviewees said they had expected it would have greater impact on real decision-making practice: "I would say most people in my profession would agree that it has less visibility than it ought to, at this stage of development" (Beccue, interview). There may be several explanations for this 'half-success'. One points to the fragility of the local achievements of decision analysts in organizational contexts that are usually enacted via short-term interventions, which may prevent Decision Analysis becoming embedded in organizational routines (Matheson & Matheson, 2007). Another explanation points to the demotivation of students who were taught Decision Theory in too arid a manner (McGrayne, 2012: 150-153). Finally, this declining trend may relate to the fact that reports on practical Decision Analysis applications tend now to be submitted to specialized journals (e.g., military, health) rather than to Decision Analysis journals (Keefer et al., 2004).

REVIVING BAYESIANISM: DISCUSSION AND IMPLICATIONS

Although our analysis of the historical case of Decision Analysis through STS and ANT concepts does not lead to straightforward prescriptions, it can help make more explicit some dimensions of any scientific enterprise that could easily be overlooked. Notably, STS and ANT stress the political and material dimensions inherent in any scientific project, and they show the value of relying on cases studies to analyze the constitution of scientific activities. In what follows, we discuss the implications of our study for the prospect of reviving Bayes' ideas in management research and practice.

The Politics of Reviving Bayesianism

Contrary to the often-implicit assumptions that the 'best theory' will win the battle for ideas, that scientific facts 'will speak for themselves' and that academics will rally behind a project for merely scientific reasons, ANT stresses the politics of science-making (Latour, 1987; Law, 2008b). Because it considers that creating a new academic discipline consists in offering a new framing of an existing scientific problem, and in assembling a network of allies, ANT points to the fact that such enterprises inevitably destabilize existing actor-networks that have been constituted to support alternative theories. It also shows that the success of a theory depends on its proponents' ability to win trials of strength.

So, a first implication of our analysis is to raise awareness of the politics inherent in any academic enterprise aiming at rejuvenating Bayesianism. In documenting the trials of strength decision analysts faced, our case has shed light on the resistance to Bayesianism that came from the frequentists in statisticians' circles, and the tactics that Bayesians adopted to overcome these obstacles. Frequentists denied the scientific value of the subjective probability concept, but Bayesians made it measurable and then defused potential criticisms by building its reputation on sound axiomatic foundations. They also found allies outside schools of statistics (e.g., schools of engineering, business schools), where opposition to Bayesianism was nonexistent (or at least less strong). In so doing, they searched for what Goethe once termed "elective affinities" (Goethe, 1809 [2008]): that is they inductively tried to find the types of decision problems that were more likely to respond well to a Bayesian approach to making decisions. But knowledge about 'where and when Decision Analysis works' remains largely tacit, so decision analysts still have difficulty in articulating why Decision Theory has been adopted in some industries, such as energy and pharmaceuticals (Keefer et al., 2004), but not in others (Lang, interview; Leonardi, interview).

Overall, while the strategy the early Bayesians adopted ensured the creation and development of an active Bayesian field of research in management research between 1970 and 1985, it still did not deliver its full promise. Contrary to the hopes of its leaders, Decision Analysis did not revolutionize the entire field of management. One explanation for its modest success might be that some leading decision analysts, although active proselytizers, would not tolerate compromise, and even fought against some Bayesian inspired decision-making approaches that they thought were not 'truthful' translation of Bayes' ideas. Their strategy thus largely consisted in 'locking' the field, and in establishing themselves as an obligatory passage point bridging Bayes' ideas and decision-making practices that was too narrow, which may have limited the scope of their Bayesian actor-network. The creation in 2008 of a new community of practitioners, the Society of Decision Professionals, and of Decision Analysis certification programs can be interpreted as possible ways to reverse this trend, and 'open-up' the Bayesian forum to more people, while ensuring integrity to Bayes' ideas.

Obviously, the current situation differs from that faced by early Bayesians. The scientific value attached to Bayesianism is less in doubt today than it was before, and a large number of applications now exist that demonstrate the value of Bayesian ideas for practitioners (Edwards et al., 2007; Keefer et al., 2004; Pourret, Naim Patrick, & Marcot, 2008). More importantly, statisticians seem more willing than ever to countenance a Bayesian approach to their discipline (Efron, 2005), which should help the proponents of Bayesianism in management research to build legitimacy among their colleagues. However, the constitution of a Bayesian stream of research in management is inevitably likely to trigger resistance. First, as our case study shows, adopting Bayes' ideas often equates to a religious conversion, as it involves questioning taken-for-granted assumptions about what a probability is. Second, frequentist statistics are widely used in management research, and promoting an alternative way of conducting statistical enquiries may threaten existing positions and ingrained habits, as Orlitzky (2012) showed in the case of the NHST (Kruschke, 2010).

What strategies can the current proponents of reviving Bayes' ideas in management adopt to overcome these potential obstacles? Our analysis suggests that there might be a trade-off between maximizing the 'truthfulness' of Bayes' ideas and their acceptance in non-specialist circles. Another lesson that emerges from our study is that not all battles need to be won: instead of fighting against alternative Bayesian methods because they might threaten the ‘integrity’ of Bayes translation, Bayesian proponents should admit that any translation is always a ‘treason’ to some extent, and rather aim to turn those who propose alternative methods (and perhaps also methods which are not Bayesian, but could usefully complement them) into allies. As in the case of a ‘standards war’, where the ability to assemble a large base of potential allies proved important in building a bandwagon, the ability to enlist a large number of partners is crucial in the battle for establishing a new theory or set of methods in scientific circles. So seeking to establish cooperation and compatibility rather than competition with proponents of alternative methods and theories can be central.

Materializing and Black-Boxing Bayes’ Concepts

ANT studies point to the often over-looked material dimensions of scientific projects. Even while they recognize the importance of framing and rhetoric in trials of strength, these works show that promoting a theory or a set of methods inevitably implies enlisting non-human entities to constitute an actor-network. So a second implication of our analysis relates to the role of materiality in moving towards Bayesianism.

Our findings suggest that the materialization of abstract entities such as subjective probability and the assembling of artifacts (e.g., decision trees, influence diagrams) played a crucial role in the adoption of Bayesian ideas 50 years ago. When computing capacities were almost non-existent, constructing artifacts that captured the essence of Bayesian Decision Theory but also enabled easy calculations was crucial. Decision tools played this role by ‘black-boxing’ Decision Theory axioms conveniently into diagrams, and becoming boundary objects coordinating decision making by heterogeneous actors (students, academics and practitioners). In so doing, they materialized Decision Theory’s concepts and enabled their use by practitioners, facilitating their enrollment into the Bayesian actor-network.

The current availability of computers and statistical software packages has drastically changed the prospects for Decision Theory translation, as it is now possible to conduct

Decision Analysis computation via standard packaged programs such as Excel, and more complex analysis of decisions by relying on 'Bayesian networks' software (Fenton & Neil, 2012). Following a similar logic, we can expect that, if the current Bayesian project in management research is to succeed, it will owe a lot to objects that operate as black boxes which embed Bayesian modes of estimation, inference and reasoning. Bayesian software packages such as 'Mplus' or 'R', which allow their users to conduct both statistical analyses using both frequentist and Bayesian methods (Muthén & Asparouhov, 2012), are likely to play an important role in the (hidden) adoption of Bayesian modes of inference in management research. These objects can turn their users into *de facto* Bayesian decision-makers or modelers (Kruschke, 2010), by acting as 'Trojan horses', supporting the adoption of black box Bayesian modes of inference, and hence the (unsuspected) import of Bayesianism into academia or practice.

However, not all objects can act as boundary objects enabling coordination across social worlds. If Bayesian statistics are to become useful in practitioners' worlds, efforts have to be made to identify devices that can be mobilized as boundary objects. The proponents of the current Bayesian revival in management research would benefit from investigating how Bayesian statistics can be black-boxed in such ways, and identifying devices that different actors can mobilize to bridge Bayesian principles and actors' practices.

Completing the Bayesian Turn

A third implication of our case study points to the value of historical cases for advancing management research (Rowlinson et al., 2014). In the early 1950s, the pioneers of Bayesianism in management were regarded as marginal in statistician circles, and were unaware of other attempts at applying Bayes' rules in practice, as most of their prior uses were either lost or classified secrets at that time. As a result, they sometimes had to rediscover the principles already theorized by Bayes and Laplace for themselves –Schlaifer's history being a case in point (McGrayne, 2012) – and develop their own new applications of Bayes' rule. A Bayesian revival in the 21st Century cannot again afford to ignore prior attempts at translating Bayes and Bayesianism's long and tortuous history more generally. Our case study shows the value of associating a contemporary project to 'go Bayes' in management with a well-established tradition: demonstrating affiliations with prestigious ancestors (e.g., Bayes, Laplace, Kolmogorov…) or established disciplines (e.g., economics, computer sciences…) may be crucial in any future trials of strength.

Our case study also stresses the diversity of forms of Bayesianism by documenting how one specific variant of Bayes' ideas – Decision Analysis – has been imported into management research and practice. As Decision Analysis has largely been interdisciplinary since its birth (Miles, 2007), other studies could document the presence of the Bayesian actor-network in disciplines such as psychology and medicine. Future research could also study the development of alternative variants of Bayesianism – particularly Bayesian networks – in related disciplines (e.g., engineering, finance, and risk management).

It is striking that the literatures about three variants of Bayesianism – Bayesian Decision Theory as described in this paper, Bayesian statistics as promoted by this special issue, and Bayesian networks – are not more connected to each other, as they would seem to be 'natural' partners. For instance, Bayesian decision theorists – who, surprisingly, do not rely on Bayesian statistics (see Nilsson, Rieskamp, & Wagenmakers, 2011 for a noticeable exception) – could be more easily enrolled in the current Bayesian project than other management scholars who are not already converted to Bayes' ideas. They can certainly be regarded as potential allies in promoting Bayesian statistics in management as they are already converted to Bayesianism. In this regard, promoting Bayesian statistics in management could enhance the dynamism of the Decision Analysis field of study, which appears to be in slow decline, and could also help enroll the community of Decision Analysis practitioners already recognizant of the virtues of Bayesianism. An alliance between promoters of Bayesian statistics and users of 'Bayesian networks' who have already demonstrated their practical value in many applied settings (finance, risk management) could also help consolidate the emerging Bayesian statistics actor-network in management.

Overall, our historical case study suggests that it could be useful to bridge various groups of Bayesian scholars promoting different translations of Bayes' ideas into management research and elsewhere. In this respect, mobilizing organizations located at the interfaces between these communities (e.g., academic associations, academic journals) as boundary organizations could help create a less fragmented Bayesian community, spanning different disciplines, and a larger range of application domains. Bridging together heterogeneous communities of Bayesian users and better aligning their interests could allow the contemporary promoters of Bayesian statistics in management to seize a unique historical opportunity to complete the 'Bayesian turn' in management.

CONCLUSION

By relying on concepts and assumptions from STS and ANT, this paper has made explicit some challenges – and their possible remedies – in the process by which Bayesian ideas could be imported in management research and practice. A case study on the history of Decision Analysis highlighted how early promoters of Bayes' ideas in management disciplined the concept of subjective probability to make it acceptable in academia; managerialized Bayesian Decision Theory to enroll reluctant practitioners; and mobilized boundary organizations to bridge theory and practice. In so doing, they facilitated the emergence of a lasting, but fragile, Bayesian actor-network. These results can inform and inspire scholars involved in the current project to 'go Bayes' in management as they stress the political dimension inherent in the project of bringing Bayes back to life; show the importance of materializing Bayes' concepts in order to make them useful and relevant; and affirm that importing Bayesianism is a long-term endeavor that needs to be appreciated in a broad historical context. It is our hope that this paper, in showing the common interest of distinct communities of scholars and practitioners for Bayes' ideas and history, will contribute to the continuous translation of Bayes' ideas in management. Beyond the case of Bayesianism in management research, our study is a reminder that the decline or dominance of any theory or set of methods in an academic field result from the continuous social, political and material practices that make things work as they do.

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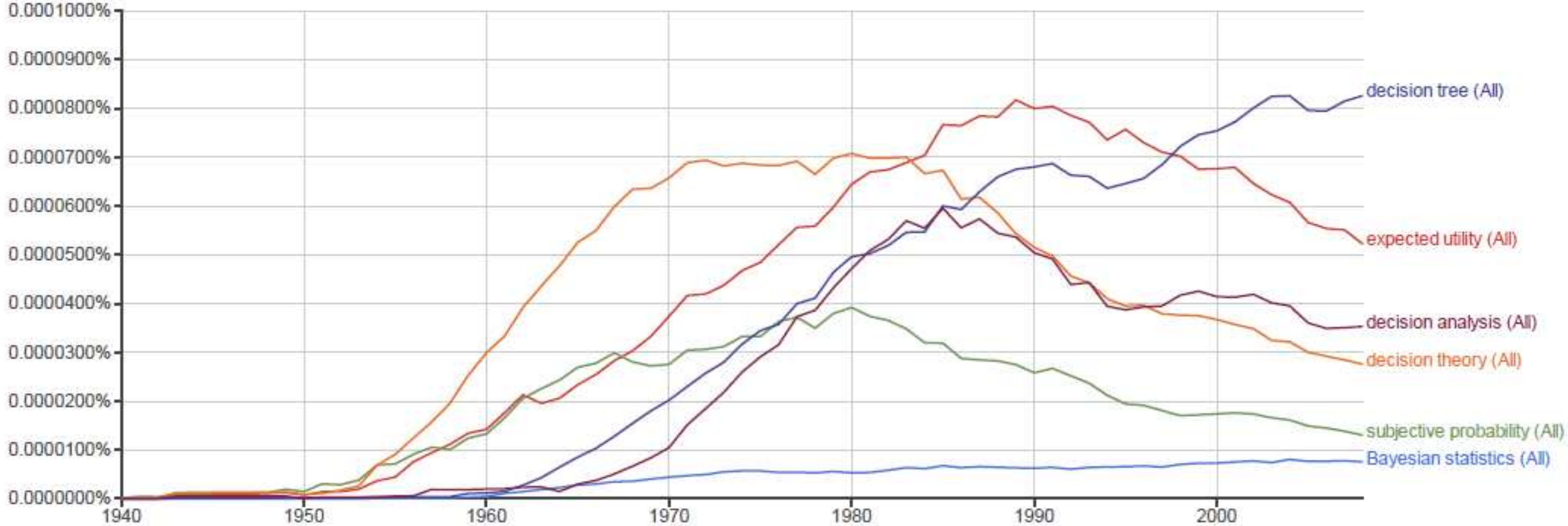
ENDNOTES

[1] Available historical evidence does not, however, fully support the view that Bayes became interested in this question for the theological reasons that motivated Price. It seems more likely that Bayes' interest in the problem of inverse probability came from his readings of Newton's work on the causes of gravity, or as an answer to Hume's philosophical essay (Bellhouse, 2004; McGrayne, 2012; Stigler, 2013).

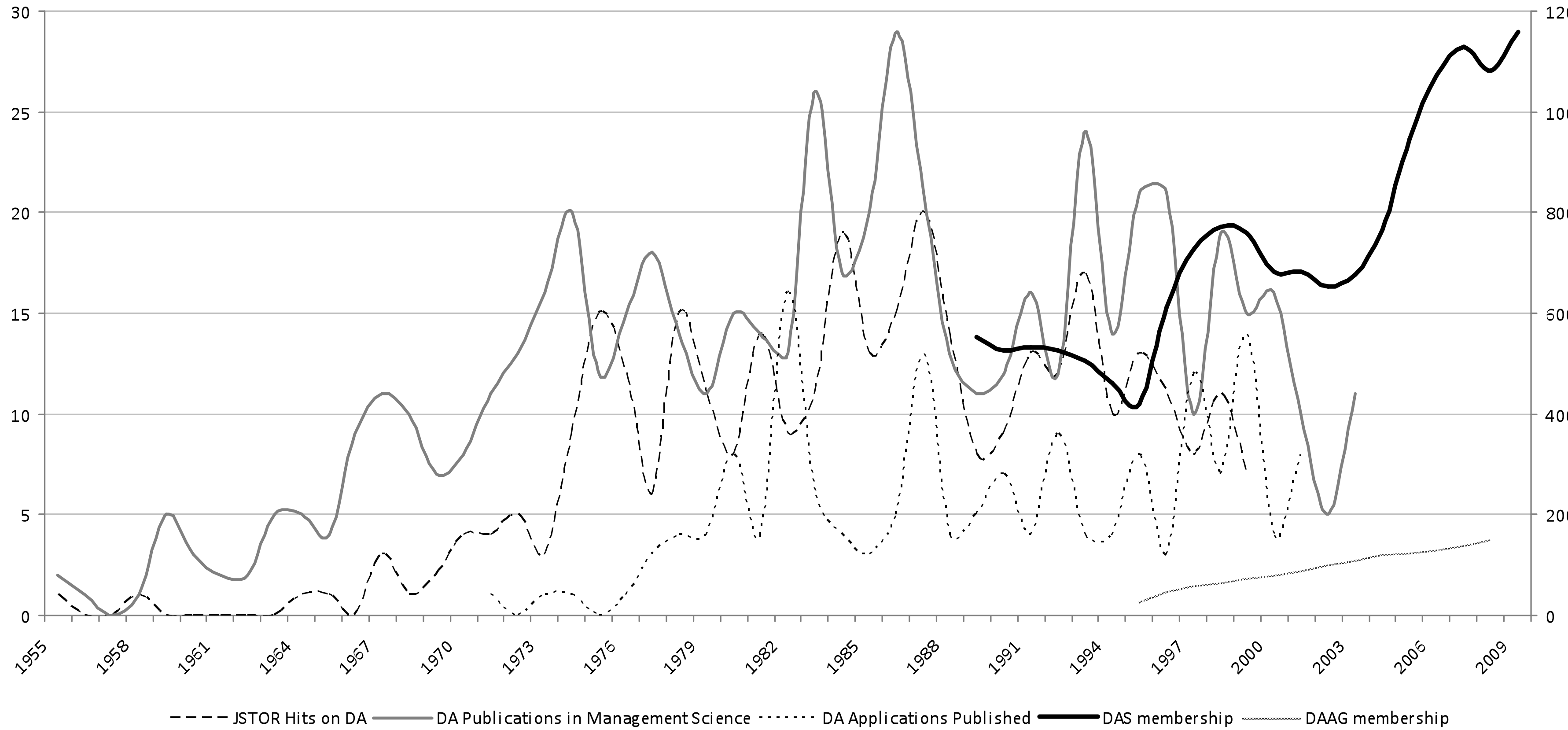
[2] The political or critical nature of ANT has been debated in recent years in organization theory, notably by Whittle and Spicer (2008), who argued that early ANT work did not focus sufficiently on politics and power. This argument is surprising, as two early essays by Callon and Latour, which were published in the section on "the techniques of power" in Law's (1986) book, deal with power. Callon (1986) explicitly describes translation as a political endeavor, while Latour (1986) explains that his aim is to generalize some insights from Foucault's work on power by considering the role of machines, techniques and the hard sciences. The 'ANT and After' stream of research also insists on the political dimension of this approach (Alcapani & Hassard, 2010; Law & Hassard, 2005 [1999]).

Figure 1
Decision Analysis and Bayesian key-words in Google books and N-Gram viewer*



** This graphic has been produced by searching within the English dictionary of Google Books N-gram Viewer for the following list of key-words for the period 1940-2009: Bayesian statistics, expected utility, subjective probability, decision theory, decision tree, decision analysis. See: https://books.google.com/ngrams.*

Figure 2
Indicators of Decision Analysis academic and professional development (1955-2009)*



** Sources: JSTOR hits on DA: Smith &Winterfeldt (2004); DA publications in Management Science: Hopp (2004); DA applications published: built out of the data provided by Corner & Kirkwood (1991) and Keefer et al. (2004); DAS (Decision Analysis Society) membership figures were kindly provided by INFORMS for the 1995-2009 period and calculated out of the DAS newsletter for 1988-1994, DAS data from 1980 to 1987 are not currently available. The DAAG membership trend has been inferred from the data provided on the DAAG website for 1995 and 2009. We kindly thank James Smith, Detolf von Winterfeldt and Wallace Hopp for providing us with their dataset on DA applications.*

Table 1: List of interviewees

Name	Affiliation (at the time of the interview)	Education	Length (*)
Beccue, Ph.	Baxter Healthcare (Director - Strategy & Portfolio Management); Formally Decision Sciences Amgen)	MSc. (or PhD), Stanford	60(P)
Bickel, E.	University of Texas at Austin (Prof); Outside consultant at SDG. Former Senior Engagement Manager at SDG)	PhD EES, Stanford 1999, MSc. EES, Stanford 1994	65(P)
Bodily, S.	Darden Grad. Business School (Professor)	PhD, mid 1970s, MIT	59(F)
Borsoi, A.	AND Research & Consulting Ltd. (Director)	MSc, LSE, 2000	85(F)
Brown, R.	George Mason Univ. (Distinguished Senior Fellow); Former Chairman of Decision Sc. Consortium, Inc.)	DBA, 1968 Harvard	143(F)
Buede, D.	IDI (Executive Principal Analyst & President)	PhD. EES, Stanford, 1977; MSc. EES Stanford, 1973	57(P)
Buyssou, D.	Univ. Paris Dauphine (Professor)	ESSEC 1980, PhD 1984, Dauphine	95(F)
Delquié, Ph.	INSEAD (Associate Professor)	PhD (OR) MIT, 1989	62(F)
De Neufville, R.	MIT (Professor)	PhD, 1965, MIT	68(F)
Dyer, J.	Univ. Texas (Professor - retired)	PhD (Bus. Admi), Texas, 1969	68(F)
French, S.	Manchester Univ. Business School (Professor)	PhD/D.phil (Molecular Bio)	56(F)
Judd, B.	SDG (Dir. Executive Education)	PhD, Stanford, 1970/mid 1970	62(F)
Keefer, D.	Arizona State Univ. (Professor)	D.Phil/PhD (OR). Michigan, 1976	64(F)
Keeney, R.	Duke University (Professor)	PhD, MIT, 1969	58(P)
Koch F.	Chevron Corporation (Decision Analysis Practice Leader)	MSc (Geology), Stanford, 1979	79(P)
Lang, J.	SDG (former President & COO)	MBA, Tuck Sch. of Bus Adm.	66(P)
Leonhardi, D.	Boeing Company (Decision Consultant)	Adv. Project Mgt Certificate, Stanford	48(P)
Lock, A.	Leeds Univ. Business School (Professor - retired)	PhD, LSE, late 1970s	53(F)
Manzella, T.	Syncopation Software, Inc. (COO)	MSc, OR, 1995	75(F)
Matheson, D.	Smart Org. (Co-founder, President and CEO)	PhD, EES, Stanford	100(P)
Munier, B.	IAE Paris, Panthéon-Sorbonne (Professor)	PhD Economics, 1969	117(F)
Parnell, G.	IDI (Executive Principal Analyst)	PhD, 1985	42(P)
Pearman, A.	Leeds Univ. Business School (Professor)	PhD, Leeds.	53(F)
Peters, M.-L.	SDG (former Partner)	MSc, EES, Stanford,	63(P)
Phillips, L.	LSE (Prof); Director of Facilitation Ltd	PhD (Psycho), Michigan, 1960s	83(F)
Pratt, J.	Harvard Business School (Emeritus)	PhD (Statistics), Stanford ~1956	66(F)
Raiffa, H.	Harvard Business School (Emeritus)	PhD (Maths), Michigan, 1961	45(F)
Roy, B.	Univ. Paris Dauphine (Emeritus).	PhD (Maths), Fr. 1961	105(F)
Sorohan, K.	Deciware (CEO)	MSc (Tech., Management), Dublin, 2006	49(F)
Spetzler, C.	SDG (Chairman and COO)	PhD, Econ. Bus Adm. Illinois Inst. Of Techno, 1968	73(P)
Thomas, H.	Warwick Business School (Professor)	PhD. 1970, University of Edinburgh	37(F)
Ulvila, J.	IDI (Exec. Principal Analyst & Vice President)	DBA, Harvard, 1979, MBA, Michigan, 1974	72(P)

*F: Face-to-face interviews – P: Interviews conducted over the telephone