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Value of information analysis: the state of application

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Abstract The value of information (VoI) is a decision analytic method for quantifying the potential benefit of additional information in the face of uncertainty. This paper reviews the prevalence of VoI applications reported in the peer-reviewed literature from the years 1990–2011. We categorize papers' applications across the types of uncertainties considered, modeling choices, and contexts of social importance (such as health care and environmental science). We obtain and analyze statistics on the range of applications and identify trends and patterns in them, and conclude with an interpretation of what these mean for researchers and practitioners as they pursue new efforts. Key results include a substantial increase over the last 20 years in published papers utilizing VoI, particularly in the medical field. Nineteen trends in VoI applications from the period of 1990–2000 to 2001–2011 were found to be at least weakly significant. Beyond simple trends, some characteristics of VoI usage depend on the area of application, and in some cases, certain sets of characteristics tend to be found together.

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1 Introduction

This paper surveys and statistically analyzes the characteristics of recently published articles that apply value of information (VoI) methods, in order to understand current uses and needs and to identify directions for future work. Decision makers are faced with ever-growing information sources, but there is no commensurate growth in human cognitive abilities or in research budgets that would help in leveraging those sources, while decision makers also face growing scrutiny, political pressure alongside calls for transparency. Thus, the need to understand the value of information is greater than ever, and thus so is the need to understand VoI application. Before analyzing applications, it is necessary to understand the concept of VoI itself.

1.1 Value of information

VoI is a methodology with formal definitions in the field of decision analysis that can be particularly useful in identifying desirable ways to improve the prospective outcomes for the chosen course of action. While basic decision analysis with expected utility[1] approaches allows decision

[1] A utility function transforms dollar values or some other nominal values into a scale for which maximizing the expectation is consistent with the axioms of rationality. There is a vast literature on utility theory. Raiffa (1968) is one source that explains utility. We also refer to multi-attribute utility (Keeney and Raiffa 1976) which involves combining utility scores—often as a weighted sum—for a number of individual attributes, where the single-attribute utility scores are often nonlinear functions of the metric for the attribute.

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makers to identify the best course of action when faced with a situation of uncertainty, VoI provides guidance on how decision makers might invest in reducing that uncertainty before selecting a course of action. In simple decision analysis problems under expected value maximization, VoI is defined as the increase in expected value that arises from making the best choice with the benefit of a piece of information compared to the best choice without the benefit of that same information. With nonlinear utility functions, VoI is the amount that could be paid to obtain the information, whereby the decision with information would result in the same certain equivalent value as the decision without information and without incurring the cost of obtaining it. It is possible for information to have value even if no specific decision problem has been modeled. For example, information can have entertainment value, or information can help to keep order, for example, an accounting system that ensures everyone is paid what they should be. This is not what is meant by VoI in the decision analytic sense, which will be the scope for the remainder of this paper.

In theory, VoI can be used to assess the value of any piece of information that helps to improve the estimate of one or more alternatives' performance on one or more criterion. In some cases, resolving uncertainty prior to making decisions has little or no actual value in a particular context, while in other cases, resolving uncertainty may be the primary enabler of value in a situation and not necessarily in a way that is intuitively obvious.

In calculating VoI, information obtained can be assumed perfect (the results obtained correspond to the actual state of the world with certainty), which provides an upper bound on the potential gain and we call this EVPI (expected value of perfect information). Alternatively, models may consider the expected value of sample information (often called EVSI) or of imperfect information. In these cases, new information increases the decision maker's knowledge of the state of the world, but the result is still uncertain. Calculations can be completed using simple decision trees (e.g., Raiffa 1968), but many applications require the use of software and probabilistic simulation results to approximate VoI. Information can take various forms, for example, different probabilities of discrete events or different probability distributions on continuous variables. Modelers may differ in their approach depending on the costs and benefits they see. For example, EVSI can require more complex computation and more subtle interpretation than EVPI, but may also provide more precise guidance about information acquisition. For a thorough background and mathematical definition of VoI, see Howard (1966) or Raiffa and Schlaifer (1976). An example of a VoI problem can be found in the "Appendix 1."

Positive VoI exists because of potential improvements in the probability distribution of the payoff associated with a decision problem. This improvement may be achieved by obtaining further information about potential consequences of possible actions prior to selecting a specific course of action. Indeed, risk is almost always associated with substantial uncertainty, and VoI targets that uncertainty with intent to understand its importance in order to reduce it selectively and advantageously. Similarly, insurance and hedging strategies, diversification, and regulation to avoid extreme conditions are tools available to the risk manager. However, in using these tools to reduce risk, decision makers give up flexibility or unnecessary resources, whereas VoI facilitates more dynamic management. For example, monitoring an environmental system may help decision makers to understand risk levels on an ongoing basis. VoI improves the ability to manage that risk by focusing resources on monitoring those parameters whose values might most affect the relative desirability of alternative strategies to secure the system. Furthermore, by guiding decision makers to obtain information that reduces negative surprises when practical, VoI can improve the robustness of the selected alternative.

1.2 Goals

Although advances in technology have tended to create more opportunities for information acquisition, and thus, perhaps, increased importance for understanding the value of acquiring information, VoI has only modest presence in policy and risk-related applications. To ease the possible expansion of that presence, we are motivated to review the current state of VoI practice and how it has developed. Rather than a conceptual review and synthesis of theoretical research that focuses on the creation of VoI methods, our focus is to collect and analyze statistics on the use of VoI methods. This is inspired by earlier surveys, especially those of Yokota and Thompson (1961, 1968), and utilizes some of their taxonomies, for example, those for VoI solution methods. Our effort differs from previous ones in several ways: we are focused on the questions of interest to the high-level planning of VoI efforts in addition to the technical details of those efforts (e.g., which distributions are used) and so we encode more and different characteristics (e.g., regarding application context); as a new paper, we have new data which allow for longitudinal analysis of VoI practice; we extend statistical analysis to search for trends and relationships among the various characteristics of VoI applications beyond what has been done in this type of review (although, in part because we using judgment to encode characteristics, not to the level of a full bibliometric citation analysis). Our intent is to understand *what* is being done *when* and *where*—these data have not previously been compiled or analyzed—with an eye toward ultimately understanding *why* and *how* VoI should be applied and improved.

Through this analysis, we aim to investigate the evolution of the published examples applying VoI from the year 1990 to 2011. Over this time period, we check for trends in the varieties of VoI models that are used and in the range and type of fields in which the analysis is used. We restrict attention exclusively to work oriented toward a specific problem area, rather than purely abstract research. Section 2 describes how applications were identified, collected, and classified. Section 3 summarizes the data obtained, followed by formal statistical analysis in Sect. 4. In Sect. 5, we interpret the findings and discuss the possible reasons for the patterns observed and their implications for researchers and practitioners.

2 Methodology

We structured this study with the objective of gaining insight into help current and future practice. While a truly exhaustive screening was not possible, we aimed to find all possible available articles within our time range, rather than taking a statistical sampling. Articles were screened tightly to ensure that they were about genuine applications of VoI in the decision analytic context described above. After collecting articles, we encoded them according to the properties of interest to the practitioner: how models were structured and how they were directed toward problems. Articles were then classified manually to form our data set.

2.1 Search methodology

The Web of Science (WOS) and Elsevier SCOPUS databases were used to search over 8,300 major journals between 1990 and 2011. The following keywords were used to direct the search: “value of information,” “value of * information,” “information value,” “value of research,” and “value of sampl*.”

The initial search yielded well over 1,000 papers. The abstracts of these papers were screened for relevance to the mathematical application of VoI, resulting in approximately 350 papers. From there, duplicate papers were eliminated as were papers containing only theoretical models. We also screened out papers that contained VoI keywords in error (e.g., information about the value of the yen), as well as conference proceedings (which would be harder to characterize systematically), and papers that were not relevant to our study (e.g., valuing information by surveying people about how much they value it). A total of 252 papers remained, representing a large portion of the published applications of VoI over the last two decades (Appendix 2). Note, 22 papers were retrieved in 2011; however, many others were not yet available for download due to their recent publication and so were not included.

2.2 Paper classification

Based on the consultation with experts and past experience of the project team, a set of characteristics was developed that represent the choices practitioners must make in applied risk management and decision support projects as well as metrics that can be used for evaluating these characteristics (Table 1). Funding source, application area, and motivation are relevant in identifying where future projects may be supported. Source of information and method of data collection are relevant in populating a VoI model. Whether the model was applied is relevant in planning exploratory work. Many more characteristics relate to the modeling work itself. The number of alternatives in decisions modeled and the number of decision stages describe the decision itself. The type of utility function used and the units in utility determine how stakeholder concerns are captured. The number of uncertainties considered, the description (or type) of uncertain variables, and whether they are treated as independent or dependent describe the richness of information represented within the model. The VoI type, solution methods, and presence of sensitivity analysis characterize the calculations of a model. The interests of stakeholders in the model are indicated by whether information cost is explicitly included and whether the frame is one of avoiding losses as opposed to pursuing potential gains. Some characteristics are real-valued and unbounded (e.g., number of uncertainties). Others are categorical or binary, (e.g., “Is a sensitivity analysis present?” can either take a “yes” or “no” value).

All the data were obtained by examination of the models or the text in each paper. During initial quality checks, readers compared judgments to ensure consistent interpretation of the definitions. Most papers were encoded by a single reader, with some discussion when necessary. Multiple readers encoded a random sampling of the papers in order to confirm consistency. At the end of the study, a single reviewer went through all the papers in a final round to ensure consistent coding, and exceptions for which the coding was not obvious were discussed by the other authors to produce the final coding. All 252 papers were classified based on these characteristics.

2.3 Data evaluation and statistical analysis

The aggregated data were first analyzed at a high level, by observing general summary statistics and trends. Trends were visualized by plotting characteristics against time and against application area.

Table 1 Characteristics and Metrics used to classify and evaluate VoI publications

Characteristic	Metrics	Description
Funding source	Private, public, N/A, both	The source of funding for the analysis
Application area	Medical, infrastructure, information science, environmental, energy, economics, ecology, agriculture, other	The problem domain to which VoI is being applied
Motivation	Corporate, individual, government, hospitals (and other health care organizations)	The role of the intended decision-making user of model results
Source of information	Physical (e.g., soil analysis), market (e.g., transaction prices and volumes), survey, web (archived data sets intended to be publicly shared)	How data considered in the analysis are generated
Data collection	Model (e.g., no actual data only illustrative numbers), empirical, literature	How the author obtained data for the application
Applied?	Yes/no	Whether the work was conducted for a specific and real decision context, as opposed to a generic or stylized problem
Number of alternatives	Any positive integer or continuous	The number of alternatives in the stated decision problem
Utility function	Single or multiple variables	Number of considerations in the valuation of outcomes
Utility methods	Dollar, MAUT (meaning explicitly nonlinear utility functions), cost-benefit analysis (meaning having explicit having non-financial dimensions).	The units in which outcome value is calculated
Assumptions of dependence	Yes/no	Whether probability distributions for any variables were conditional on value of any other variable
Number of uncertainties	Any positive integer	Number of uncertain variables in the model
Description of uncertainties	Continuous, discrete, both	Type of uncertain variables in the model
Number of decision stages	Any positive integer	Number of points in time at which decision occurs in the model
VoI type	Perfect information, partial/sample/imperfect information, both	Type of VoI calculated in the study
Solving methods	Closed form, simulation, decision tree	Structure used to calculate VoI
Information cost	Yes/no	Whether the analysis accounts in some way for the costs of gathering additional information
Loss avoidance	Yes/no/ambiguous	Whether the featured decision focused primarily on avoiding potential negative consequences rather than on gaining positive results that improve the status quo
Sensitivity analysis?	Yes/no	Whether sensitivity analysis was included in the paper

From visual inspection of the various graphs, changes (both over time and in application) were noted, but their significance was not clear. To better make sense of temporal patterns, we divided the data into two 11-year period, 1990–2000 and 2001–2011. We can then compare the number of papers within each period in absolute terms (e.g., the total volume of papers identified by our screen was roughly three times greater in the second period than in the first) or in terms of proportions of the total papers in each period. Our goal was to confirm the visual trend and used p values calculated with a 2-sample, 1-sided test of proportions using the normal (Z) approximation. With this consolidation, we use statistical tests to determine where there were significant changes in the proportion of papers with various characteristics.

In order to identify patterns in the way that different VoI methods are applied in different situations, we created binary variables for membership in each category, for example, if a paper described an application to an energy problem, we set “Energy Problem” to 1 while other variables associated with the problem domain (“Medical Problem” and “Environmental Problem”) would be set to 0. We then checked whether the proportions of applications were consistent across categories. Many cases where there are significant differences are not meaningful, for example, it is not surprising that applications in the medical domain are more likely to have in mind a health care decision maker, or that private funded efforts are more common among applications with a corporate decision maker. We focus on the following three broad questions:

(a) Are there significant differences in how data or technical approaches are used in different problem domains?
(b) Are some combinations technical approaches more or less likely to be used together?
(c) Are some technical approaches more or less likely to be used with different types of data?

A set of chi-squared tests were used, similar to the proportion tests above, to explore the data for significant relationships in category proportions across pairs of characteristics. However, given the relatively small number of samples, we do not expect this to tell the whole story, that is, there may not be statistical significance even where there is a relationship, and given the many technical connections between the variables, such significance when it is found may often be spurious. So in addition to the formal calculations, we develop a set of observations about the relationships based on thorough inspection of the data.

3 Results

The data presented in Sect. 3 depict the distribution of applications and the change in applications over time. It is apparent that in most areas, the total number of applications has increased. In addition, the overall volume of VoI papers has greatly increased. Beyond that overall trend, we are concerned with trends and patterns in how VoI is applied.

3.1 Summary statistics and visual trend analysis

Table 2 presents the proportion of papers analyzed falling within each metric for each characteristic. Drilling down, we observe in Fig. 1 that some of the characteristics (utility method in this case) vary in prevalence by area of application, for example., medical applications tend to use cost-benefit-based value measures, while agricultural applications tend to use dollar value. Some of the patterns are clear, for example, 74 % of these studies were applied to generic situations but not to specifically identifiable individual decisions and decision makers. Simulation was the primary solution method (across application areas); information cost was most often not included (although this varies substantially by application area); the loss avoidance frame appears in 47 % of the applications (but this also varies substantially across areas). Sensitivity analysis is used in 29 % of papers, and there is not an easily identified difference in its use across areas. Additional patterns are also suggested, but not so clearly.

Figure 2 shows the number of applications per year by area, grouped into three-year period starting at 1990. The total has grown more than fourfold. Growth in the medical area appears strongest, while trends in other areas are less obvious. Note that "Other" contains a variety of application areas that did not commonly appear, such as Anthropology, Chemistry, Defense, Geology, Transportation, and Education.

To gain further insight, we charted the trajectory for the prevalence of projects categorized by various characteristics over the same time frame. For example, Fig. 3 shows an increase in the use of continuous uncertainties in applications of recent years.

3.2 Significance in temporal trends

We found that a number of trends were significant using a proportion (Z) test to compare the proportions for the two periods. Eight were highly significant with $p < 0.01$, eight more were significant with $p < 0.05$, and three more were weakly significant with $p < 0.1$. The p values for these trends are shown below, rounded to two significant figures. In Table 3, p values are shown for categories where changes were significant at any level, and those application dimensions for which any change appeared significant are indicated with an asterisk.

3.3 Trends in application patterns

Table 1 in the Supplemental Information lists the total number of applications within the category of interest for one characteristic at a time, and the number of these applications that fall into the various categories for another characteristic. For example, out of 75 applications that were ultimately connected to real problems, 34 used empirical data, while among the 191 applications that did not, 13 used empirical data. Table 4 indicates the significance of the relationship between each pair of characteristics. We note that there are indeed many significant relationships, including between the use of technical approaches and problem domains, data sources and other types of technical approaches. To explore these at the finer level of exactly which approaches are used under which circumstances, we now interpret qualitatively some patterns from Table 1 in the Supplemental Information.

3.3.1 Problem domains and decision makers

Applications vary across the range of characteristics, and in many cases, it appears this variation is associated with the area of application. These differences tend to be in the

Table 2 Application characteristics

Area	
Agriculture	35
Ecological	11
Economics	54
Energy	6
Environmental	30
Information	11
Infrastructure	6
Medical	81
Funding source	
Public	141
Private	26
NA	81
Both	4
Applied on real problem	
Yes	73
No	179
Utility function	
Single	209
Multi	43
Valuation method	
Dollar	125
CB	93
MAUT	34
Dependence	
Yes	23
No	229
Uncertainties	
Discrete	52
Continuous	147
Both	37
NA	16
VoI type	
Perfect	88
Imperfect	134
Both	30
Solution method	
Closed form	43
Simulation	175
Decision tree	34
Information cost	
Yes	90
No	162
Loss avoidance	
Yes	119
No	133
Sensitivity analysis	
Yes	77
No	175

Table 2 continued

Motivation (decision maker)	
Corporate	69
Individual	46
Public	64
Hospital	73
Source of information	
Physical	188
Market	45
Survey	16
Web	3
Data collection	
Model	123
Empirical	44
Literature	85

characteristics that connect the model to the real-world decision: those involving valuation of outcomes, sources of information to be used, and alternatives to a lesser degree. There is somewhat less variation across application areas with respect to internal model characteristics.

3.3.1.1 Values Applications in the Agriculture, Energy, Economics, and Information Science problem domains are more likely to use dollar value as the criterion than applications in the other domains. In contrast, the three domains involving human health (medicine, ecology, and environment) involve loss avoidance more often than other applications. This is not surprising, but still useful to note. Similarly, applications to ecological problems and applications involving a public decision maker are more likely to use multiple attributes in their value measure than are other applications.

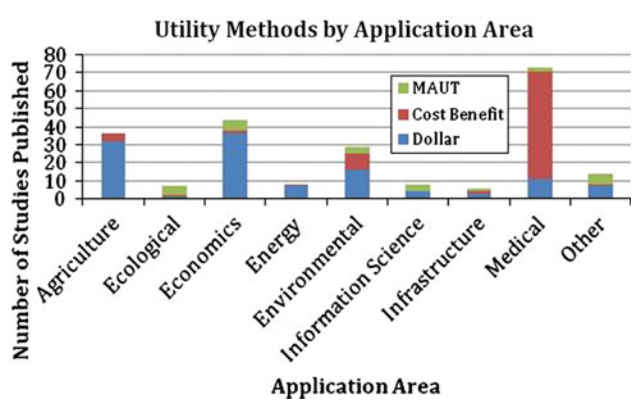

Fig. 1 The proportions of papers in each research area that utilized MAUT, cost-benefit, and simple dollar decision analysis methods

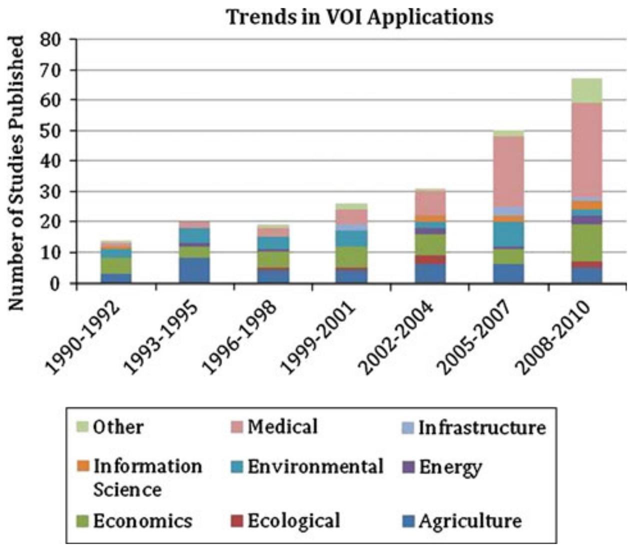

Fig. 2 Twenty-year trends of the use of value of information analysis in several scientific fields of study

3.3.1.2 Alternatives Perhaps, due to the fact that many medical interventions involve formal procedures for specific conditions, applications with a health care decision maker (or in the medical domain) are less likely than others to use continuous alternatives. In contrast, interventions for ecological problems span time and space, and the VoI models tend to feature more alternatives than other applications.

3.3.1.3 Information There are differences in the degree to which applications in different problem domains use information cost. Not surprisingly, areas that are largely business-oriented tend to rely on market information. Applications to energy problems use market information more frequently than do other areas.

3.3.1.4 Likewise Applications for both individual and corporate decision makers are more likely to use market information than are applications for public or health care decision makers. On the other hand, applications involving health care decision makers and public decision makers more often use physical (perhaps scientifically verifiable) information than are other applications. In fact, physical information is the dominant type in these applications. Applications to environmental problems involve larger systems and are less likely to use empirical data than are other applications.

While sources vary by application type, there is little variation in the distribution of the more modeling-oriented characteristic of using perfect versus imperfect information.

3.3.1.5 Other characteristics Several other points are observed regarding the type of application.

- Applications to economic problems, where mathematical theoretical models are common, more often use closed form solutions, whereas agricultural problems may be specific to the commodities and locations with unique parameter values and more likely to use simulation.
- Applications for corporate decision makers are more likely to be privately funded than are other applications. In fact, no applications to ecological problems in our study were privately funded.
- Although there is not an easily identified pattern, some areas (by problem area and by other characteristics) do have substantially greater proportions of applications to

Fig. 3 Types of random variables used by applications in each 3-year period 1990–2010

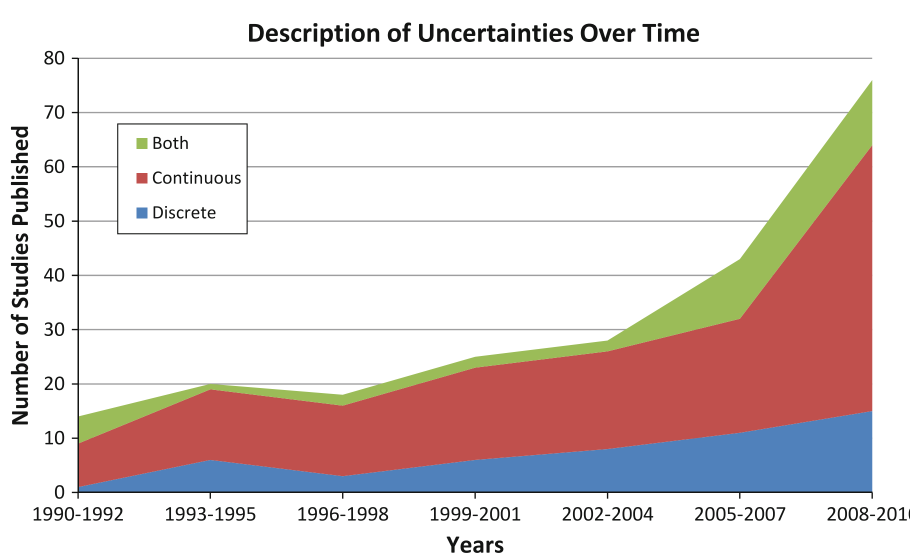

Table 3 Significance of changes in the proportion of applications from 1990–2000 to 2001–2011

Characteristic	Category	Trend	*p* value
Funding source*	Public	Increase	0.081
	Private/NA/both	None	–
Type*	Agriculture	Decrease	0.00073
	Ecological	Decrease	0.048
	Economics/energy/other	None	–
	Environmental	Decrease	0.0011
	Information science	Increase	0.048
	Infrastructure	Increase	0.0064
	Medical	Increase	0.00000068
Applied	Yes/no	None	–
Utility function	Single/multi-attribute	None	–
Method*	Dollar	Decrease	0.000020
	CB	Increase	0.000030
	MAUT	None	–
Dependence	Yes/no	None	–
Uncertainties*	Discrete/both	None	–
	Continuous	Decrease	0.043
	NA	Increase	0.068
VOI type	Perfect/imperfect/both	None	–
Solving method*	Closed form/simulation	None	–
	Decision tree	Increase	0.037
Information cost*	Yes	Increase	0.063
	No	Decrease	0.063
Loss avoidance	Yes/no	None	–
Sensitivity analysis*	Yes	Increase	0.012
	No	Decrease	0.012
Motivation*	Corporate/public	None	–
	Individual	Decrease	0.007
	Hospital	Increase	0.000022
Source of Info*	Physical/market	None	–
	Survey	Increase	0.068
	Web	Increase	0.040
Data collection*	Model	Decrease	0.046

real problems as opposed to illustrative problems, especially medical and to some extent ecological.

3.3.2 Technical approaches: model structures and techniques

Looking from a more technical perspective at the internal characteristics describing how models are built and solved, there seems to be some alignment that may reveal patterns of efficient modeling.

3.3.2.1 Values Applications in loss avoidance contexts are more likely to use cost-benefit criteria and less likely to use dollar value as a criterion than applications that are not in loss avoidance contexts. Related to this observation, applications that calculate VoI with decision trees are more likely to use cost-benefit value measures and less likely to use dollar-based value measures than applications that used other solution methods. In addition, information cost is more likely to be used in conjunction with cost-benefit value measures than with other value measures. These patterns may be due to the relatively frequent use of decision trees, cost-benefit value measures, and information cost in medical problems.

When multiple criteria are used, dollar value tends not to be used. Utility is relatively more likely to be used in multiple criteria rather than single criterion applications. When utility is used, applications are more likely to use closed-form solutions than at other times.

3.3.2.2 Uncertainties and alternatives Several features are associated with the use of a greater number of uncertainties. Applications that include sensitivity analysis feature more uncertainties than other applications, as do applications that use simulation and those involving perfect information. It may be that these modeling approaches can more effectively incorporate additional uncertainties. Applications connected to specific real problems also feature more uncertainties, perhaps because the need to incorporate specific uncertainties is more apparent on such applications. Similarly, real applications tend to include more alternatives than generic applications.

Certain features affect the number and type of alternatives used. Overall, the high use of continuous alternatives was a surprise to the authors. Still, while decision trees are not a dominant approach, they are used to some degree in almost all areas. Continuous alternatives more commonly associated with continuous uncertainties than are discrete alternatives.

Not surprisingly, applications that calculate VoI using decision trees do not use continuous alternatives. Somewhat less intuitively, applications involving loss avoidance are more likely to feature decision trees, discrete alternatives, and discrete uncertainties. This may again be driven by their frequency in medical applications, but it may also be that in loss avoidance contexts, less of the range of possible action is of interest than in gain contexts. Finally, applications involving imperfect information feature fewer alternatives than applications involving only perfect information. This may help to keep models tractable by limiting the number of end point conditions that must be considered.

3.3.3 Data

From the articles, there are patterns and non-patterns involving the type of data used. Although increasing, use of

Table 4 Significance of relationships between pairs of characteristics

	Funding source	Problem domain	Decision maker	Info type	Data source	Applied	Alter-natives	Attributes	Utility units	Depen-dencies	Continuous uncertainty	Discrete uncertainty	One decision stage	Perfect info	Imperfect info	Solution method	Info cost	Loss avoidance	Sensitivity analysis
Funding source																			
Problem domain																			
Decision maker	***	***																	
Info type		***	***																
Data source	**	*	**	***															
Applied	*	**	**	***	***														
Alternatives		***	***	**	*	*													
Attributes		***	**	*															
Utility units		***	***	***		*	***	***											
Dependencies		*																	
Continuous uncertainty		*					**												
Discrete uncertainty		**	***	*	*		***		*		***								
One decision stage											**	*							
Perfect info			*										***						
Imperfect info													***	***					
Solution method		**		**	***		*		*		*	**	***						
Info cost		***	***			**	***		***		**		***						
Loss avoidance		***	***	***	*	***	***		***		*	***	***			***	**		
Sensitivity analysis		**	***			*			***				***			*	**	***	

Key: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

survey data remains low across the board. Also, there seems to be little variation across problem domain in the frequency with which model data are used. However, real applications are much more likely to use empirical data (which is more likely to be available) than are other applications. Information cost may be more salient in applications with empirical data, and in fact it is more likely to be considered in such cases. While there is no reason to expect empirical data to follow well-behaved relationships and probability distributions, the researcher has more control when using model data, and such applications are more likely to use closed-form solutions.

4 Discussion and conclusions

Based on our own experience in the field, we have some informed speculation on what might be driving some of these trends and patterns, and what their implications may be for researchers and practitioners.

4.1 Temporal trends

4.1.1 Applications have moved from the organic toward the technological

While agricultural, ecological, and environmental applications decreased in proportion, infrastructure, medical, and information science applications increased. This may be due to the increasing role of technology in the world and the economy, or it may be due to a changed political climate.

4.1.2 Problem-driven aspects of technical methods are stable

For the most part, the choice of technical methods did not change significantly (utility functions, ultimate application, probabilistic dependence, perfect vs. imperfect information, and loss vs. gain focused problems). These technical choices may be driven mostly by the technical needs based on the scientific decision problem rather than by the capabilities of the analyst or the intended use by decision makers.

4.1.3 Growth in medical applications

In recent years, there has been greater concern about treatment cost, greater availability of tests that also have associated cost, and more centralized decisions about at least some medical guidelines. As a result, patients' risk may be managed by acquiring information, but only within limits. Not only does the decision structure (clear alternatives, clear information options, clear outcomes) make this a well-suited application, but there are institutions with a financial interest in VoI being applied, and a large number of rather clearly delimited problems (about one per disease) on which to apply it. Medical applications follow a distinct pattern. They tend to focus on loss avoidance and use single-attribute cost-benefit value measures, information cost, sensitivity analysis, decision trees, discrete uncertainties (and more of them), and discrete alternatives. This fact explains some of the changes discussed regarding the types of methodologies used.

4.1.4 Methods are influenced by available technology

Counter to the previous point is the increase in the use of explicit decision tree solutions and a corresponding decrease in the use of continuously distributed random variables, which may be due to something as simple as increased availability of associated software. Since simulation software is also more available but has not increased in use, there may be another explanation. Decision trees are quite well known. The use of continuous distributions tends to require more mathematical sophistication on the part of the researcher or modeler, and it may be that as the usefulness of VoI becomes more widely appreciated, it is being used by people more based on the areas of applications rather than by decision analysis specialists reaching out to those fields. We also found increased use of surveys and secondary web-based sources (e.g., archived data sets intended to be publicly shared), and less use of models without actual data. This trend may be due to easier availability of these types of data. Whether or not that is the driver, it represents an advance in ability to produce relevant results.

4.1.5 More focus on producing insights

We found increased use of aspects of the analysis that focus on producing insight of various types. Sensitivity analysis allows broader application beyond the case analyzed, incorporation of costs of analysis allows for the development of testing strategies, while use of cost-benefit rather than dollar-based value metrics allows for application across richer institutional problem domains than, say, solely profit or cost-driven business decisions. All of these trends are consistent with the movement away from problems of individual decision makers and toward those of institutions, especially in health care.

4.2 Trends in application patterns

4.2.1 Applications differ across problem domains

The list of observations in the previous section largely speaks for itself. The growing medical area seems quite distinct from others. Beyond that, values are modeled differently for public- and private-oriented applications. Types of information and detail of uncertainties differ by area depending on the extant knowledge in that area (e.g., scientific vs. market issues). Otherwise, we do not see much difference in technical approaches across domains.

4.2.2 *Technically sophisticated methods may be synergistic in use*

Examples of sophisticated methods include use of continuous variables and conducting sensitivity analysis. Perhaps, models with more underlying mathematical structure (e.g., continuous variables) are more easily manipulated to produce a range of results (e.g., sensitivity analysis), and thus, if it is worth developing the former, it is worth including the latter.

4.2.3 *Greater detail in one dimension may be balanced by less detail in another dimension*

For example, imperfect information is associated with fewer uncertainties and alternatives. Part of the art of modeling is deciding which dimensions to develop in order to gain insights without getting swamped in data requirements or outputs.

4.3 Conclusion

The overall picture is that of a rich field of practice taking on larger and more complex problems in a way that is more enmeshed with governance in a number of areas. VoI is not difficult to use, especially in contexts where extensive probabilistic analysis is already being performed. Thus, it is our hope that, as awareness of the VoI and its usefulness grows, it may find more use, for example, as a method in risk analysis. If so, we may see more focus on loss avoidance problems, perhaps with increased use of loss functions for utility. Given the rich environment in which risk analysis is practiced today, we may also see more use of multi-attribute value models (at least compared to earlier use of VoI in risk analysis). Finally, VoI may be a bridge that allows risk analysis to connect more strongly with fields that already use decision analytic techniques, especially health care.

Viewing this survey from the perspective of the applied researcher, we find these results appealing. There is fertile ground for relevant and interesting applications that use standard calculation methods but dig deep in order to obtain the most useful results. Of course, use of VoI techniques is constrained by what modelers and decision makers have articulated, that is, the variables, their uncertainty, and potential sources of information about them. This makes it important to focus on better understanding of the broader context within which decisions are made and how information acquisition may improve them. Alternatively, theoretical research could develop an understanding of the robustness of VoI, that is, when decision models can achieve a high level of precision in the valuation of information even when their valuation of alternatives is less precise. There is also the possibility of expanding the role of VoI. For example, VoI can be automated and applied on many decisions in parallel, for example, to guide data mining, or to prioritize research about a portfolio of new technologies (Linkov et al. 2011). While emerging analytics techniques are effective at rapid and large-scale characterization of statistical relationships, the challenge here is to combine it with similarly efficient characterization of decision problems. Finally, because information itself can be structured in infinitely many ways, there is much potential to adapt VoI techniques to varied situations as the creativity of the modeler allows.

The finding that more detail in one area (e.g., number of alternatives) is balanced by less detail in others (e.g., number of uncertainties) may be of practical significance. An underlying issue in facilitating the use of VoI in established application areas, as well as in developing new applications, is the cost of modeling. Analysts and their clients have limited time, which makes larger and more complicated models less desirable. However, we do not see consideration of the cost of modeling discussed either explicitly or implicitly in the VoI literature. Better integration of this concept would likely increase the acceptability and attractiveness of VoI methods to potential users. There is value in understanding the range and trends in VoI applications. For researchers and practitioners considering possible new applications, this insight may help in order to: find areas where VoI has been successful or growing, and so can be expected to remain useful; to find the ways in which VoI has been and is becoming successfully applied across settings, and so can be expected to prove useful if applied in similar ways in future similar settings; or to identify areas or ways in which VoI has not yet been applied in order to identify untapped potential for its use.

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Appendix 1

As an example of VoI in use, consider the following case in which a decision maker has two options, to continue passively or to make an investment. Continuing passively has a payoff of $*10*, while investing has an uncertain payoff, $*x*. The decision maker believes that if conditions are favorable to the investment, *x* will be 1,000; if conditions are neutral, *x* will be 100; and if conditions are unfavorable, x will be −500. Furthermore, the decision maker believes there is a 50 % chance conditions will be unfavorable, a 30 % chance they will be neutral, and only a 20 % chance they will be positive. Without any additional information about conditions, the decision maker will choose to do nothing, because the expected value of the investment is 50 % * (−$500) + 30 % * $100 + 20 % * $1,000 = −$20, which is worse than continuing passively. However, if the decision makers were to obtain perfect information about investment conditions before acting, there is, naturally, a 50 % chance they would be revealed to be negative, a 30 % they would be neutral, and a 20 % chance they would be positive. If conditions were found to be negative, the decision maker would still be passive and receive $10, but if conditions were found to be neutral or positive, the decision maker would invest and receive a payoff of $100 or $1,000, respectively. Thus, with this information, the decision maker has an expected payoff of 50 % * $10 + 30 % * $100 + 20 % * $1,000 = $235, an increase of $225 over the original situation. The increase in expected value from $10 (by continuing passively in all cases) to $235 (by being passive only when conditions are poor) results from having information prior to the decision. If the decision maker is concerned with expected monetary value, we call this increase, $225 in this case, the "expected value of perfect information."

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