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Joseph Kasprzyk
University of Colorado Boulder, joseph.kasprzyk@colorado.edu

Joshua Kollat
DecisionVis, jkollat@decisionvis.com

Chris Danilo
DecisionVis, cdanilo@decisionvis.com

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Balancing Conflicting Management Objectives Using Interactive, Three-Dimensional Visual Analytics

Joseph Kasprzyk[1], Joshua Kollat[2], Chris Danilo[2]

1. University of Colorado Boulder, Civil Environmental and Architectural Engineering, UCB 428, Boulder, CO, 80309, USA (joseph.kasprzyk@colorado.edu)
2. DecisionVis, LLC, State College, PA, USA (jkollat@decisionvis.com; cdanilo@decisionvis.com)

Abstract: In the US, the recently introduced Principles and Requirements for Federal Investment in Water Resources captures an increasing trend for using multiple objective approaches to make funding decisions for water resources and environmental problems. Moreover, advanced search tools such as multi objective evolutionary algorithms can develop solutions to such problems, even when the problems are characterized by non-linearities, uncertainty, and false optima. However, our presentation argues that multiobjective decision support requires innovative methods for visualizing complex tradeoffs between conflicting objectives, interrogating design possibilities, imposing preferences between objectives, and eventually negotiating a small set of final alternatives. Specifically we present a recently developed version of a software framework called AeroVis, which interfaces with spreadsheet software to integrate tabular visualizations of data with immersive, three dimensional glyph plots that show up to 7 objectives simultaneously. AeroVis has been used both in the design of complex engineered systems as well as water resources management decision making problems. Our results show how a large amount of information can be quickly processed by the user, integrating the emerging concept of "big data" to support environmental decision making with human pattern recognition.

Keywords: Visual analytics; multi-objective optimization; Evolutionary algorithms

1 INTRODUCTION

Cost-benefit analysis, the practice of aggregating all of a project's benefits together and comparing to cost to determine funding, started in the U.S. with the Flood Control Act of 1936 (Reuss, 2005). Flood control is a poignant example of a decision making problem that is fraught with conflicts between objectives and uncertainty. For example, in order to provide reservoir storage to mitigate flood waves, planners often have to lower the amount of storage that is available for drinking water. These objectives usually also conflict with managers' desire to provide storage for recreational uses such as boating or fishing. Therefore, a single-objective cost benefit analysis may be problematic for such problems. Although researchers at the Harvard Water Program espoused a multi-objective planning approach as early as 1962 (Maass et al. 1962), technological limitations precluded formal multi-objective planning until recently. A multiobjective approach to decision making was recently advocated by the new US Principles and Requirements for Federal Investiments in Water Resources (US CEQ 2013)

A type of analysis termed Many Objective Analysis (MOA) is gaining popularity in facilitating decision making. The term 'many objective' in the acronym refers to optimization problems of four or more objectives, which can be difficult to solve (Reed et al. 2013). Optimization within MOA seeks to find values of decision variables (in other words, actions that decision makers or designers can take) that balance multiple conflicting objectives (quantitative metrics of solution performance). Unlike traditional optimization, MOA uses multiobjective evolutionary algorithm (MOEA) optimization, which embeds simulation models in the problem in order to evaluate candidate solutions' performance. Therefore, if planners "trust" the simulation model, there is more "buy-in" with the results. As an example of a recent use of MOA in a real decision making context, Basdekas (2014) discusses use of MOEAs for drought policy analysis at Colorado Springs Utilities (CSU). In the CSU study, they evaluated different drought policies (the decision variables) with respect to multiple objectives including delivering water in the current year versus hedging the supply to store for future droughts. They found that by generating and evaluating new management alternatives with a MOEA, their performance was better in almost all metrics compared to their baseline starting scenario. Their manuscript also posits that human decision making is a key part to a MOA analysis, stating "[g]ood analytical skills are required to formulate reasonable objective functions and then process the results in a meaningful way in order to evaluate the metrics together with any state variables. We cannot remove the human element from the most complex analysis, and there must be a willingness to deeply investigate results" (Basdekas 2014, p. 276).

This presentation introduces and demonstrates AeroVis, a software platform originally developed at Penn State University and now by DecisionVis, LLC, which facilitates detailed, interactive analysis of MOEA tradeoff results. Our intent is to complement other presentations at this conference, including use of these visualizations in a decision making context (Herman et al. 2014a) and an exploration of the types of reasoning that can be performed using the software (Kasprzyk et al. 2014). In the remainder of the paper, we will provide background on MOA optimization and visualization, explain an illustrative example, and provide concluding remarks.

2 BACKGROUND

2.1 Multiobjective Optimization Using MOEAs

In general, optimization seeks to modify values of decision variables to improve one or more objective functions. Classical optimization, such as linear programming (LP), has a strict requirement that the objective function and constraints are linear functions of the decision variables. Solving a LP can yield solutions that can be proven mathematically optimal, and LPs have found favour especially in applications that have few uncertainties. However, in environmental applications, it is often difficult to formulate an LP without providing simplifying assumptions that reduce the fidelity of the analysis. In the flood planning example from the prior section, reservoirs are often managed with "if-then" type rules based on the time of the year and the elevation of the reservoir. Planners often use detailed simulation models of such systems, and analysis can progress by formulating an LP and then analysing the results in a detailed simulation model (e.g., Jacoby and Loucks 1972).

Multiobjective Evolutionary Algorithms (MOEAs) alleviate the challenges of creating simplified objective functions by using simulation models directly within the search. MOEAs are a population based search procedure, which means they operate on a population of multiple candidate solutions instead of one. The MOEAs use an iterative process of selecting good solutions and combining them in novel ways to "evolve" the population of solutions toward better and better objective function values. MOEAs have multiple objectives to quantify performance, so as the search progresses, the population gets closer and closer to what is called the Pareto optimal front. In general, solutions are Pareto optimal if you cannot achieve better objective function performance in one objective without degrading performance in another. In order to mathematically prove Pareto optimality, an analyst would need to enumerate each feasible solution in the search space, comparing these solutions to all others to find which solutions are Pareto optimal. In practice, this is difficult or impossible for complicated problems, so a MOEA is able to find Pareto-approximate solutions, which are locally 'non-dominated'.

For more information on MOEAs, please consult the following references. General references on MOEAs are given by Deb (2001) and Coello Coello et al (2007). Nicklow et al. (2010) reviews use of MOEAs in water resources problems, and Efstriadis and Koutsoyiannis (2010) review their use in multiobjective calibration. Reed et al. (2013) provide a comparative analysis of state of the art MOEAs on several water resources planning problems, and several studies in this conference utilize MOEAs (Herman et al. 2014a, Kasprzyk et al. 2014, Houle and Kasprzyk 2014), as well as many recent published studies (for some examples see Kasprzyk et al. 2012, Mortazavi et al 2012, Kollat et al. 2012, Herman et al. 2014b, Hurford et al. 2014).

2.2 Interactive Visual Analytics

Interactive visual analytics refers to the use of an interactive system of multiple, linked views of data (e.g. Keim et al. 2010), which can facilitate an analyst's understanding of multivariate datasets. Woodruff et al. (2013) review several available packages for visual analytics, including popular commercial software including JMP, R, and MATLAB. Our position is that while such software can aid in the analysis of data from a MOA analysis, MOA is well served by specialized software that can handle the unique data and analysis requirements of the approach. AeroVis was designed to meet these requirements, including (i) providing interactive plotting, including multiple types of plotting instruments (e.g. shapes) to show tradeoffs in up to seven dimensions (ii) handling plotting a dataset that changes in time, to show progressions of MOEA search (iii) showing individual attributes of solutions, including their decision variable and objective values and (iv) "brushing" solutions out of view and imposing mutable visibility preferences on the dataset.

The main plotting mechanism of AeroVis is three dimensional visualizations of "glyphs," where the coordinate positions of the glyphs indicate the values for plotted data. Additionally, properties of the glyphs can be used to indicate other values, including their size, color, transparency, and orientation (used mainly for cones, which have a clear direction of orientation). These properties function as additional "axes" or "dimensions" on which a user can plot their variables of interest. An example of such a plot is shown in section 3; which uses color, orientation, and three dimensions of space simultaneously. A further strength of AeroVis is that it allows the user to interactively explore their dataset by physically rotating and zooming into the plotting space, immersing the user in the data. The user can quickly change which axes are plotted, and also modify the plotting bounds to focus on a certain region of the space. As mentioned earlier, brushing allows the user to impose preferences on both plotted and unplotted variables. This allows users to ensure that their constraints permeate the entire data set to reflect the viewer's preference, whether or not the data are visible in the current plot. AeroVis was developed as an academic tool specifically for water resource management, but is now being recast commercially to suit other fields (e.g. Aerospace Engineering, Electrical Antenna design).

For more information on plotting in multiobjective datasets, please consult Lotov and Miettinen (2008), Kollat and Reed (2007), Stump et al. (2009) and Woodruff et al. (2013).

3 ILLUSTRATIVE EXAMPLE

This section presents a brief example of an AeroVis visualization from prior research. The example comes from a study in review at Journal of Hydrology (Matrosov et al. In-Review), where the authors sought to develop long-term infrastructure planning for the Thames Basin in London, UK.

Surprisingly, although London is often considered a humid place, there have been several severe droughts over the last 90 years. Climate change and population growth exacerbate these concerns. Water managers are considering portfolios of management strategies, including building a new reservoir, enacting water transfer schemes, and improving efficiency (i.e., leak reduction). Current evaluations of such plans use a single objective cost benefit analysis to determine the optimal choice of strategy. The approach in Matrosov et al. (In-Review) seeks to show tradeoffs between conflicting objectives for the Thames problem and allow the consideration of many portfolios, as compared to only a small number. A representative plot from this work is shown in Figure 1.

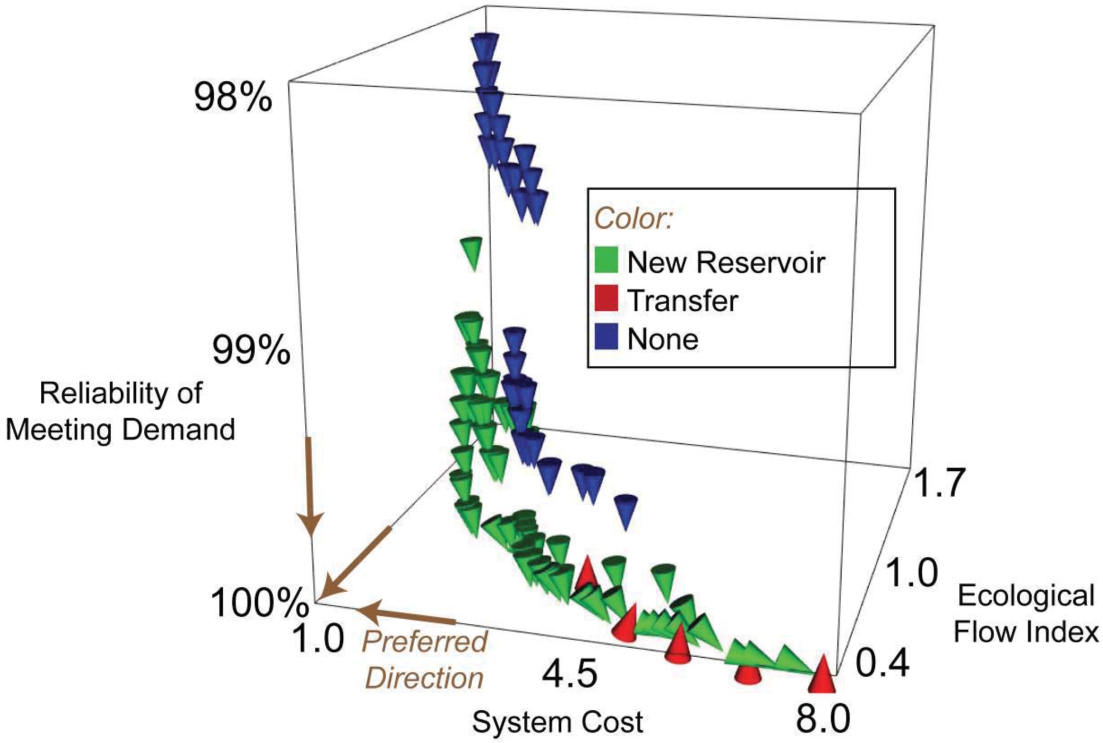

Figure 1 Representative AeroVis result, where orientation shows higher energy use as cones point toward the top of the figure, with a tradeoff adapted from Matrosov et al. [In-Review].

Spatial axes in Figure 1 show planning objectives for the problem. The ecological flow index is a measure of the variance of outflow at one of the supply nodes; lower values are preferred (as shown by the brown arrow). Cost aggregates operating and capital costs, with lower costs toward the left corner of the plot. The third axis shows the reliability of meeting London's demand, with higher reliabilities plotted toward the bottom part of the plot. The cone glyphs each represent one portfolio of options for the system, and the cones' spatial coordinates indicate the values on each of the axes. If there were a plan that met all three objectives, there would be a glyph at the lower left corner of the plot. However, there is a clear tradeoff, because for example lowering system cost also reduces the ecological flow index and reliability. Recall that AeroVis is an interactive program, so users can impose preferences on objectives to determine if there are solutions that meet all their needs (e.g. cost thresholds due to budgetary limitations).

An additional set of plotting mechanisms in Figure 1 gives more relevant information for decision makers. For example, the colour of the glyphs can be used to plot variables (e.g., objective function values or, as shown in Figure 1, attributes of the design of the portfolios). In the study, two of the infrastructure decisions were mutually exclusive: building a reservoir, and providing a large transfer scheme. Three colours are used in the plot: green points show portfolios that built the reservoir, red points show portfolios that enacted the transfer scheme, and blue solutions did neither (note that AeroVis also supports other colour schemes that are compatible with colour-blind users). Orientation of the cones shows each portfolio's energy use (i.e., for pumping), with cones pointing toward the top of the figure using more energy than the cones point toward the lower part of the figure.

Combining all plotting mechanisms yields some interesting insights about the Thames tradeoffs. For example, solutions that enact the transfer end up using a lot of energy (which is intuitive because transferring water requires pumping). These solutions, though, are able to maintain good performance with ecological flows and supply reliability, although they are costly. Comparing the green solutions to the blue ones, it is apparent that building the reservoir allows better reliability and ecological flow performance, and cost (in other words, the green solutions are slightly closer to the lower left corner of the figure compared to the blue solutions).

Each glyph in the figure represents an entire portfolio of schemes. When using AeroVis on this problem, the analyst can change which variables are plotted and rotate the plot to see different views. Some additional views can be seen in the study manuscript (Matrosov et al. In-Review). The analyst can also easily interrogate the qualities of individual designs by utilizing several plugins that interface with programs like Matlab and Microsoft Excel. Kollat and Reed (2007) also gives an example of how a dataset can be viewed in many different ways to increase the analyst's insight. For more information please consult companion studies in this conference: Kasprzyk et al. (2014) seek to explore the types of reasoning that can occur when using AeroVis: Harou (2014) discusses the Thames work in the context of new methodologies for water planning.

4 CONCLUSION

In this study, we have introduced how multiobjective evolutionary algorithm search, and interactive visualization can help aid environmental management problems. The specific tool we are introducing is called AeroVis, and we also review several studies that have presented similar visualization approaches. A short illustrative example showed the type of insights that can be gained from a single multiobjective tradeoff plot.

As the popularity of multiobjective evolutionary algorithm decision support grows, it will be critical to enable visualizations and improved mechanisms for analysing the large volume of data that comes out of such work. Interactive visual analytics exploits the power of human cognition with the graphical capabilities of computers. We encourage the use of these tools to further advance the practice of using environmental modelling and software to help decision making. Such visualizations could be used in advanced, three dimensional virtual environments in the future. The AeroVis software is freely available for academic and non-commercial users at https://www.decisionvis.com. Similarly, more information about the Borg MOEA can be found at http://www.borgmoea.org for academic users or the DecisionVis website for commercial inquiries.

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