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Many-objective Management of Population and Drought Risks: A Case for De Novo Programming

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Abstract: There is a growing consensus that non-structural supply management instruments such as water markets have significant potential to reduce the risks and vulnerabilities in complex urban water systems. This paper asks a common question, “What are the tradeoffs for a city using water market supply instruments?”. This question emerges quickly in policy and management, but we contend its answer is deceptively difficult to attain using traditional planning tools and management frameworks. This paper demonstrates these issues using visualization and many-objective planning tools demonstrated in the context of a city in the Lower Rio Grande Valley (LRGV) of Texas, USA determining how to use its regional water market to manage population and drought risks.

Keywords: many-objective optimization, visual analytics, sensitivity analysis

1. INTRODUCTION

In this paper we demonstrate a broader exploration of the issues of “nonstationarity” and “uncertainty” in urban water planning. As we invest in new information and prediction frameworks for the coupled human-natural systems that define our water resources, our problem definitions (i.e., objectives, constraints, preferences, and hypotheses) themselves evolve. From a formal mathematical perspective, this means that our management problems are structurally uncertain and nonstationary (i.e., the definition of optimality changes across regions, times, and stakeholders). This uncertainty and nonstationarity in our problem definitions needs to be more explicitly acknowledged in *adaptive management* and *integrated water resources management*.

In this research, we propose to merge innovations in many-objective search [Kasprzyk *et al.*, 2009], visual analytics [Sanfilippo *et al.*, 2009], and de novo programming [Zeleny, 1981; 1989; 2005] to better address the nonstationarity and uncertainty in water management models’ formulations. This work represents a shift in focus from classical efforts to define the single optimal solution towards more rigorous evaluations problem formulations. Specifically, we are focusing on answering the question: *what is the nondominated problem formulation?*

2. SENSITIVITY INFORMED MANY-OBJECTIVE DE NOVO ANALYSIS

As highlighted by Zeleny [2005] our conception for optimality is dynamic and should account for the processes of learning and exploration. This philosophy has been repeatedly motivated within the systems planning and decision science literature [Brill *et al.*, 1990; Tsoukias, 2008]. In this paper, we are building on the recent work of Kasprzyk *et al.* [2009] to consider the potential benefits of a formalized methodology for de novo (i.e., adaptive) many-objective problem formulation that formalizes our ability to attain and

incorporate new problem knowledge into our management formulations. Figure 1 provides an overview of the primary components of our proposed methodology.

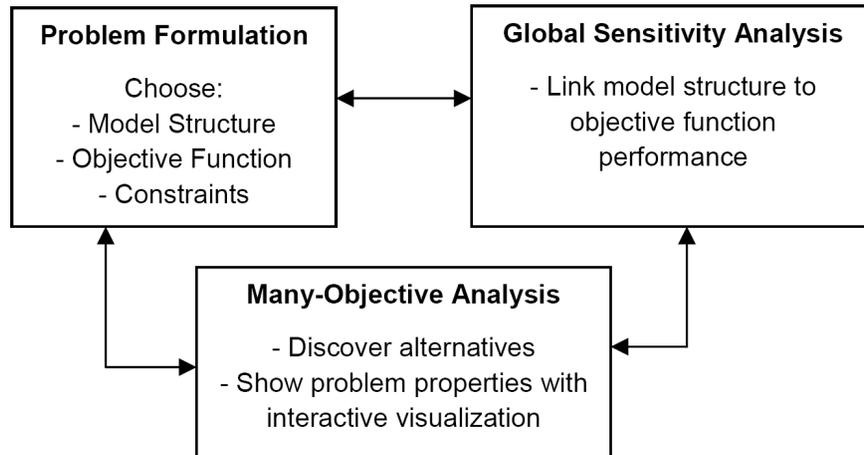


Figure 1. De novo analysis composed of an iterative advancement through problem formulation, global sensitivity analysis, and many-objective optimization.

Using the urban water portfolio planning context from Kasprzyk et al. [2009], we will demonstrate an example de novo many objective analysis. In this analysis, we will further explore a critically constrained urban water planning formulation shown to prevent severe water shortfalls for severe droughts. Kasprzyk et al. [2009] designated this problem formulation as CASE D in their analysis. The case explored the tradeoffs between 6-objectives (cost, reliability, surplus water, dropped transfers, number of leases) that result from the decisions for purchasing permanent rights to reservoir inflows, a two-period risk-based threshold for leasing water transfers, and an adaptive options contract. This initial problem formulation is then used in our subsequent global sensitivity analysis.

3. GLOBAL SENSITIVITY ANALYSIS

We are interested in the full multivariate controls that our permanent rights, leases, and options decisions have on a range of objectives. Are they all important? Necessary? We evaluated these questions using Sobol global sensitivity analysis [Sobol, 2001]. The approach can be classified as a variance decomposition technique which can provide insights into the 1st order single parameter effects and interactive parameter effects [Saltelli, 2002; Tang et al., 2007]. In our analysis, we have divided LRGV water portfolio performance criteria into efficiency and risk metrics.

Figure 2 on the subsequent page provides a summary the sensitivity rankings. In the figures total order effects represents the full sensitivity of a decision variable in terms of its individual impacts and its interactions with other decisions. First order effects represent the contribution to the model's ensemble variance by a single decision. The difference between total and first order effects provides a sense of the interactive multi-decision sensitivities. It should be noted that a high-degree of interactive effects causes search problems to be more difficult because multiple decision variables impact performance in component objectives.

The results of Figure 2 show a fair level of insensitivity for many of the decision variables used by Kasprzyk et al. [2009] in the CASE D formulation. The permanent rights and alpha variables impacting leasing provide the strongest sensitivities across the range of metrics tested. The variables for options contracts and the Beta controls on the magnitude of transfers are shown to have a limited impact. The risk indicator metrics show a very strong degree of interaction relative to the efficiency metrics.

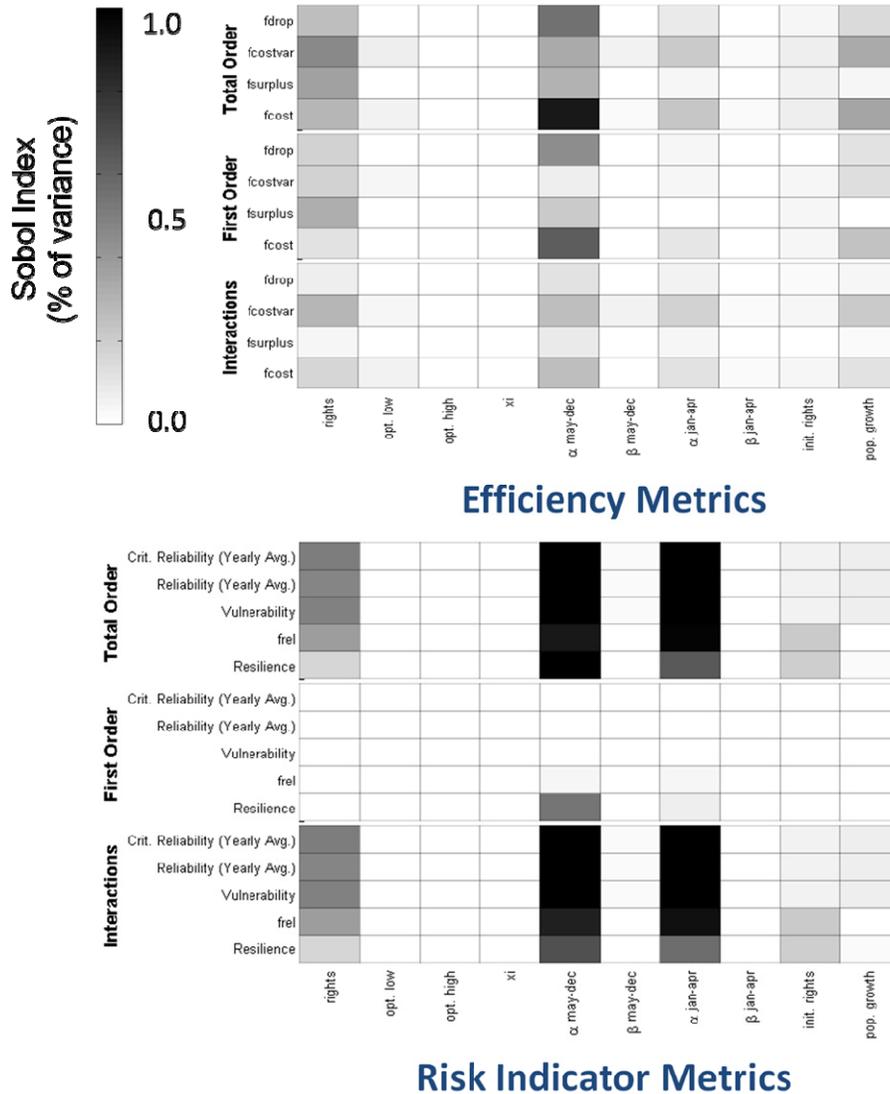


Figure 2. Metrics of interest are shown in rows while variables are shown in columns, with darker shades of gray indicating higher Sobol indices, and more sensitive parameters.

4. WHAT IS THE NON-DOMINATED PROBLEM?

The sensitivity results from Figure 2 motivate the potential to explore simplifications of the CASE D formulation from Kasprzyk et al. [2009]. Figure 3 provides a synopsis of 4 problem instances analyzed to determine structural changes in our many-objective water portfolio analysis. The figure shows alternative formulations of the problem from the simplest variant focused on permanent rights and the use of a single alpha trigger for options/leases to the full CASE D formulation (designated formulation IV). The second formulation uses a winter and summer risk threshold for leasing or optioning water. The third formulation adds the beta decision that provides a factor of safety by providing a percentage increase in the alpha purchasing decisions. The fourth formulation includes the full adaptive options contract, multi-period alphas, and betas. In evaluating these problems, we sorted them based on their resultant optimized many-objective tradeoffs to

yield a the sorted color-coded results in Figure 4. Figure 4 provides a multiobjective evaluation of the problem formulations where a portfolio solution for any given formulation has to be nondominated in the application's six objectives (i.e., they cannot be exceeded in performance in all six objectives and have to be better in at least one objective).

	Volumetric Decisions	Strategy Decisions	Percent of Set
I	Permanent Rights, Static Options Contract (single-volume)	Alpha: "when / how much water to acquire"	36%
II		Alpha (Jan-Apr), Alpha (May-Dec)	20%
III		Alpha (Jan-Apr), (May- Dec): "when" Beta (Jan-Apr), (May- Dec): "how much"	18%
IV	Permanent Rights, Adaptive Options		26%

Figure 3. Decision variable sets of increasing complexity used from the simplest formulation to the full adaptive options, leasing, and permanent rights approach of formulation IV. Also shown in the percentage of solutions each formulation contributes to the best overall nondominated solutions across all formulations.

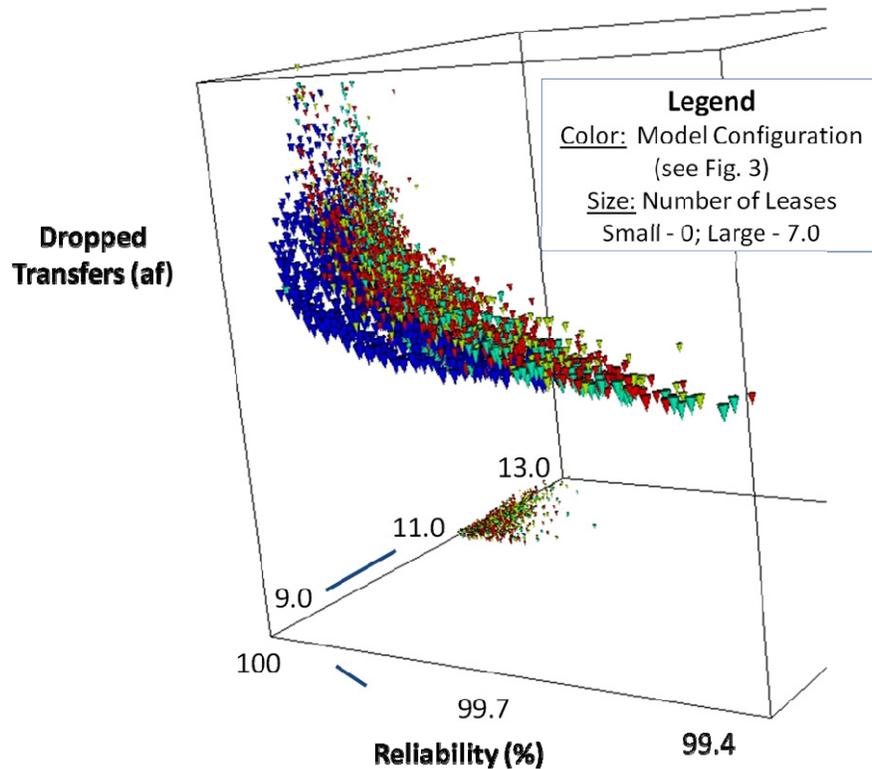


Figure 4. Reference set combining each formulation analyzed where Blue = I, Aqua = II, Yellow = III, and Red = IV from prior figure.

Figure 4 shows that the simplest formulation generally minimizes dropped transfers, maintains lower costs, and attains high reliabilities by using leases. Overall the results demonstrate that the more complex formulations serve to identify solution near the bounding the values of each of the six-objectives considered. In general the simplest formulation dominates the other problem instances in the compromise region of the LRGV planning problem's tradeoffs. This has the computational benefit of potentially reducing the computational demands posed by the application while enhancing its solution.

5. CONCLUSIONS

Risk-based management strategies for water systems often require the consideration of a broad range of performance metrics (cost, risk, reliability, adaptability, etc.). This increase in the complexity of the problems must be accompanied with methodological advances that allow decision makers to better understand the benefits, limits, and controls in how they represent systems with their problem formulations. This paper demonstrates a formalized de novo framework that has the potential to provide more informed, evolving representations of water management problems. The case study builds on prior results for the LRGV water market and demonstrates that a strongly simplified policy and decision representation of water portfolio planning problem can provide enhanced results. This work move beyond classical multiobjective analysis by shifting the focus from optimal solutions towards improved problem formulations.

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