Taking Uncertainty into Account in Data Processing and Decision Making: An Overview of the Current Research

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1. Outline

- General Techniques for Processing Uncertainty
  Presenter: A. Pownuk
- Applications to Geophysics & Geotechnical Engr.
  Presenters: A. Gholamy and P. Barragan
- Applications to Environmental Science
- Applications to General Image and Signal Processing
  Presenters: F. Cervantes and C. Servin
- Applications to Systems
  Presenter: F. Zapata
- Decision Making Under Uncertainty
  Presenters: M. Afravi and M. Osegueda
- Applications to Education
  Presenters: V. Felix and J. Lorkowski

2. General Techniques for Processing Uncertainty: Team

- Rodrigo Romero, PhD
  Electrical and Computer Engineering
- Andrzej Pownuk, PhD student
  Computational Science

3. General Techniques for Processing Uncertainty: Project

- How uncertainty with which we know inputs $x_1, \ldots, x_n$ affects the result $y = f(x_1, \ldots, x_n)$ of data processing?
- There are many *efficient algorithms* for interval and for probabilistic uncertainty.
- However, there are also *open problems:*
  - What if we only have partial information about probabilities?
  - Methods are often slow; how can we speed them up?
  - How to take into account that the model $y = f(x_1, \ldots, x_n)$ is usually also only approximate?
- *What we do:* we have developed techniques for all three open problems.

4. Publications

- Vladik Kreinovich, Andrzej Pownuk, and Olga Kosheleva, "Combining Interval and Probabilistic Uncertainty: What Is Computable?", in: Panos Pardalos, Anatoly Zhigljavsky, and Julius Zilinskas, *Advances in Stochastic and Deterministic Global Optimization*, Springer Verlag, to appear.
- Andrzej Pownuk, Olga Kosheleva, and Vladik Kreinovich, "Limitations of Realistic Monte-Carlo Techniques", *Proceedings of the 7th International Workshop on Reliable Engineering Computing REC'2016*, Bochum, Germany, June 15–17, 2016, to appear.

5. Publications (cont-d)

- Vladik Kreinovich, Olga Kosheleva, Andrzej Pownuk, and Rodrigo Romero, "How to Take into Account Model Inaccuracy When Estimating the Uncertainty of the Result of Data Processing", *Proceedings of the ASME 2015 International Mechanical Engineering Congress & Exposition IMECE'2015*, Houston, Texas, November 13–19, 2015.
- Chrysostomos D. Stylios, Andrzej Pownuk, and Vladik Kreinovich, "Sometimes, It Is Beneficial to Process Different Types of Uncertainty Separately", *Proceedings of the Annual Conference of the North American Fuzzy Information Processing Society NAFIPS'2015 and 5th World Conference on Soft Computing*, Redmond, Washington, August 17–19, 2015.

6. Applications to Geophysics and Geotechnical Engineering: Team

- Afshin Gholamy, Doctoral Student
  Geological Sciences
- Perdo Barragan Olague, Undergraduate Student
  Computer Science
- Carlos Tafoya, Undergraduate Student
  Computer Science

7. Applications to Geophysics and Geotechnical Engineering: Project

- In geophysics and in geotechnical engineering, there is a need for a lot of data processing under uncertainty.
- As a result, researchers and practitioners have come up with many successful data processing techniques.
- These techniques have two major limitations:
  - they are not theoretically justified; so there's no guarantee that they will work on other examples;
  - they are not perfect, and it is not a priori clear how to improve them.
- Our team's objective:
  - find theoretical justification for the existing techniques, and
  - use these justifications to come up with more general techniques.

8. Applications to Geophysics and Geotechnical Engineering: Details

- In general, we are looking for a function – e.g., for the dependence on density $\rho(x)$ on spatial location x.
- We need to determine this function from observations.
- To describe a general function, we need to use infinitely many parameters – e.g., all its values $\rho(x)$.
- However, we have only finitely many observations.
- So, we can only determine finitely many parameters.
- We thus need to select a finite-parametric family of functions.
- Empirically, in many problems, special Ricker wavelets work the best.
- In our work, *we have justified* the use of Ricker wavelets and provided a more general family of wavelets.

9. Applications to Geophysics and Geotechnical Engineering: Details (cont-d)

- Inverse problems are ill-posed: without additional constraints, we cannot reconstruct $\rho(x)$ with any accuracy.
- Traditional approach of Tikhonov regularization assumes that the dependence is smooth.
- In geophysics and geotechnical engineering, we have abrupt (non-smooth) transitions between layers.
- To deal with such transitions, Sergei Fomel proposed shaping regularization heuristics.
- *We provide a theoretical justification* for this heuristic.
- Another problem is that we cannot process all the data, we need to split it into subsets.
- *We justify* a *local attributes* method, an empirically successful way of dividing into subsets.

10. Case Study: Intelligent Compacting

- How to gauge quality (stiffness) of the pavement?
  - we run simulations;
  - based on the simulations results, we extract stiffness from measured characteristics such as f_2/f_1.
- *Task:* to run simulations, we must know soil's elastic properties, i.e., the resilient modulus M_r.
- *What we did:* theoretically justified an empirical model for M_r – and came up with a more general model.
- *Task:* we need to solve the corresponding nonlinear equations.
- *We explained* the relevant generalized trig functions.
- We need to explain why f_2/f_1: work in progress.
- We also need to develop an appropriate design of experiments: work in progress.

11. Publications

- Pedro Barragan, Soheil Nazarian, Vladik Kreinovich, Afshin Gholamy and Mehran Mazari, "How to Estimate Resilient Modulus for Unbound Aggregate Materials: A Theoretical Explanation of an Empirical Formula, *Proceedings of the 2016 World Conference on Soft Computing*, Berkeley, California, May 22–25, 2016, to appear.
- Pedro Barragan Olague and Vladik Kreinovich, "How to Explain The Empirical Success of Generalized Trigonometric Functions in Processing Discontinuous Signals", *Mathematical Structures and Modeling*, 2016, Vol. 37, pp. 25–29.

12. Publications (cont-d)

- Afshin Gholamy and Vladik Kreinovich, "How geophysicists' intuition helps seismic data processing", *Proceedings of the World Congress of the International Fuzzy Systems Association IFSA'2015, joint with the Annual Conference of the European Society for Fuzzy Logic and Technology EUSFLAT'2015*, Gijon, Asturias, Spain, June 30 – July 3, 2015, pp. 749–756.
- Afshin Gholamy and Vladik Kreinovich, "Why Ricker Wavelets Are Successful in Processing Seismic Data: Towards a Theoretical Explanation", *Proceedings of the IEEE Symposium on Computational Intelligence for Engineering Solutions CIES'2014*, Orlando, Florida, December 9–12, 2014, pp. 11–16.

13. Applications to Environmental Science: Team

- Craig Tweedie, PhD
  Environmental Science
- Stephen Escarzaga, PhD student
  Environmental Science

14. Applications to Environmental Science: Project

- In most locations, the environmental changes are reasonably slow.
- However, at the borders between ecological zones, changes are much faster.
- Example: shoreline.
- It is therefore important to properly gauge shoreline erosion.
- We show how to do it under uncertainty.
- Shorelines are important, since they are a habitat for many species, e.g., birds.
- It is therefore important to predict their nesting sites.
- We show how this can be done under uncertainty.

15. Publications

- Stephen M. Escarzaga, Craig Tweedie, Olga Kosheleva, and Vladik Kreinovich, "How to Predict Nesting Sites and How to Measure Shoreline Erosion: Fuzzy and Probabilistic Techniques for Environment-Related Spatial Data Processing", submitted to *Proceedings of the 2016 World Conference on Soft Computing*, Berkeley, California, May 22–25, 2016.
- Stephen Escarzaga, Craig Tweedie, and Vladik Kreinovich, "How to Predict Nesting Sites?", Journal of Uncertain Systems, 2017, Vol. 11, to appear.

16. Applications to General Image and Signal Processing: Team

- Christian Servin, PhD
  Computational Science
- Fernando Cervantes, Doctoral Student
  Electrical and Computer Engineering
- Leobardo Valera, Doctoral Student
  Computational Science

17. Applications to General Image and Signal Processing: Project

- Traditional approach to signal and image processing assumes that signals and images are smooth.
- In practice, signals and images are often not smooth.
- To take that into account, researchers minimize $\sum |e_i|^p$ instead of the usual least squares $\sum |e_i|^2$.
- *Problem:* ℓ^p-idea is not theoretically justified.
- *What we did:* we provided such a justification.
- Another helpful idea: signals and images are often sparse.
- *What we did:* provided a theoretical justification for sparsity techniques.
- *Result:* we came up with a more efficient technique for image deconvolution.

18. Case Study: How to Determine Accuracy of State-of-the-Art Measuring Instruments

- How to gauge accuracy of a measuring instrument?
- *Usual way:* compare its measurement result with a state-of-the-art instrument.
- But how can we determine the accuracy σ of a state-of-the-art instrument?
- For two identical instruments, $\sigma = (1/\sqrt{2})\cdot$ mean square diff. σ_{ij} between their measurement results.
- If all measuring instruments are different, then we can find σ_i from the equations $\sigma_i^2 + \sigma_j^2 = \sigma_{ij}^2$.
- *Problem:* when distributions are non-Gaussian, we also need to know higher moments.
- *We can:* similarly determine these higher moments.

19. Publications

- Fernando Cervantes, Bryan Usevitch, and Vladik Kreinovich, "Why ℓ^p-methods in Signal and Image Processing: A Fuzzy-Based Explanation", *Proceedings of the Annual Conference of the North American Fuzzy Information Processing Society NAFIPS'2016*, El Paso, Texas, October 31 – November 4, 2016, to appear.
- Fernando Cervantes, Brian Usevitch, Leobardo Valera, and Vladik Kreinovich, "Why Sparse? Fuzzy Techniques Explain Empirical Efficiency of Sparsity-Based Data- and Image-Processing Algorithms", *Proceedings of the 2016 World Conference on Soft Computing*, Berkeley, California, May 22–25, 2016, to appear.

20. Publications (cont-d)

- Christian Servin and Vladik Kreinovich, "Comparisons of Measurement Results as Constraints on Accuracies of Measuring Instruments: When Can We Determine the Accuracies from These Constraints?", In: Martine Ceberio and Vladik Kreinovich (eds.), *Constraint Programming and Decision Making: Theory and Applications*, Springer Verlag, Berlin, Heidelberg, to appear.

21. Applications to Systems: Team

- Francisco Zapata, PhD
  Computer Science

22. Applications to Systems: Project

- To design and maintain systems, it is important to predict how changes will affect system performance.
- There exist many empirical dependencies.
- The problem is people are reluctant to use these dependencies since:
  - they are not theoretically justified and
  - thus, it is not clear that they will work in new situations as well.
- Example: group productivity log-normally depends on group size.
- *What we do:* look for theoretical justification for such dependencies.
- *Successful application:* the use of such dependencies led to a drastic speed-up of software migration.

23. Publications

- Francisco Zapata, Olga Kosheleva, and Vladik Kreinovich, "Why Dependence of Productivity on Group Size Is Log-Normal", *Journal of Computing and Optimization*, to appear.
- Francisco Zapata, Octavio Lerma, Leobardo Valera, and Vladik Kreinovich, "How to Speed Up Software Migration and Modernization: Successful Strategies Developed by Precisiating Expert Knowledge", *Proceedings of the Annual Conference of the North American Fuzzy Information Processing Society NAFIPS'2015 and 5th World Conference on Soft Computing*, Redmond, Washington, August 17–19, 2015.

24. Decision Making Under Uncertainty: Team

- Nantiworn Thianpaen, PhD
  Visiting Researcher
- Mahdokht Afravi, Undergraduate Student
  Computer Science
- Martha Osegueda Escobar, Undergraduate Student
  Computer Science

25. Decision Making Under Uncertainty: Project

- Traditional cooperative game theory describes what to do in situations with complete information.
- *Challenges:*
  1) It is sometimes not clear how to compute the corresponding solutions.
     - E.g, no algorithm is known for von Neumann-Morgenstern (vNM) set (non-dominated solutions).
  2) In practice, we often only know the utilities of different participants with uncertainty.
- *Our solution:* taking uncertainty into account can makes computations possible.
- Specifically, vNM solutions can be computed.

26. Case Study: Territorial Division

- For each location x in a disputed territory, we know the i-th person utility $u_i(x)$.
- According to J. Nash, we maximize the product of utilities $U_i = \int_{S_i} u_i(x)\,dx$.
- *Known solution:* each x is assigned to a party with largest $u_i(x)/t_i$ for some thresholds t_i.
- *Challenge:* in practice, we only know $u_i(x)$ with uncertainty.
- *We show* how to compute S_i.
- *Challenge:* we need to take emotions into account.
- *We show* how to do it.
- *Challenge:* solutions are often made step-by-step.
- *We show* that this is not an optimal approach.

27. Case Study: Economic Forecasts

- To make proper economic decisions, it is important to understand the trends and make forecasts.
- There are many statistical techniques for forecasting.
- Most these techniques assume that the underlying model correctly describes the economics.
- In practice, all models are approximate.
- It is important to take this approximate character into account.
- *Preliminary results:*
  - *we show* how to take this uncertainty into account;
  - *how:* we use Thierry Denoeux's version of the Dempster-Shafer approach.

28. Publications

- Mahdokht Afravi and Vladik Kreinovich, "How to Make a Solution to a Territorial Dispute More Realistic: Taking into Account Uncertainty, Emotions, and Step-by-Step Approach", *Proceedings of the 2016 World Conference on Soft Computing*, Berkeley, California, May 22–25, 2016, to appear.
- Mahdokht Afravi and Vladik Kreinovich, "Positive Consequences of Negative Attitude: Game-Theoretic Analysis", *International Journal of Contemporary Mathematical Sciences*, 2016, Vol. 11, No. 3, pp. 113–118.
- Mahdokht Afravi and Vladik Kreinovich, "How to Divide a Territory: an Argument in Favor of Private Property", *Proceedings of the 3rd International Conference on Mathematical and Computer Modeling*, Omsk, Russia, November 12, 2015, pp. 20–22.

29. Publications (cont-d)

- Martha Osegueda Escobar and Vladik Kreinovich, "How to Compute von Neumann-Morgenstern Solutions", *Mathematical Structures and Modeling*, 2016, Vol. 37, to appear.

30. Applications to Education: Team

- Joe Lorkowski, PhD
  Computer Science
- Olga Kosheleva, PhD
  Teacher Education
- Viannette Felix, Undergraduate Student
  Computer Science

31. Applications to Education: Project

- Traditional methods of gauging student knowledge simply count the number of correct answers.
- They do not take into account that sometimes, students are uncertain about these answers.
- A confident *correct* answer is better than an uncertain one.
- On the other hand, a confident *wrong* answer is worse than an uncertain one.
- We propose a method for taking such student's uncertainty into account when grading the exam.
- The degree of certainty is elicited from a student.
- Our method is the only one that encourages students to correctly mark their degree of certainty.

32. Publications

- Olga Kosheleva, Joe Lorkowski, Viannette Felix, and Vladik Kreinovich, "How to Take into Account Student's Degree of Confidence When Grading Exams", *Abstracts of the 13th International Sun Conference on Teaching and Learning*, El Paso, Texas, March 17–18, 2016.
- Olga Kosheleva, Joe Lorkowski, Viannette Felix, and Vladik Kreinovich, "How to Take Into Account Student's Degree of Confidence When Grading Exams", *Proceedings of the 5th International Conference "Mathematics Education: Theory and Practice" MATHEDU'2015*, Kazan, Russia, November 27–28, 2015, pp. 29–30.