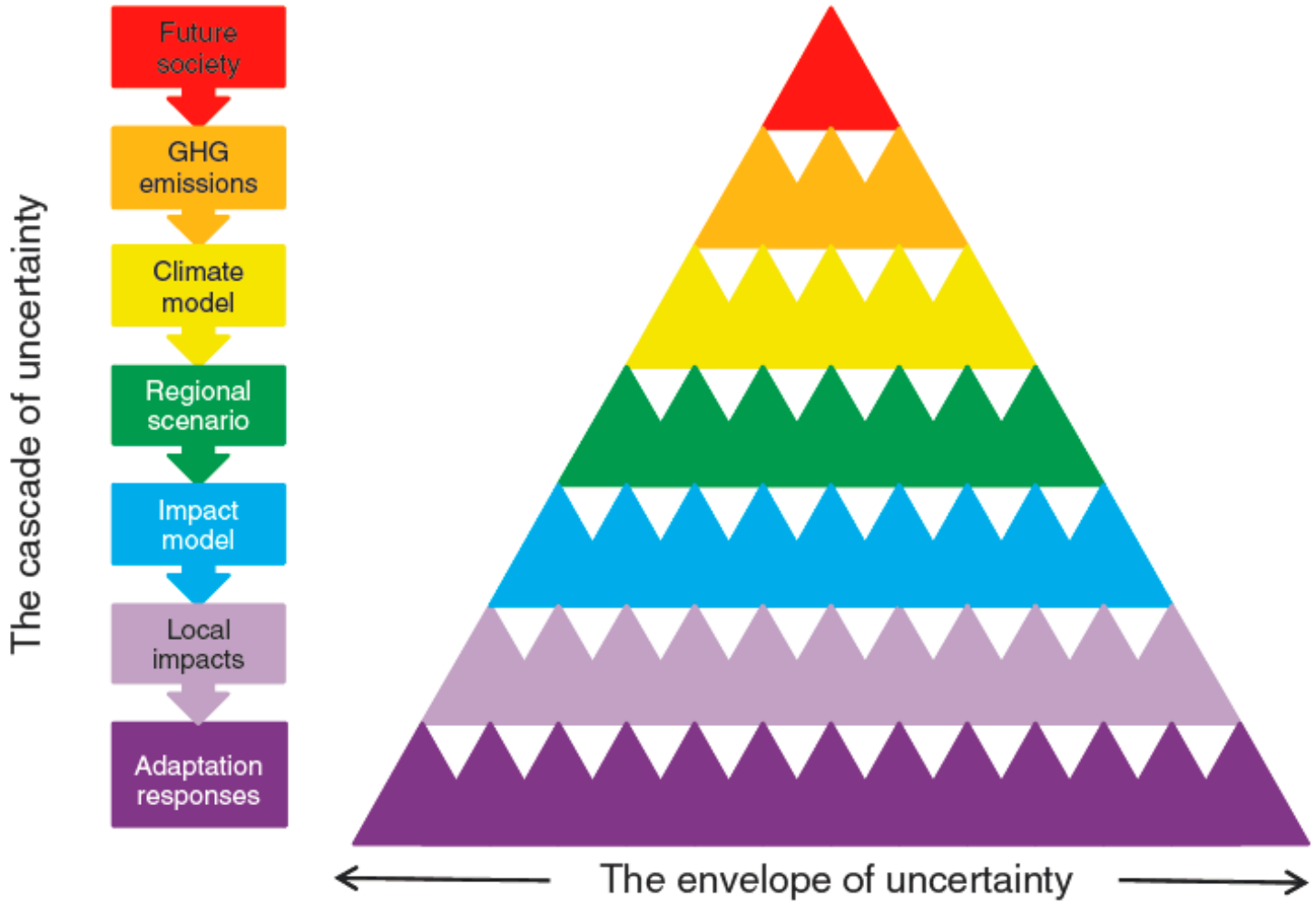
Global Sensitivity Analysis

Andrea Saltelli

June 17, 2026, École d'été PRISMA,
Université de Genève

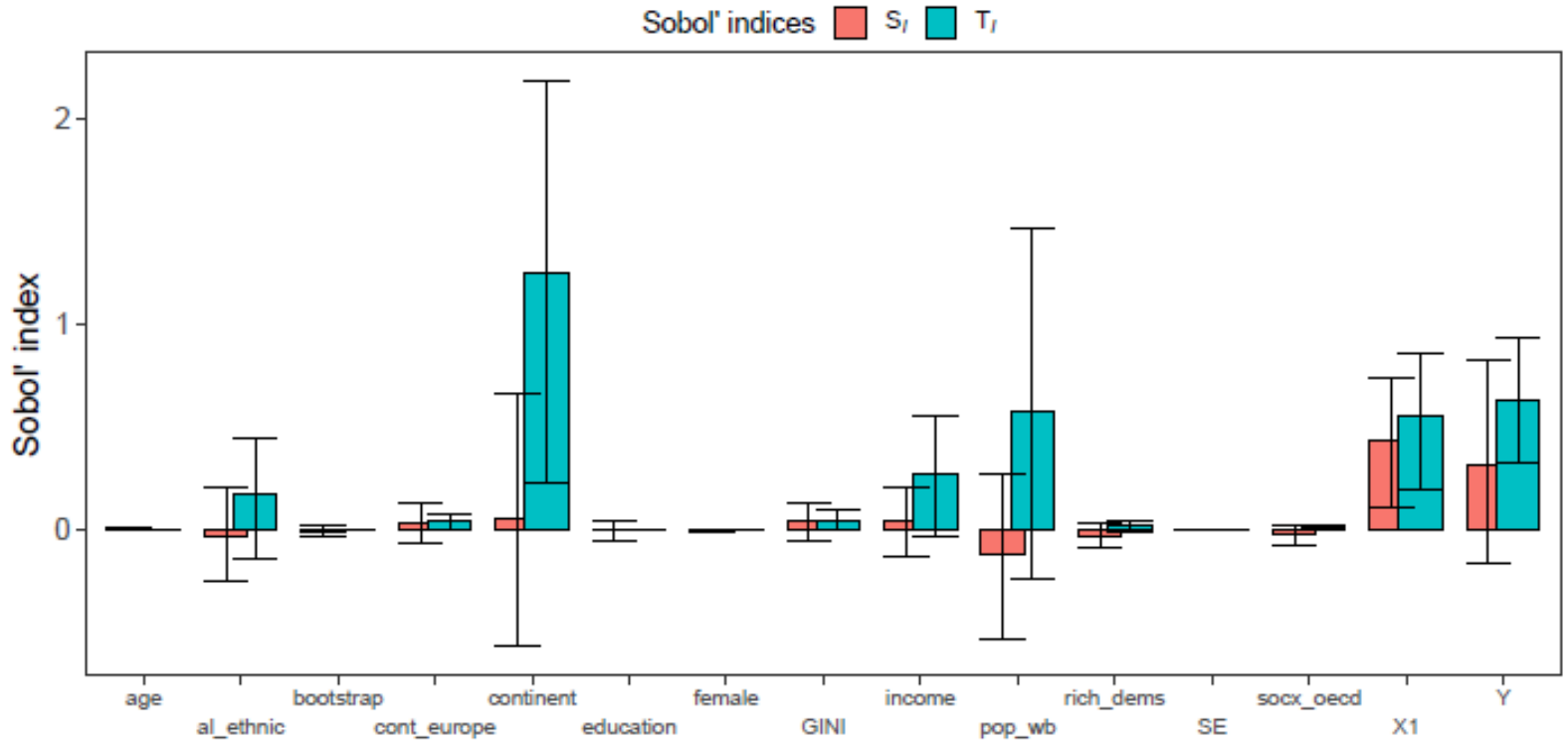
Part I - What are uncertainty analysis and global sensitivity analysis?

Uncertainty analysis: the study of the uncertainty in model output

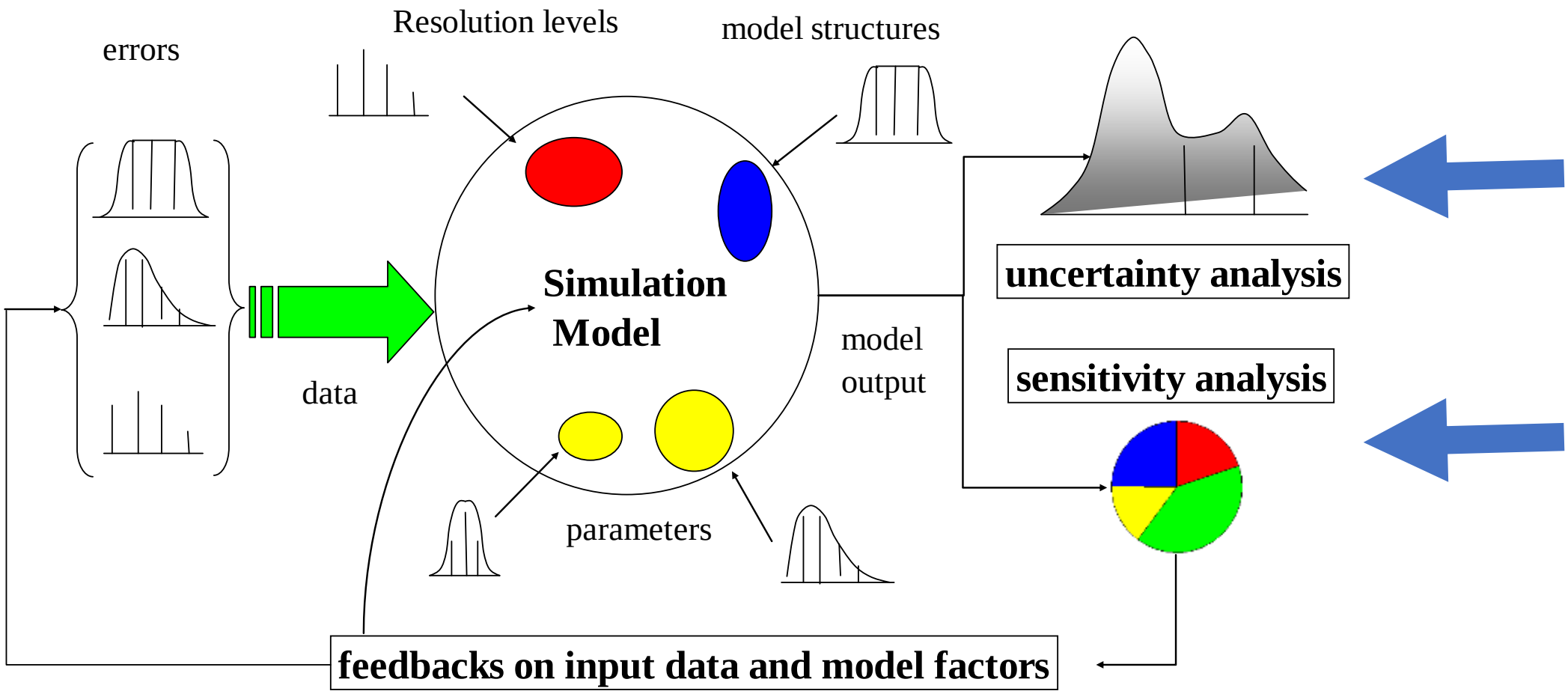


Source: https://www.climate-lab-book.ac.uk/2014/cascade-of-uncertainty/

Sensitivity analysis: the study of the relative importance of different input factors on the model output



Stefano Tarantola, circa 2008



Why global? Why don't we simply move one factor At a Time (OAT)

A geometric proof

Environmental Modelling & Software 25 (2010) 1508–1517

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

How to avoid a perfunctory sensitivity analysis

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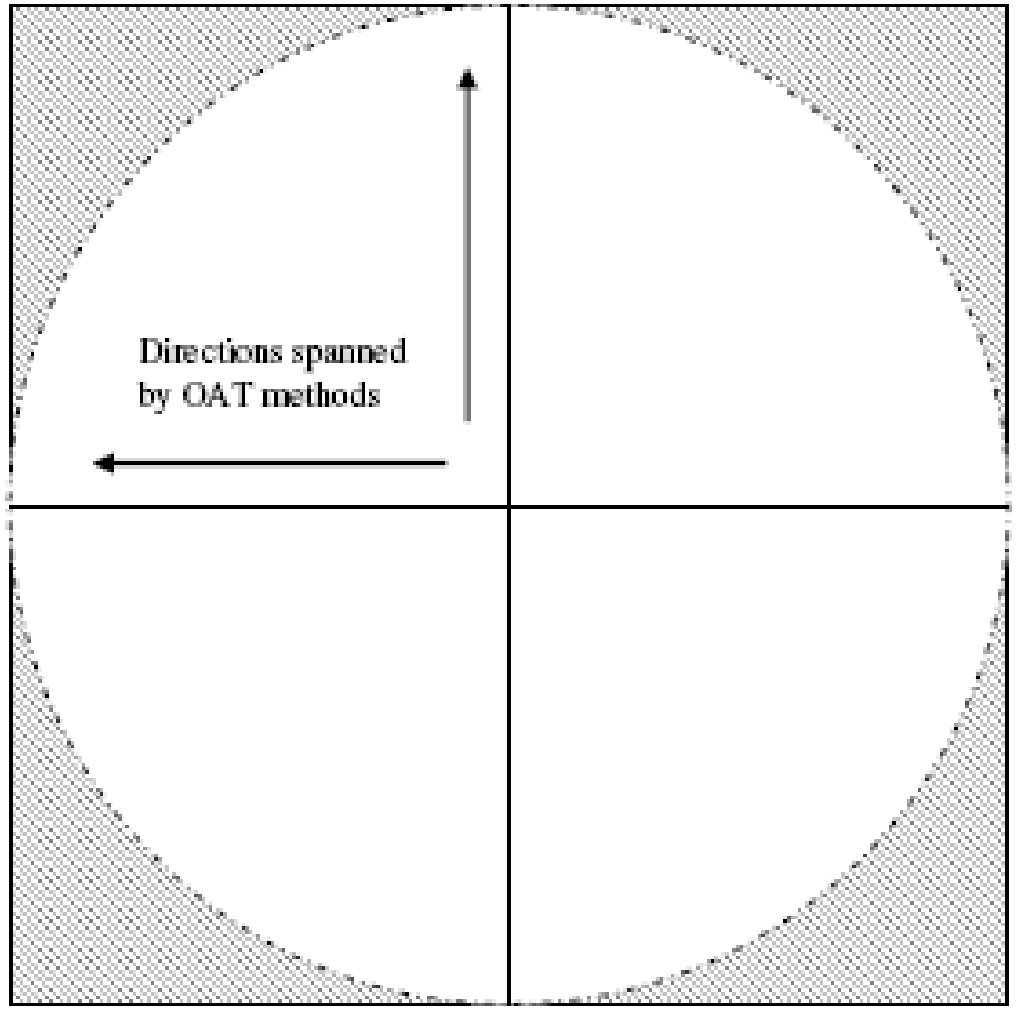
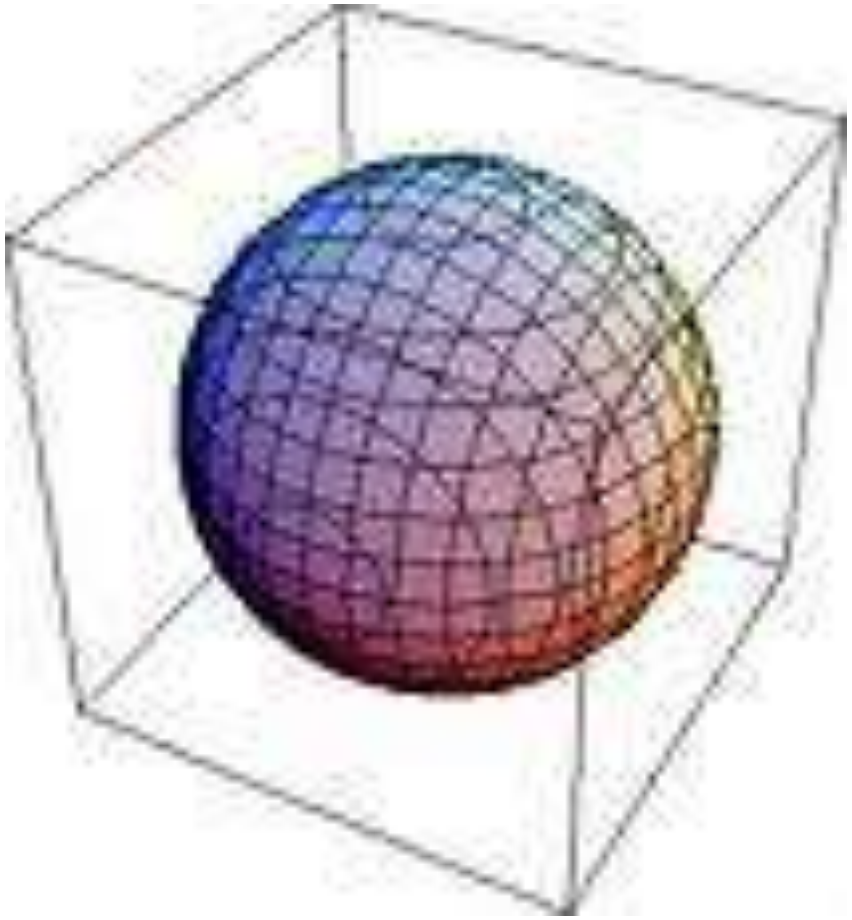
OAT in 2 dimensions



Area circle / area square =?

~ 3/4

OAT in 3 dimensions



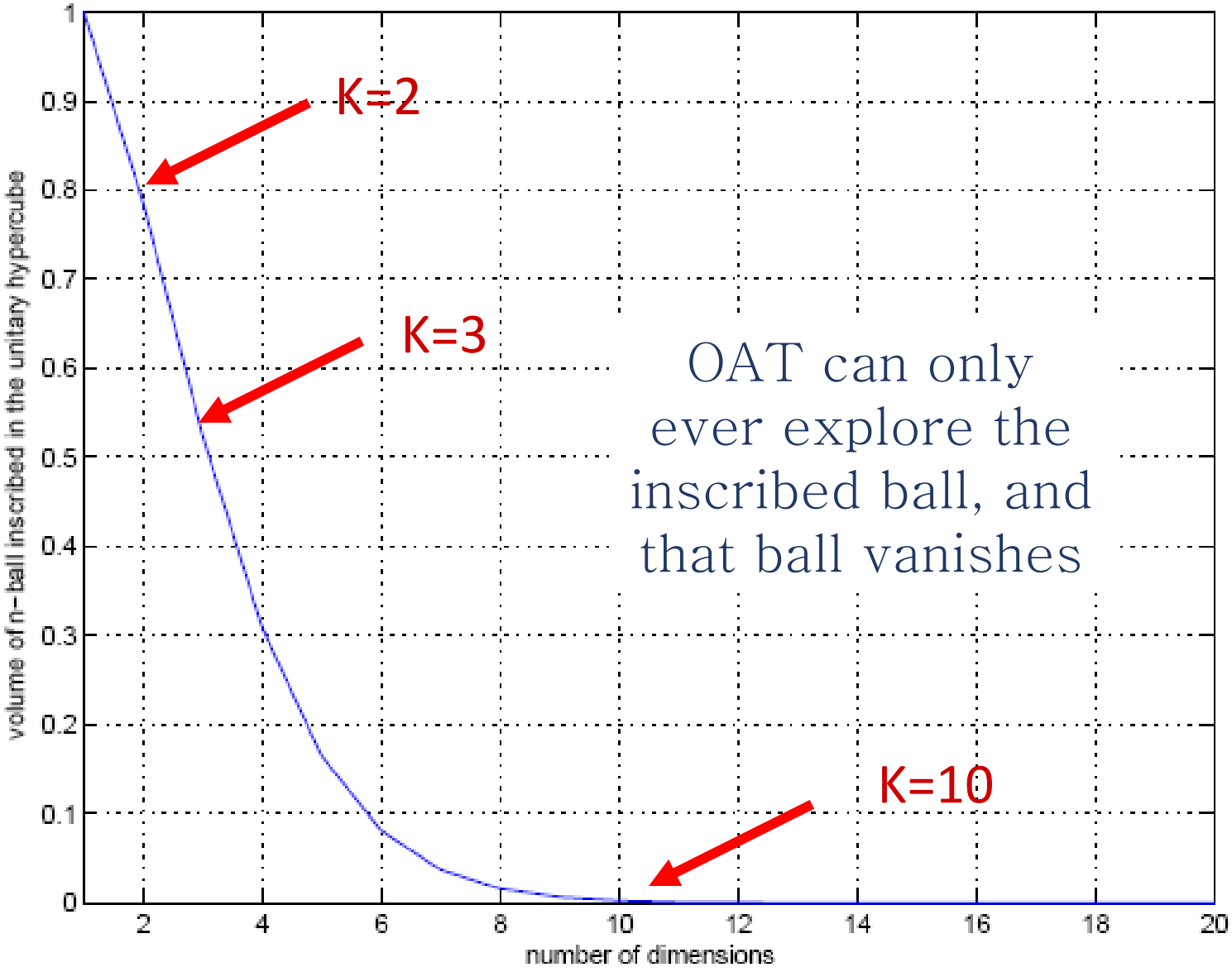
Volume sphere / volume cube =?

~ 1/2

OAT in 10 dimensions; Volume hypersphere / volume ten dimensional hypercube =?

~ 0.0025

OAT in k dimensions

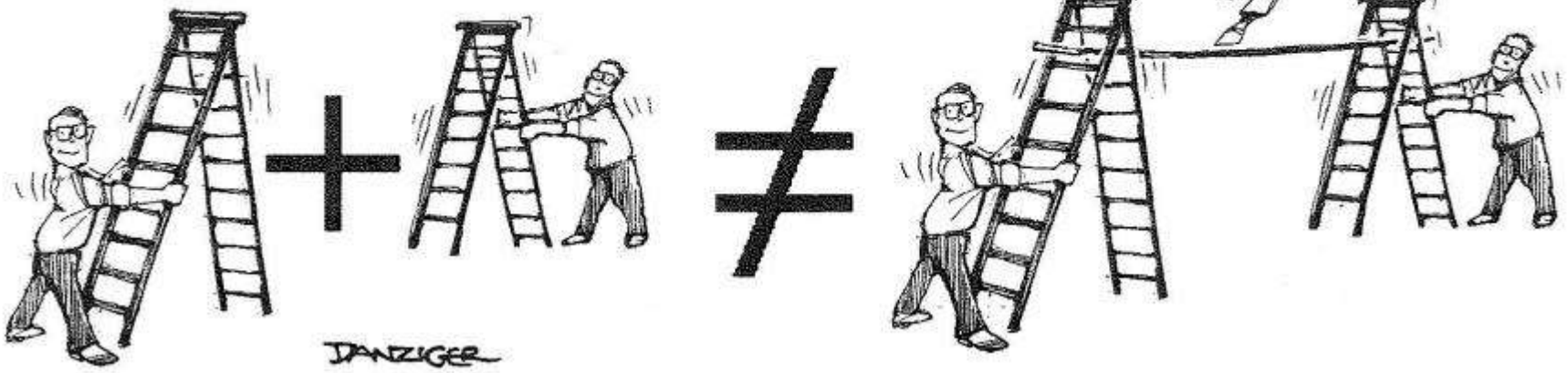


OAT does not capture interactions

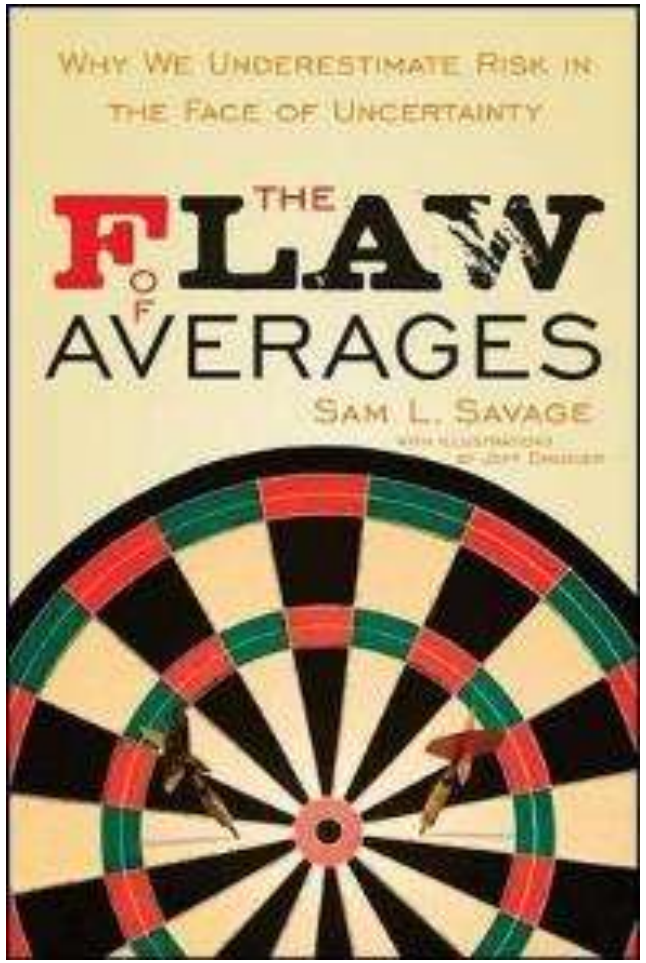
➔ The resulting analysis is non conservative

How would you test the scaffolding?

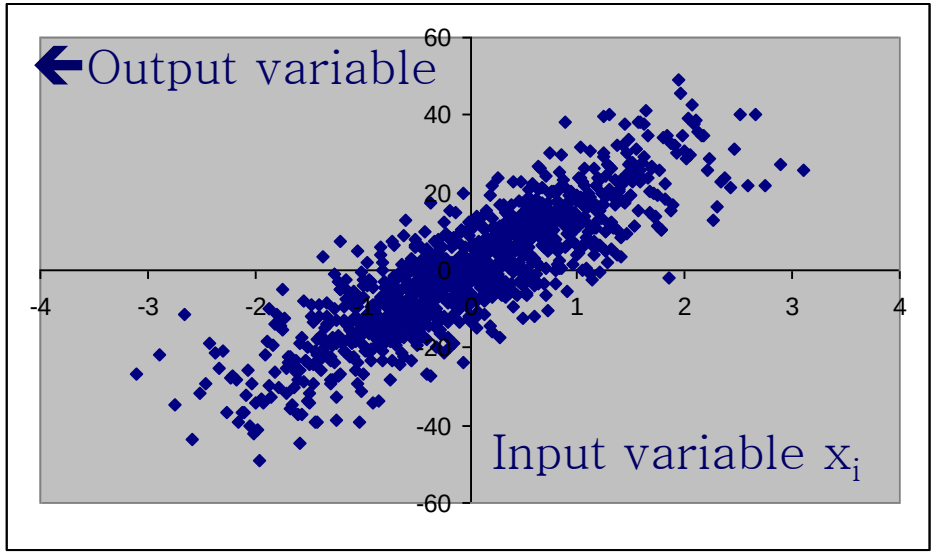
How coupled ladders are shaken in most of available literature

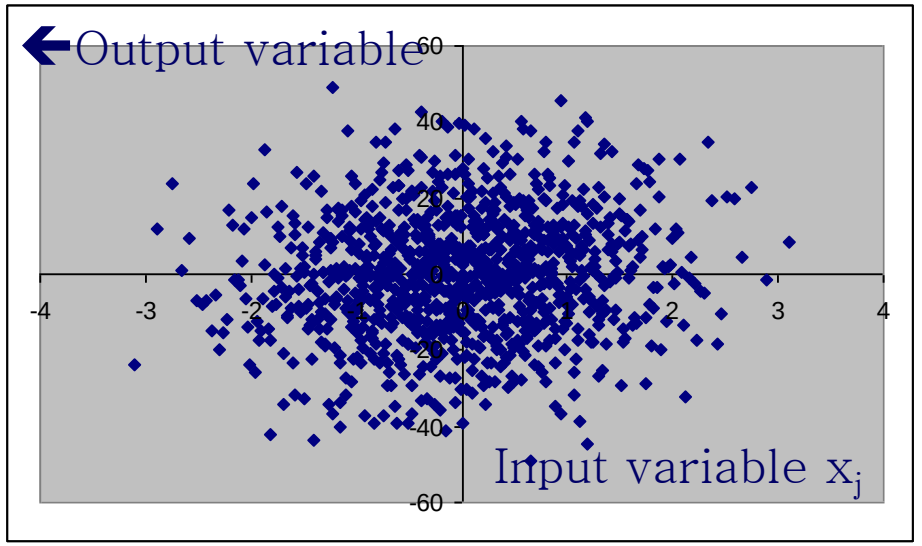


How to shake coupled ladders



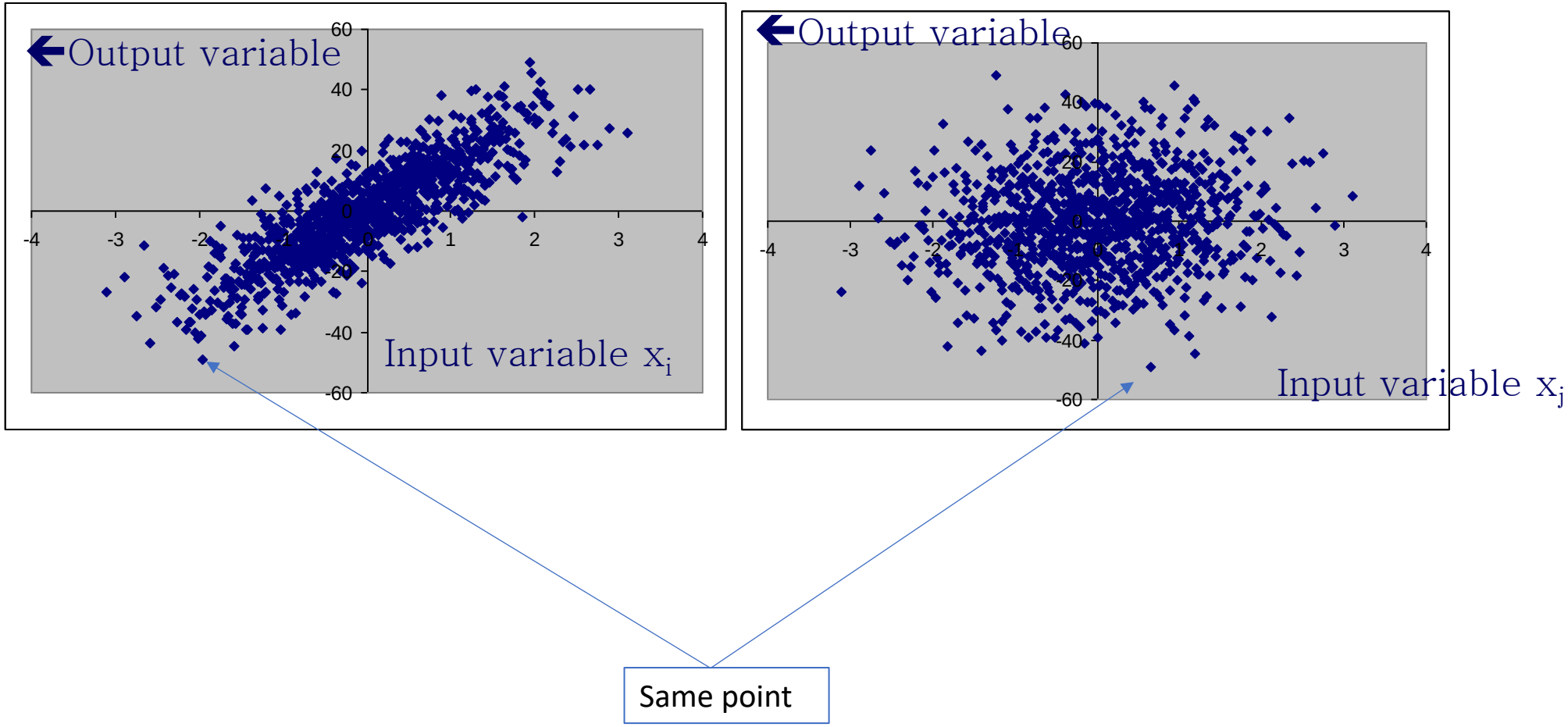
Variance-based methods



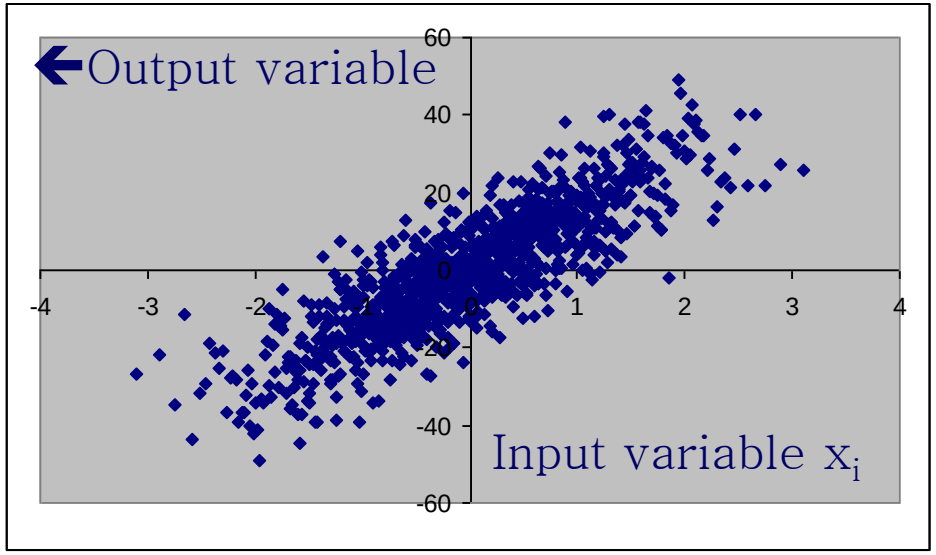


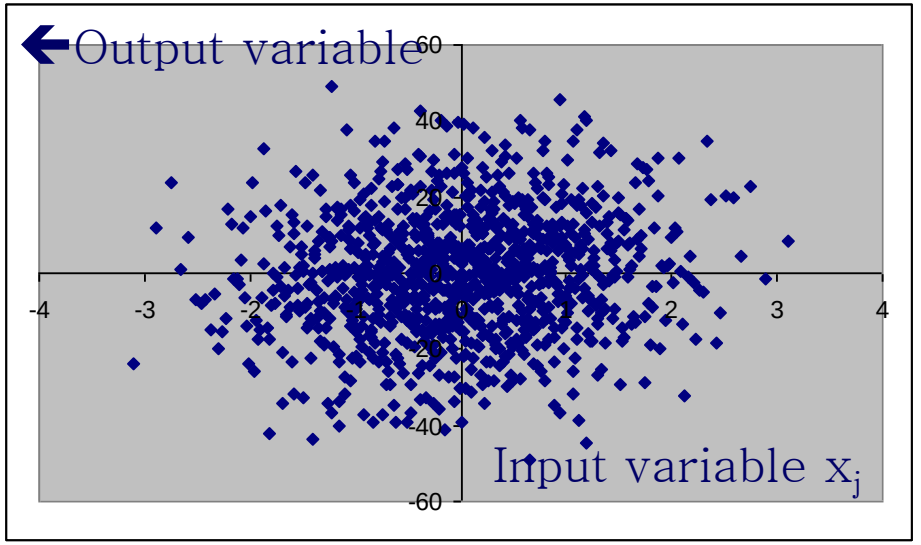
Plotting the output as a function of two different input factors:

The model has been run 1,000 times sampling all uncertain factors; two of them are shown here, x_i (left) and x_j (right). The output variable has first been sorted by increasing x_i then by increasing x_j.



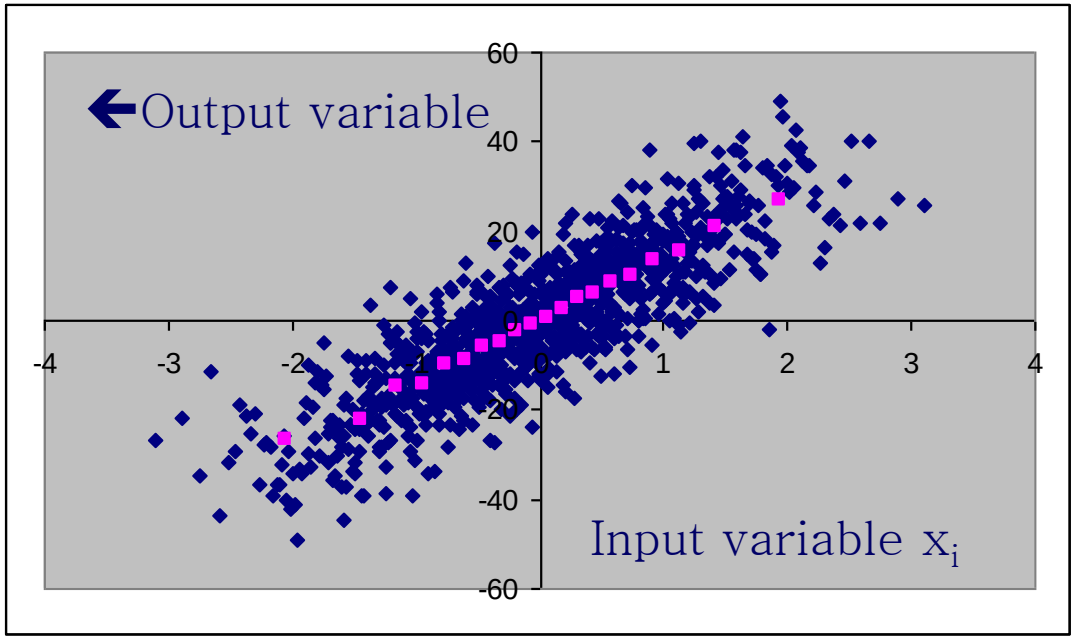
The points are always the same, only sorted differently

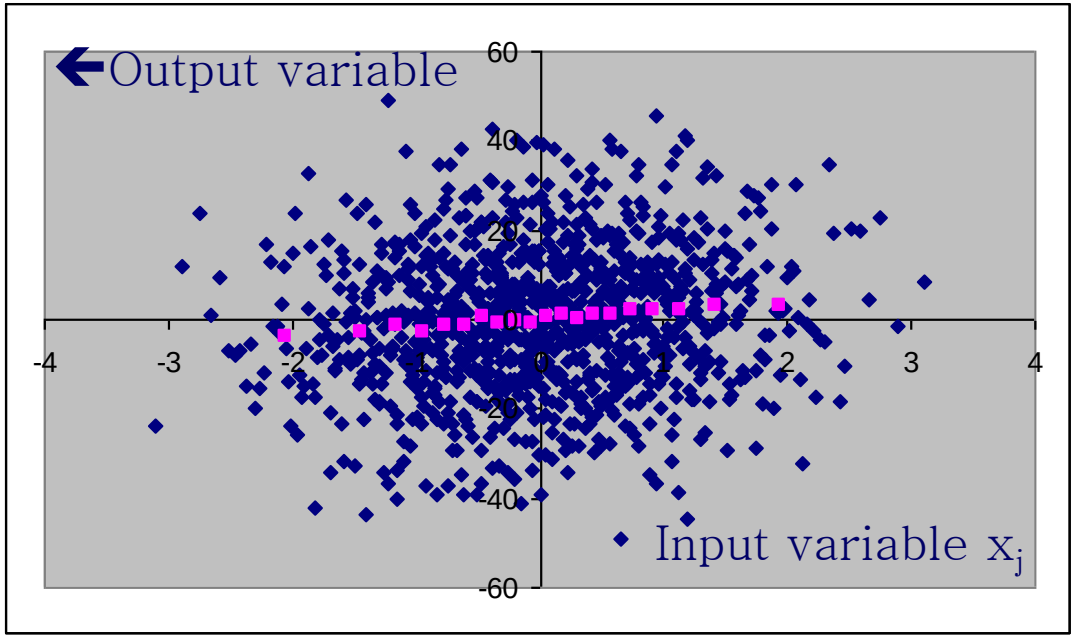




Plotting the output as a function of two different input factors

Which factor is more important?

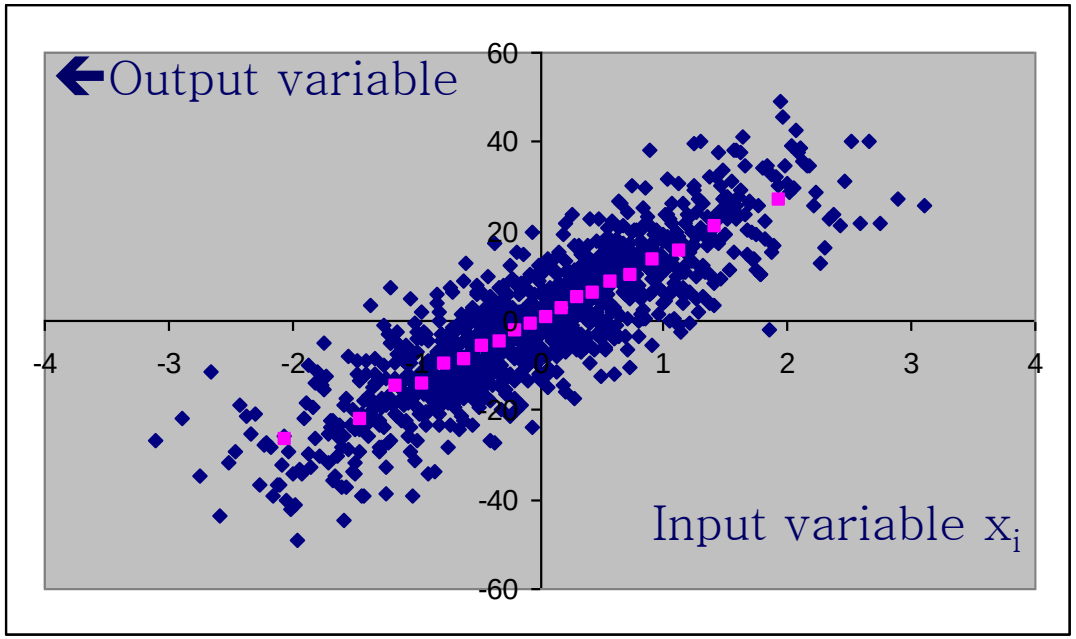




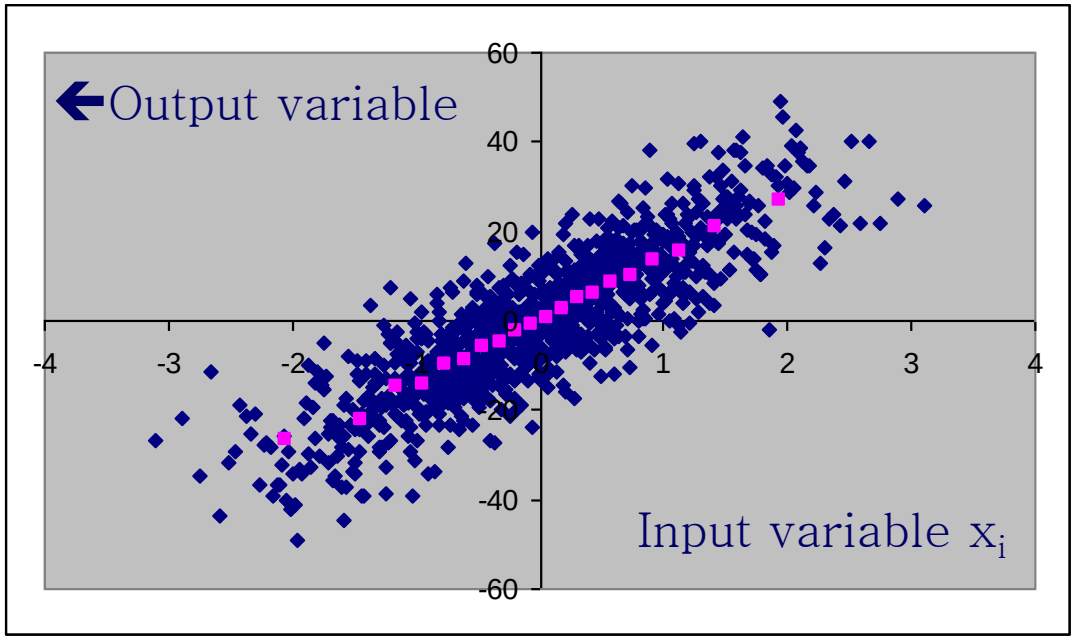
~1,000 blue points

Divide them in 20 bins of ~ 50 points

Compute the bin's average (pink dots)

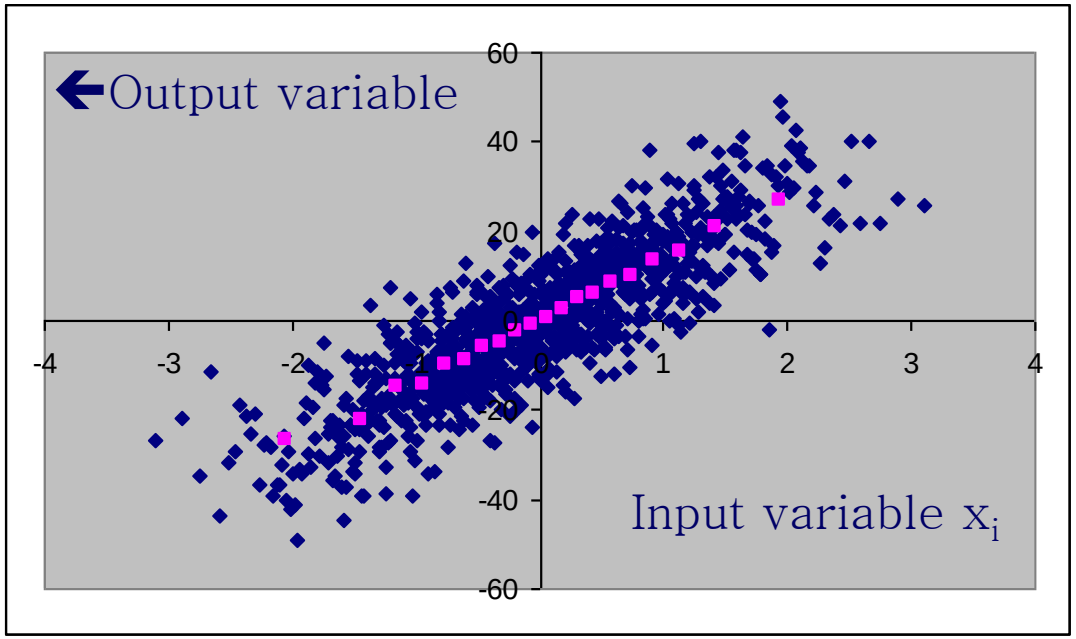


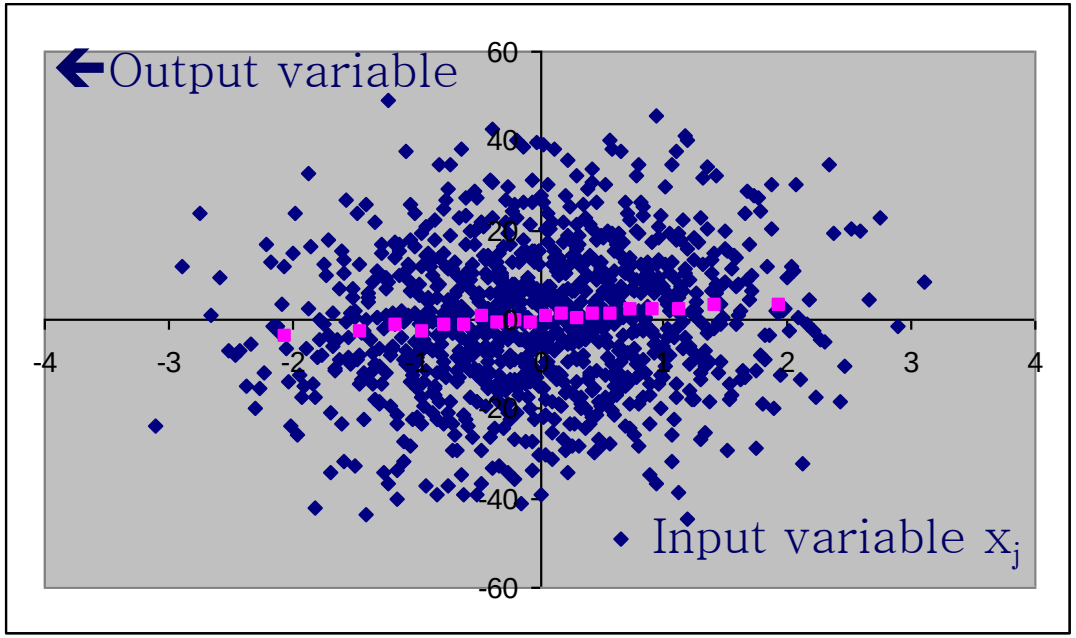
Each pink point is ~ $E_{\mathbf{X}_{\sim i}}\left(Y \middle| X_i\right)$



Taking the variance of the pink points one obtains a sensitivity measure

$$V_{X_i}\left(E_{\mathbf{X}_{\sim i}}\left(Y|X_i\right)\right)$$





Which factor has the highest

$$V_{X_i}\left(E_{\mathbf{X}_{\sim i}}\left(Y\middle|X_i\right)\right)?$$

$$S_i = \frac{V_{X_i}\left(E_{\mathbf{X}_{\sim i}}\left(Y|X_i\right)\right)}{V(Y)}$$

The partial variance divided by the total variance is the so-called sensitivity index of the first order

$$S_i = \frac{V_{X_i}\left(E_{\mathbf{X}_{\sim i}}\left(Y|X_i\right)\right)}{V(Y)}$$

The partial variance divided by the total variance is the so-called sensitivity index of the first order

There are terms which capture two-way, three way, … interactions among variables

All these terms are linked by a formula

Variance decomposition (ANOVA)

$$V(Y) =$$

$$\sum_{i} V_i + \sum_{i,\, j>i} V_{ij} + \ldots + V_{123\ldots k}$$

Variance decomposition (ANOVA)

The total variance can be decomposed into main effects and interaction effects up to the order k, the dimensionality of the problem (only for independent factors)

In fact, interaction terms are awkward to handle: just the second-order terms for a model with k factors are as many as k(k-1)/2 …

(10 factors=45 second order terms)

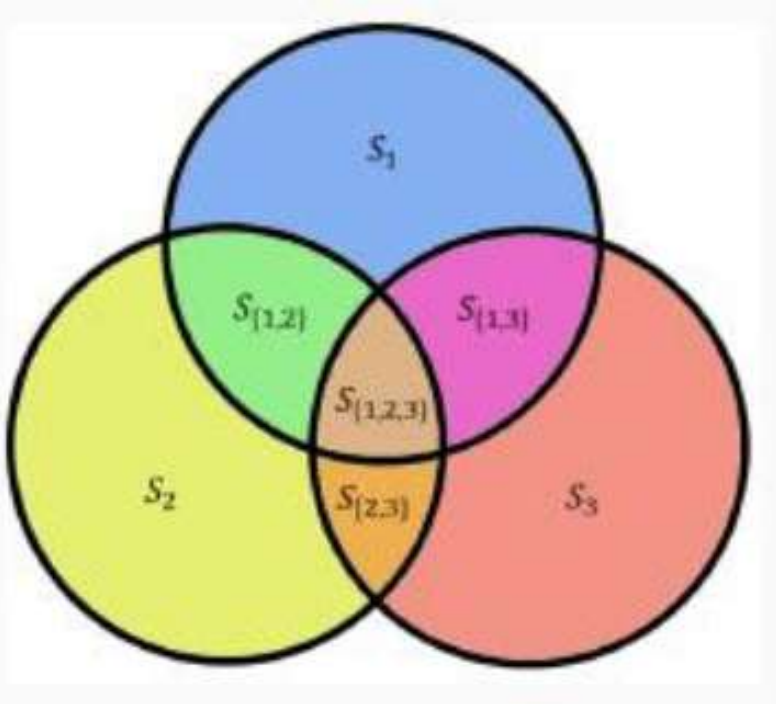
How about a single ‘importance’ term for all effects?

In fact, such terms exist and can be computed easily, without knowledge of the individual interaction terms

Thus, given a 3-factor model $f(X_1, X_2, X_3)$

Where the variance decomposition would read $1 = S_1 + S_2 + S_3 + S_{12} + S_{13} + S_{23} + S_{123}$

We compute



$$T_1 = S_1 + S_{12} + S_{13} + S_{123}$$

$$T_2 = S_2 + S_{12} + S_{23} + S_{123}$$

$$T_3 = S_3 + S_{13} + S_{23} + S_{123}$$

Before moving to the total index, let us finish with the first-order one

$$S_i = \frac{V_{X_i}\left(E_{\mathbf{X}_{\sim i}}\left(Y|X_i\right)\right)}{V(Y)}$$

Known as:

- Pearson's correlation ratio (Pearson)
- First order effect (Sobol' & disciples)
- Top marginal variance (Jansen)

$$S_i = \frac{V_{X_i}\left(E_{\mathbf{X}_{\sim i}}\left(Y \middle| X_i\right)\right)}{V(Y)}$$

We need to understand what the numerator is in plain English

$$V_{X_i}\left(E_{\mathbf{X}_{\sim i}}\left(Y \middle| X_i\right)\right)$$

$$V_{X_i}\left(E_{\mathbf{X}_{\sim i}}\left(Y|X_i\right)\right)$$

Top marginal variance=
= the expected reduction in variance than would be achieved if factor Xi could be fixed.

Why?

Because:

$$V_{X_i}\left(E_{\mathbf{X}_{\sim i}}\left(Y|X_i\right)\right)+$$
$$+E_{X_i}\left(V_{\mathbf{X}_{\sim i}}\left(Y|X_i\right)\right)=V(Y)$$

One of the exercises in the book: prove this using $V(\bullet)=E(\bullet)^2-E^2(\bullet)$

Because:

= then this is the reduction in variance if X_i could be fixed

$$V_{X_i}\left(E_{\mathbf{X}_{\sim i}}\left(Y|X_i\right)\right)+$$

$$+E_{X_i}\left(V_{\mathbf{X}_{\sim i}}\left(Y|X_i\right)\right)=V(Y)$$

(By inspection) this is what variance would be left (on average) if X_i could be fixed

For additive systems one can decompose the total variance as a sum of first order effects

$$\sum_i V_{X_i}\left(E_{\mathbf{X}_{\sim i}}\left(Y|X_i\right)\right)\approx V(Y)$$

How to get from first order to total order

From

$$V_{X_i}\left(E_{\mathbf{X}_{\sim i}}\left(Y|X_i\right)\right)$$ Main effect of factor X_i

replacing X_i with $\boldsymbol{X}_{\sim i}$

Gives the main effect of non-X_i

$$V_{\mathbf{X}_{\sim i}}\left(E_{X_i}\left(Y|\mathbf{X}_{\sim i}\right)\right)$$

But again:

$$V_{\mathbf{X}_{\sim i}}\left(E_{X_i}\left(Y|\mathbf{X}_{\sim i}\right)\right)+$$
$$E_{\mathbf{X}_{\sim i}}\left(V_{X_i}\left(Y|\mathbf{X}_{\sim i}\right)\right)=V\left(Y\right)$$

If this = main effect on non$-X_i$

$$E_{\mathbf{X}_{\sim i}}\left(V_{X_i}\left(Y|\mathbf{X}_{\sim i}\right)\right)$$

$$V_{\mathbf{X}_{\sim i}}\left(E_{X_i}\left(Y|\mathbf{X}_{\sim i}\right)\right)$$

… then all remaining variance must be due to X_i and its interactions; this divided the total variance gives the total effect T_i

Total effect term

$$T_i = \frac{V_{X_i}\left(E_{\mathbf{X}_{\sim i}}\left(Y \middle| X_i\right)\right)}{V(Y)}$$

Homma, Toshimitsu, and Andrea Saltelli. 1996. ‘Importance Measures in Global Sensitivity Analysis of Nonlinear Models’. *Reliability Engineering & System Safety* 52 (1): 1–17. https://doi.org/10.1016/0951-8320(96)00002-6.

How to compute S_i and T_i ?

If k is the number of factors we need $n(2 + k)$ simulation where n is the size of a ‘base’ matrix.

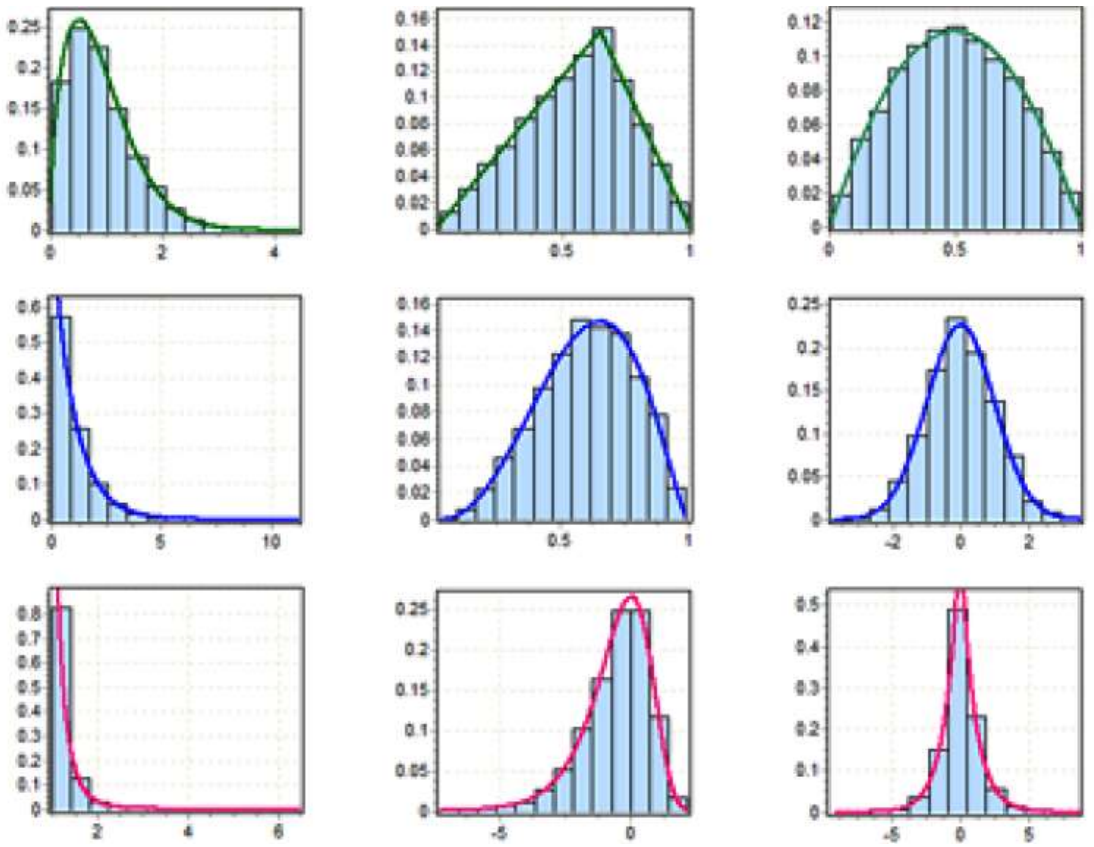
What is needed is a design (as in statistical DOE theory)

Building a Monte Carlo analysis

$$\begin{matrix} x_{11} & x_{12}\ldots & x_{1k} \\ x_{21} & x_{22}\ldots & x_{2k} \\ \ldots & \ldots & \ldots \\ x_{N1} & x_{N2} & x_{Nk1} \end{matrix}$$

Input matrix: each column is a sample of size N from the distribution of a factor

Each row is a sample trial of size k to generate a value of y



Examples of distributions of input factors

$$\mathbf{M}_1 = \begin{pmatrix} x_{11} & x_{12} & \dots & x_{1k} \\ x_{21} & x_{22} & \dots & x_{2k} \\ \dots & & & \\ x_{n1} & x_{n2} & \dots & x_{nk} \end{pmatrix}$$

Base matrix M_1

$$\mathbf{M}_2 = \begin{pmatrix} x'_{11} & x'_{12} & \dots & x'_{1k} \\ x'_{21} & x'_{22} & \dots & x'_{2k} \\ \dots & & & \\ x'_{n1} & x'_{n2} & \dots & x'_{nk} \end{pmatrix}$$

Base matrix M_2

$$\mathbf{N}_j = \begin{pmatrix} x'_{11} & x'_{12} & \dots & x_{1j} & \dots & x'_{1k} \\ x'_{21} & x'_{22} & \dots & x_{2j} & \dots & x'_{2k} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ x'_{n1} & x'_{n2} & \dots & x_{nj} & \dots & x'_{nk} \end{pmatrix}$$

k of these are needed

Matrix quasi-M_2 for factor j

'quasi' because all columns are from M_2 but column j from M_1

$$\mathbf{M}_1 = \begin{pmatrix} x_{11} & x_{12} & \dots & x_{1k} \\ x_{21} & x_{22} & \dots & x_{2k} \\ \dots & & & \\ x_{n1} & x_{n2} & \dots & x_{nk} \end{pmatrix}$$

Base matrix M_1

$$\mathbf{M}_2 = \begin{pmatrix} x'_{11} & x'_{12} & \dots & x'_{1k} \\ x'_{21} & x'_{22} & \dots & x'_{2k} \\ \dots & & & \\ x'_{n1} & x'_{n2} & \dots & x'_{nk} \end{pmatrix}$$

Base matrix M_2

S_j

T_j

$$\mathbf{N}_j = \begin{pmatrix} x'_{11} & x'_{12} & \dots & x_{1j} & \dots & x'_{1k} \\ x'_{21} & x'_{22} & \dots & x_{2j} & \dots & x'_{2k} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ x'_{n1} & x'_{n2} & \dots & x_{nj} & \dots & x'_{nk} \end{pmatrix}$$

k of these are needed

Matrix quasi-M_2 for factor j

Saltelli A., 2002, Making best use of model evaluations to compute sensitivity indices, Computer Physics Communications, 145, 280-297.

How about Shapley?

$$S_i \leq \mathrm{Sh}_i \leq T_i,$$

Shapley sits between S_i and T_i for uncorrelated input

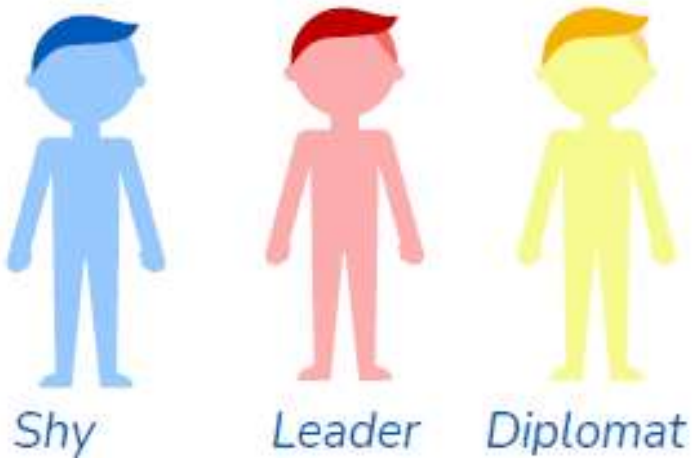
Why?

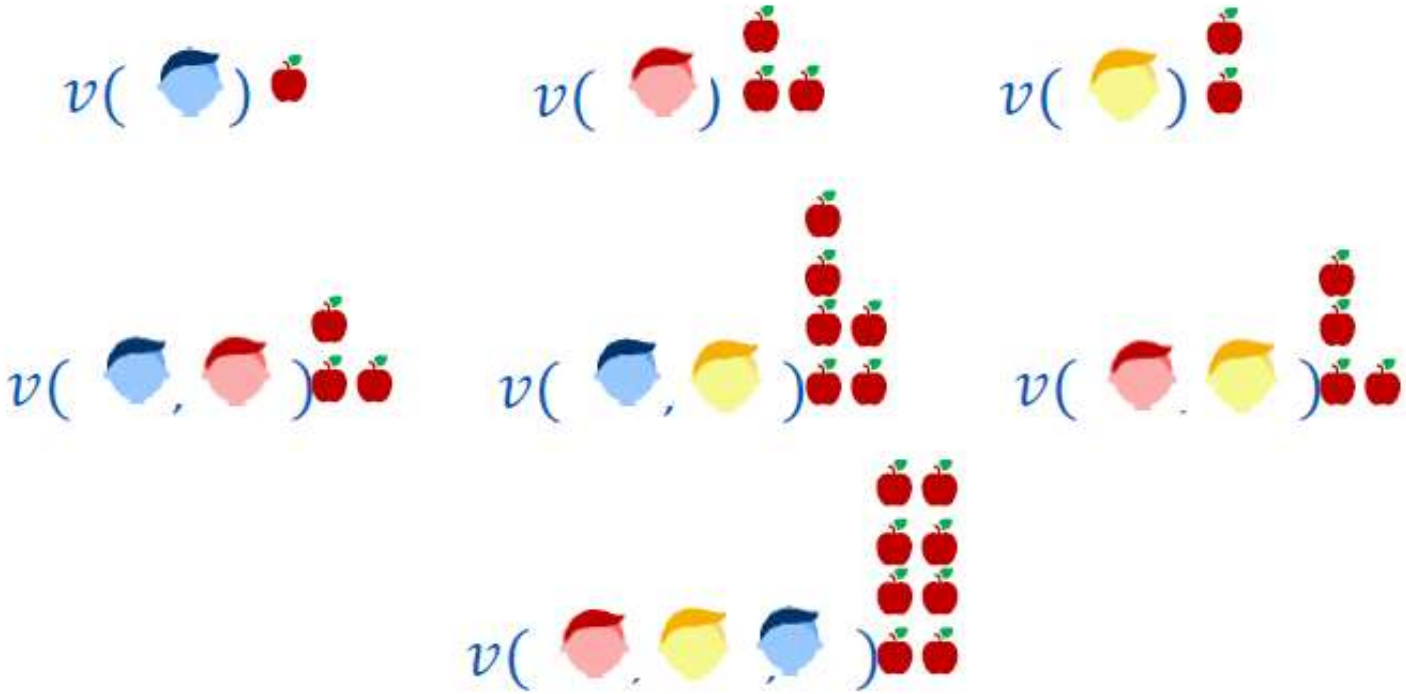
Owen, A. B. (2014). "Sobol' indices and Shapley value."
SIAM/ASA Journal on Uncertainty Quantification, 2(1), 245–251.

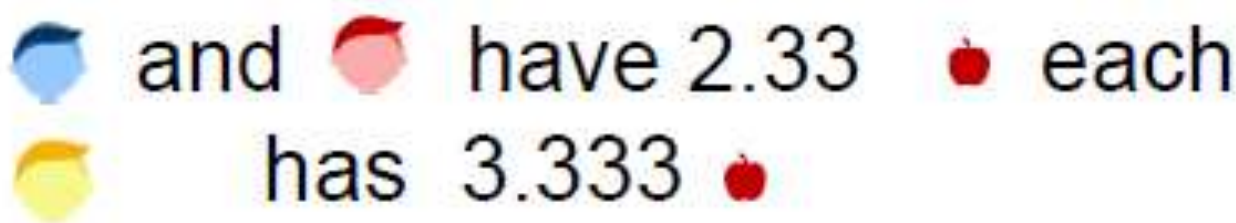
$$S_i \leq \mathrm{Sh}_i \leq T_i,$$

- Si gets none of the interactions
- Ti gets all of the interactions belonging to X_i
- Shapley value splits each interaction term *equally* among the variables
- Shapley effects sum exactly to the total variance (or to 1 if normalised)

$T_i - S_i$ is the interaction that Shapley redistributes.







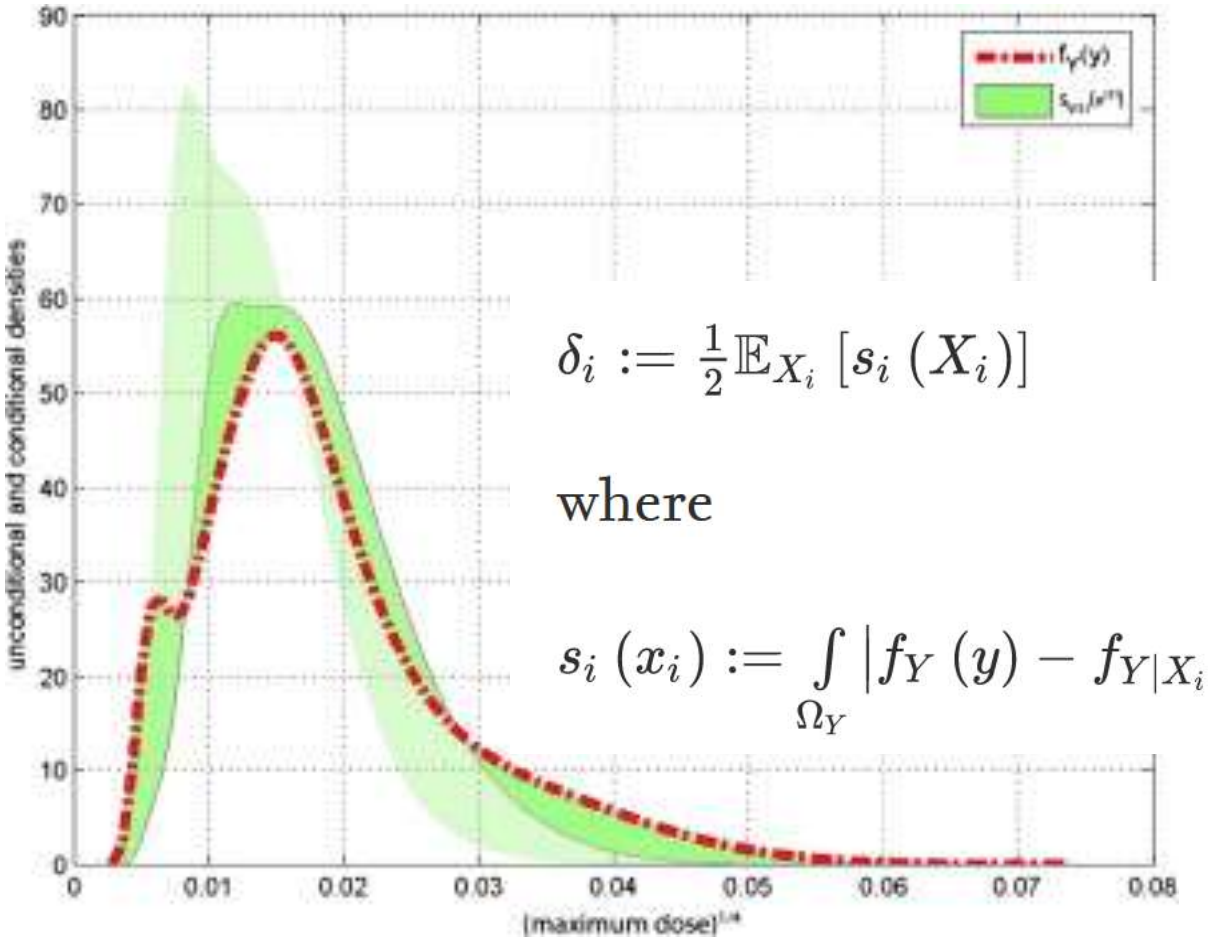
Images courtesy from Bertrand Iooss, Electricité de France (EDF)

A link between $I(X^j)$, a measure of permutation importance in ML, and the total sensitivity index

$$ST_j = \frac{I(X^j)}{2Var(Y)}$$

Antoniadis, Anestis, Sophie Lambert-Lacroix, and Jean-Michel Poggi. 2021. 'Random Forests for Global Sensitivity Analysis: A Selective Review'. Reliability Engineering & System Safety 206 (February): 107312. https://doi.org/10.1016/j.ress.2020.107312.

… but there are other methods that can be used for different settings, e.g. moment-independent:



$$\delta_i := \frac{1}{2}\mathbb{E}_{X_i}\left[s_i\left(X_i\right)\right]$$

where

$$s_i\left(x_i\right) := \int_{\Omega_Y} \left| f_Y\left(y\right) - f_{Y|X_i=x_i}\left(y\right) \right| dy$$

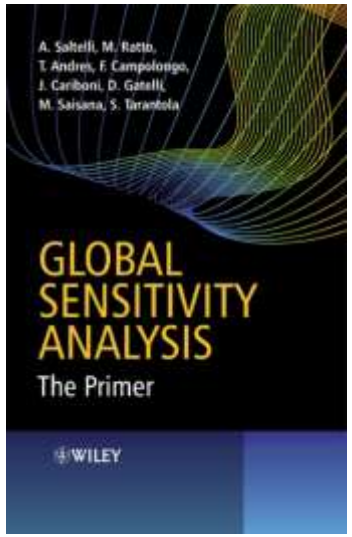
ELSEVIER

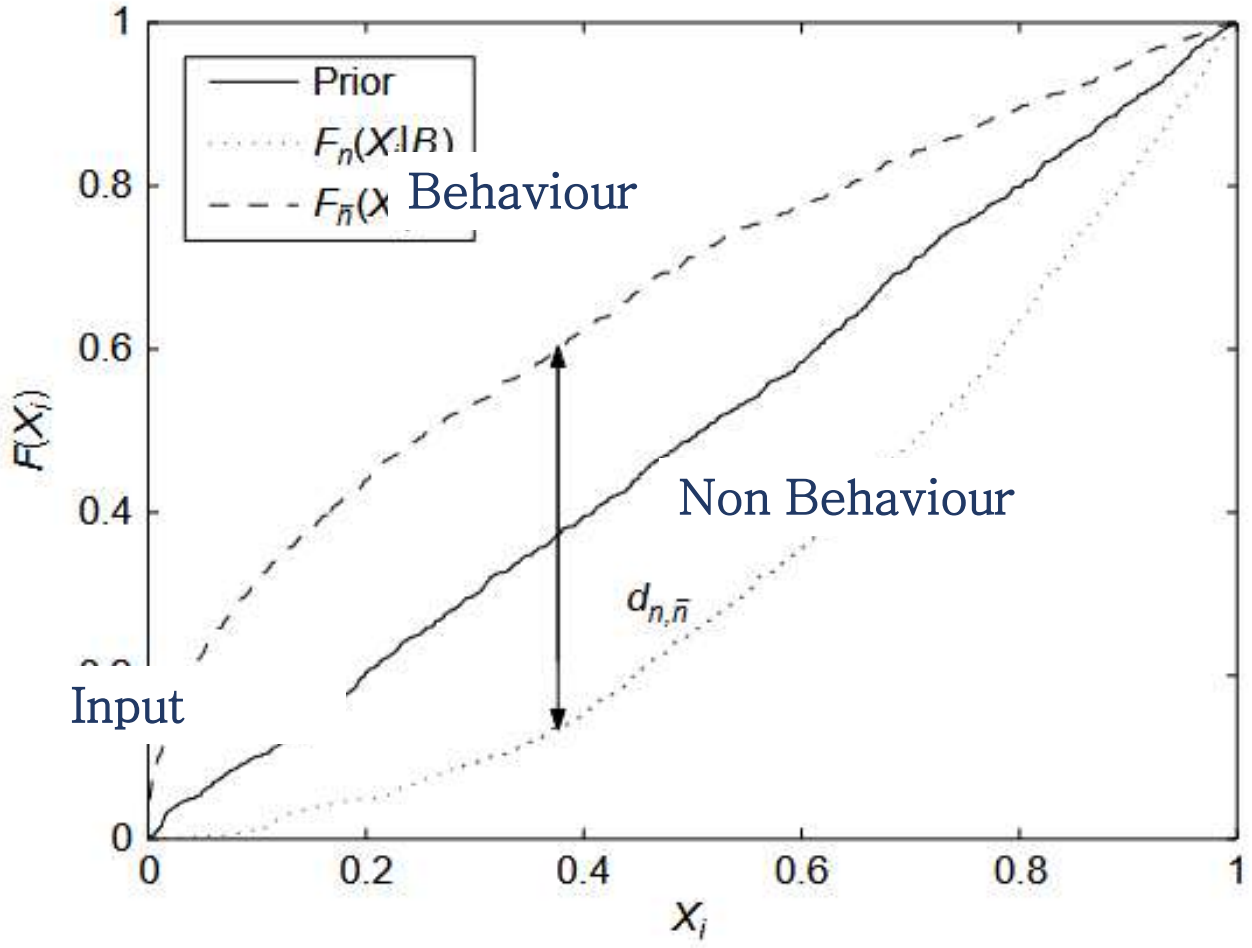
Environmental Modelling & Software

Volume 34, June 2012, Pages 105-115

Model emulation and moment-independent sensitivity analysis: An application to environmental modelling

E. Borgonovo [a], W. Castaings [b, c], S. Tarantola [d]

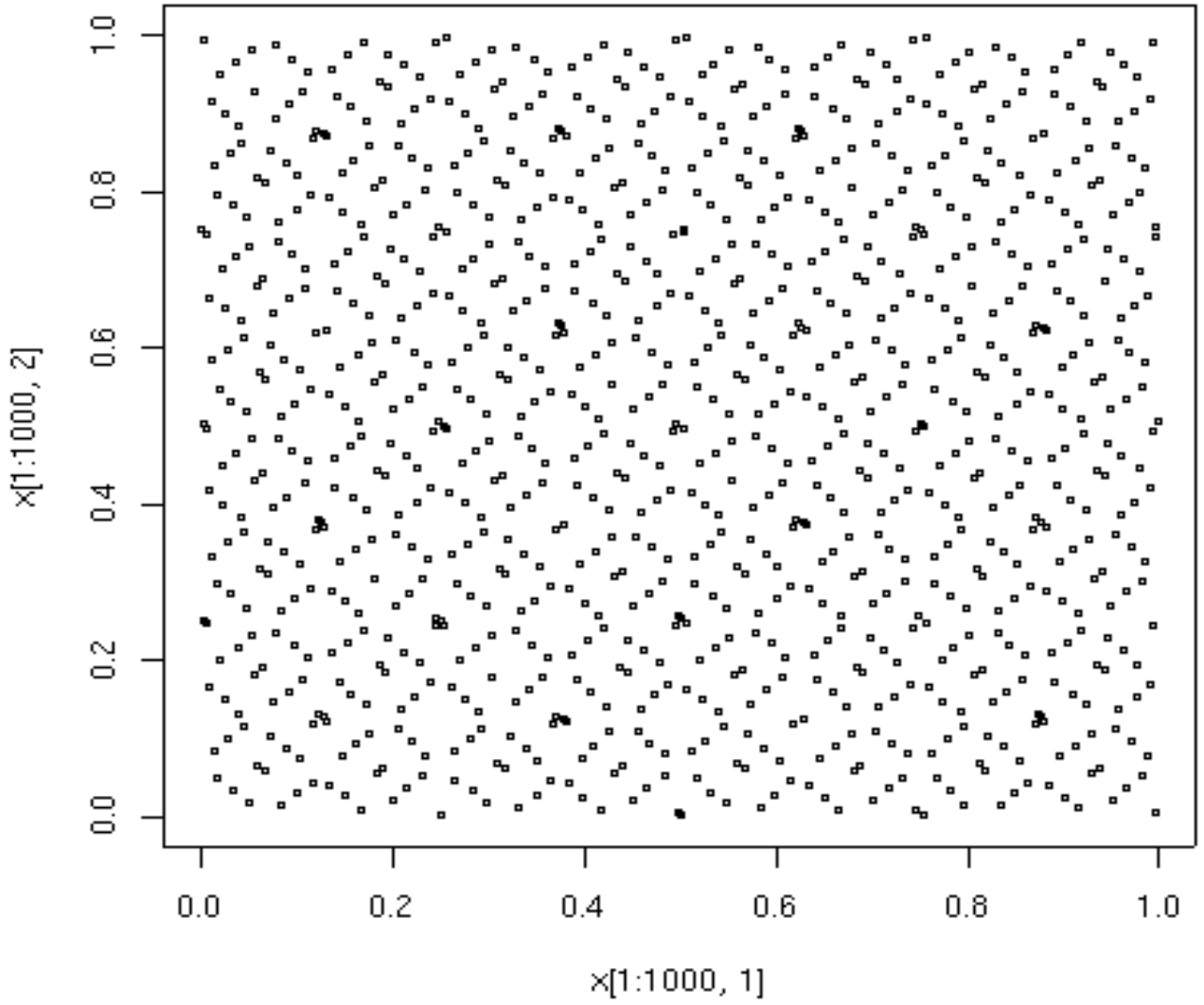




Regionalised sensitivity analysis; the input distribution is split according to Y being **Behaviour** or **Non-Behaviour**

Exploring the multidimensional cube

(Go quasirandom)



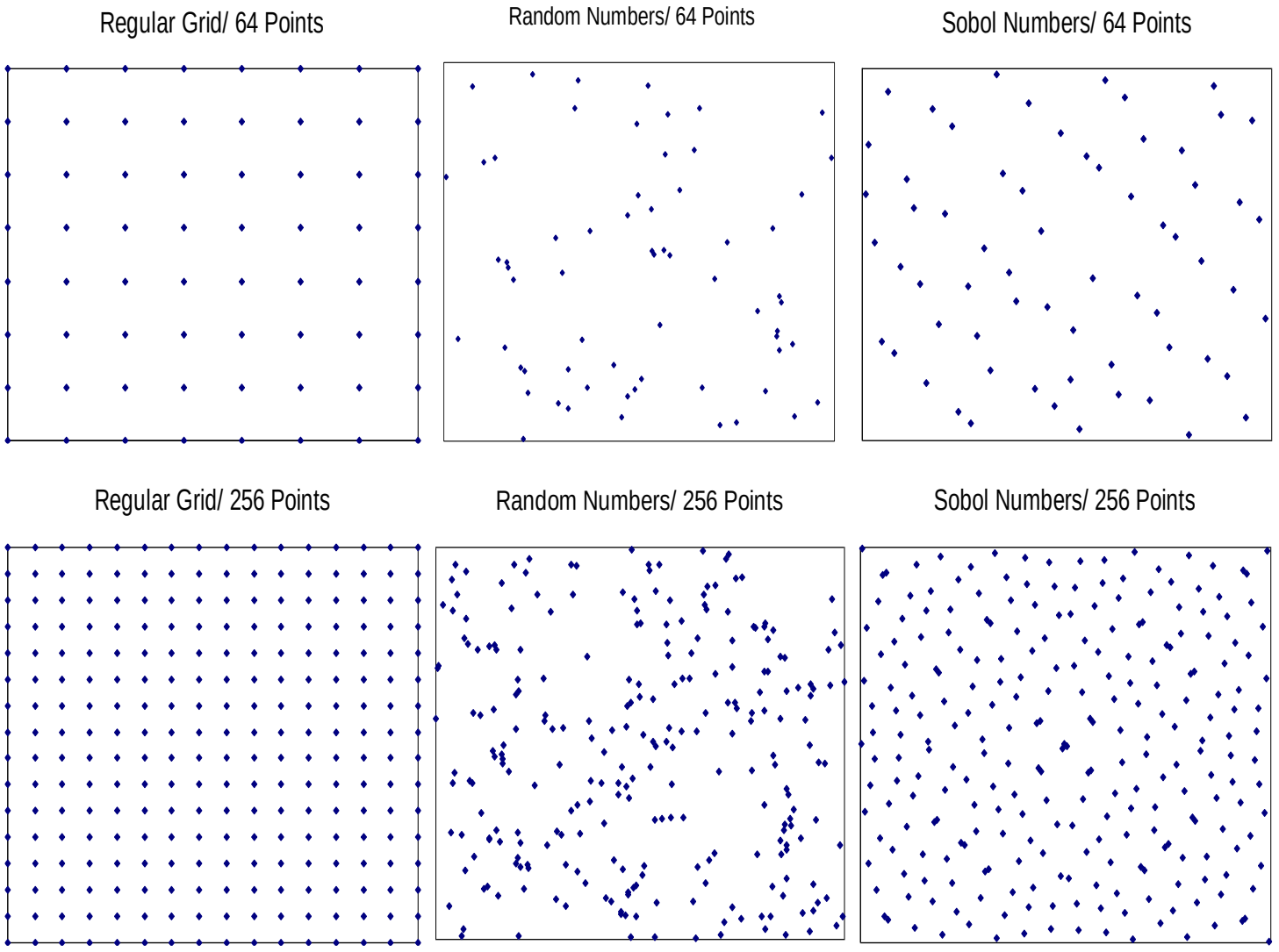
An LP_τ sequence

Ilya M Sobol'
1926-2025

Sensitivity buffs use quasirandom sequences, preferentially Sobol' LP-TAU sequences

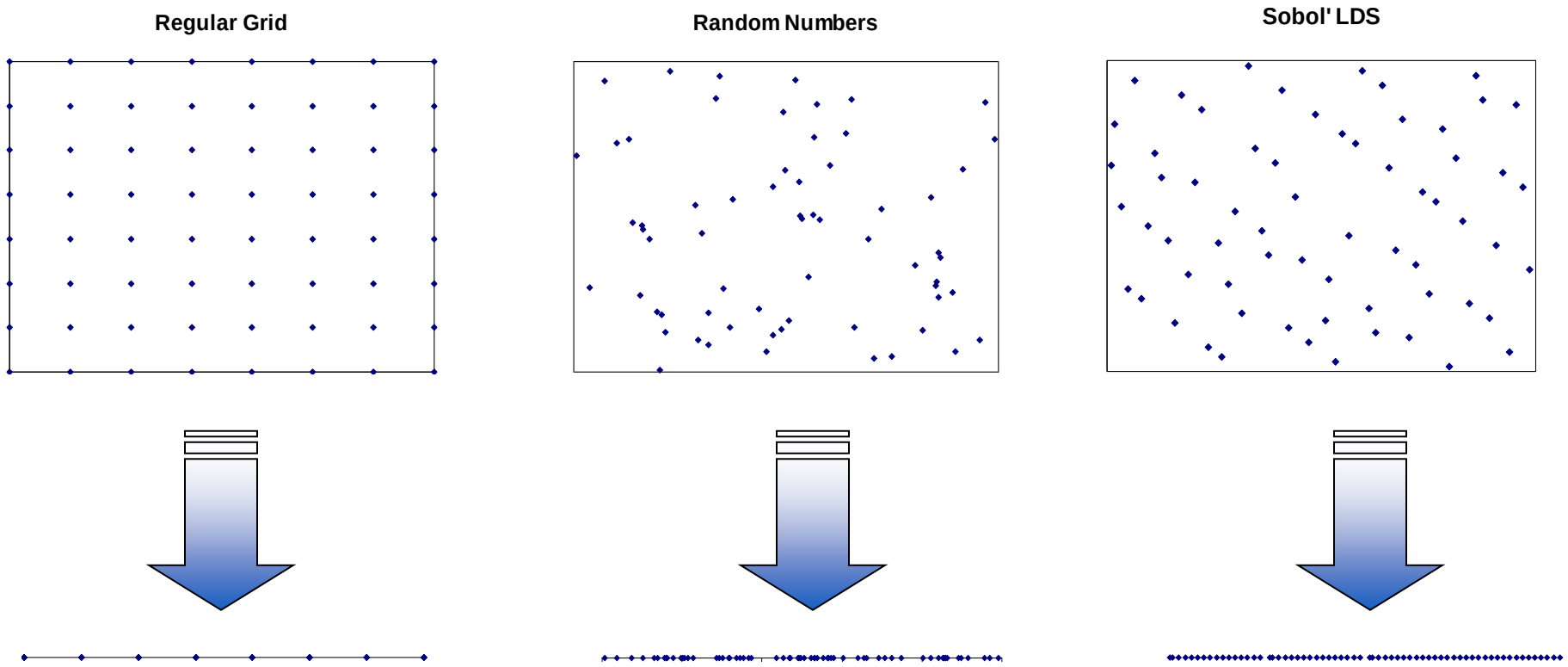
Sobol' Sequences vrs Random numbers and regular grid

Slide courtesy of Sergei Kucherenko, Imperial College London



Slide courtesy of Sergei Kucherenko, Imperial College >London

Projections of Different 2D sequences to 1D

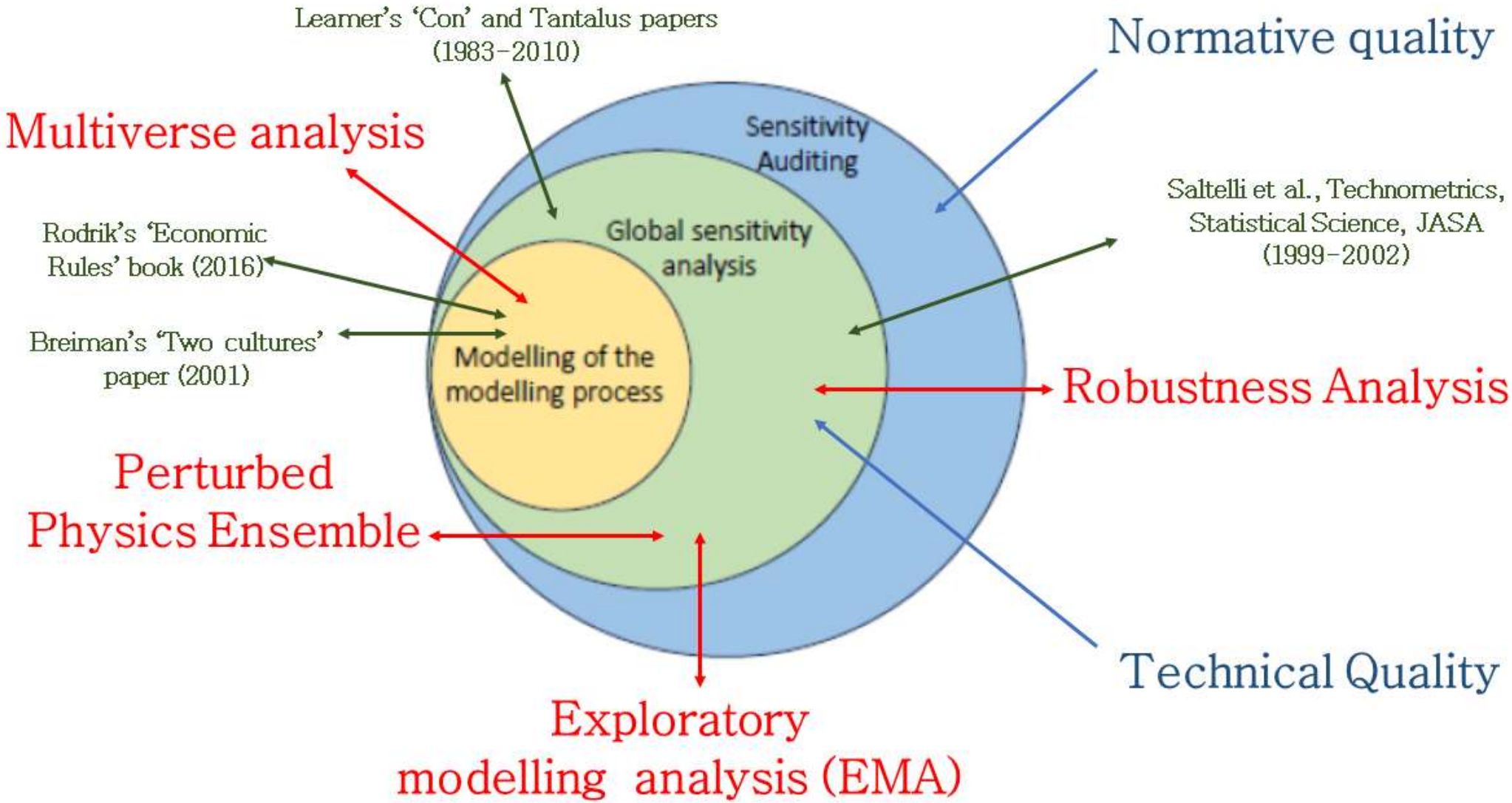


Shadow effect
(64 -> 8 points)

Clustering

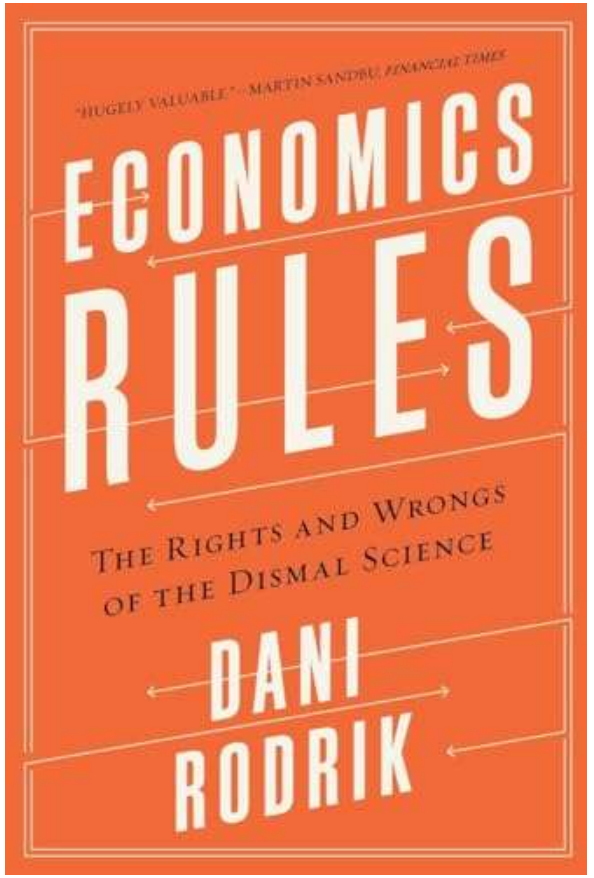
Uniform distribution

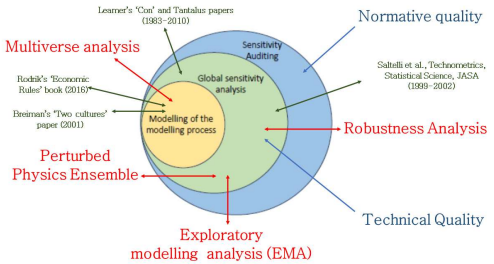
Part II – Who does GSA?


Learner's 'Con' and Tantalus papers (1983-2010)
Normative quality
Multiverse analysis
Sensitivity Auditing
Saltelli et al., Technometrics, Statistical Science, JASA (1999-2002)
Rodrik's 'Economic Rules' book (2016)
Global sensitivity analysis
Breiman's 'Two cultures' paper (2001)
Modelling of the modelling process
Robustness Analysis
Perturbed Physics Ensemble
Technical Quality
Exploratory modelling analysis (EMA)

Rodrik's rules about models (and GSA)

- Economics is a collection of models; cherish their diversity.
- It's a model, not the model.
- Make your model simple enough to isolate specific causes and how they work, but not so simple that it leaves out key interactions among causes.
- Unrealistic assumptions are OK; unrealistic critical assumptions are not OK



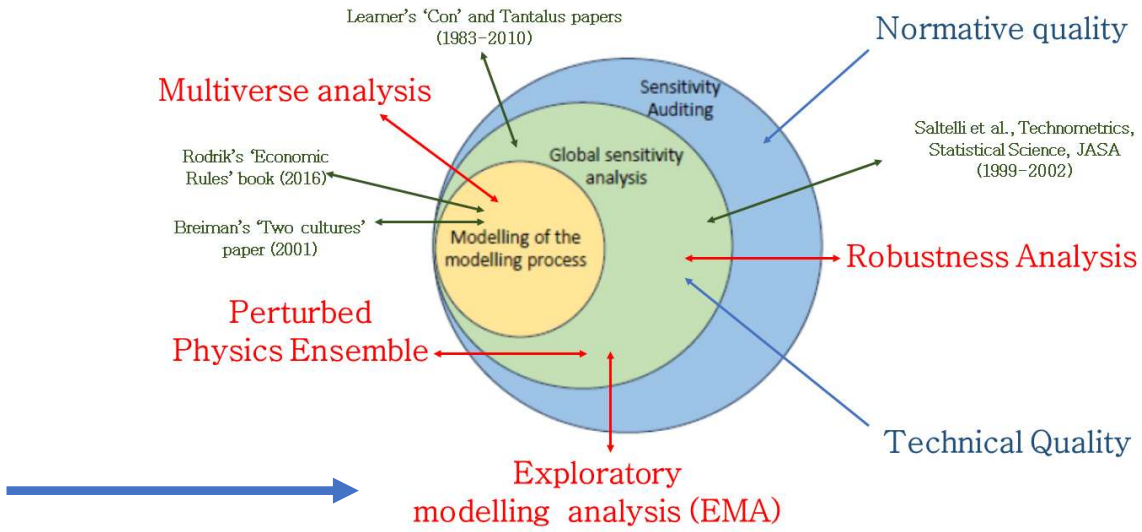


→ When modelling, move horizontally rather than vertically

Exploratory modelling analysis (RAND corporation)

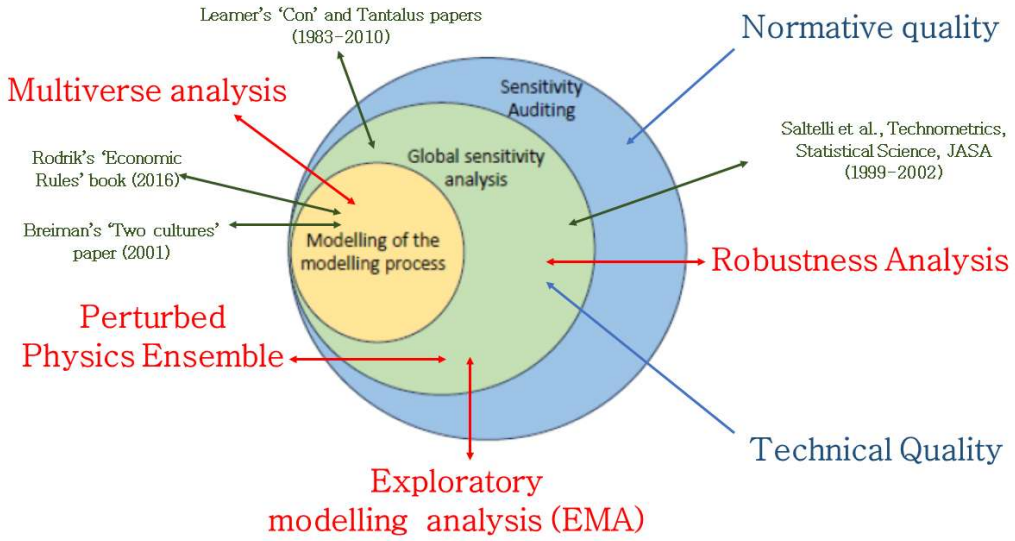
Explore scenarios and simulate

How wide is wide enough?



Jan H. Kwakkel and Erik Pruyt. Exploratory Modeling and Analysis, an approach for model-based foresight under deep uncertainty. Technological Forecasting and Social Change, 80(3):419-431, March 2013.

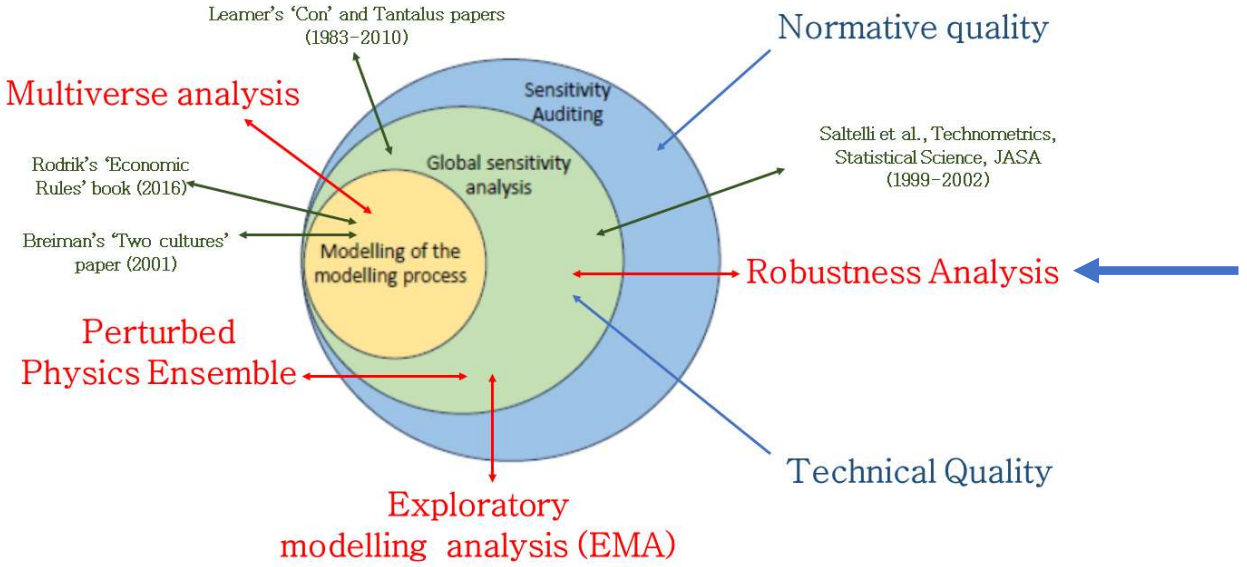
Perturbed parameter (or physics) ensemble: same as uncertainty quantification and sensitivity analysis when done by physicists in climate modelling



John W. Rostron, David M. H. Sexton, Carol F. McSweeney, Kuniko Yamazaki, Timothy Andrews, Kalli Furtado, Mark A. Ringer, and Yoko Tsushima. The impact of performance filtering on climate feedbacks in a perturbed parameter ensemble. Climate Dynamics, 55(3):521–551, August 2020. doi:10.1007/s00382-020-05281-8

Robustness analysis (Houkes et al., 2024)

parameter RA ➔ dependence on model parameters
structural RA ➔ dependence on structural assumption
representational RA ➔ model philosophy, e.g., moving from a math / differential equations to agent-based modelling



Wybo Houkes, Dunja Šešelja, and Krist Vaesen. Robustness Analysis. In Tarja Knuuttila, Natalia Carrillo, and Rami Koskinen, editors, The Routledge Handbook of Philosophy of Scientific Modeling, pages 195–207. Routledge, Abingdon, Oxon ; New York, NY, 2024.

Application to Machine Learning

Example use SA to ascertain that an algorithm does not make implicit use of protected attributes

More reading about explainable ML

Lu, Xuefei, and Emanuele Borgonovo. 2026. “How Do I Explain That Decision? A New Approach Combining Counterfactuals and Sensitivity Analyses.” European Journal of Operational Research 334 (1): 200–215. https://doi.org/10.1016/j.ejor.2026.04.035.

Giulia Vannucci, Roberta Siciliano, Andrea Saltelli, 2026, Global sensitivity analysis in random forests: unveiling generative variable importance. Statistical Methods and Applications, 34(5), https://doi.org/10.1007/s10260-026-00839-y.

Bénesse, C., Gamboa, F., Loubes, J.-M., & Boissin, T. (2022). Fairness seen as Global Sensitivity Analysis. *Machine Learning*. https://doi.org/10.1007/s10994-022-06202-y

More reading about explainable ML

Bénesse, C., Gamboa, F., Loubes, J.-M., & Boissin, T. (2022). Fairness seen as Global Sensitivity Analysis. *Machine Learning*. https://doi.org/10.1007/s10994-022-06202-y

"fairness can be defined using a special framework based on Global Sensitivity Analysis …"

More reading about explainable ML: combining counterfactual and Shapley values

Lu, Xuefei, and Emanuele Borgonovo. 2026. “How Do I Explain That Decision? A New Approach Combining Counterfactuals and Sensitivity Analyses.” European Journal of Operational Research 334 (1): 200–215. https://doi.org/10.1016/j.ejor.2026.04.035.

“In machine learning, [the idea is]to treat features as players and model predictions as rewards”

Sensitivity analysis in the garden

The garden of forking paths: Why multiple comparisons can be a problem, even when there is no "fishing expedition" or "p-hacking" and the research hypothesis was posited ahead of time*

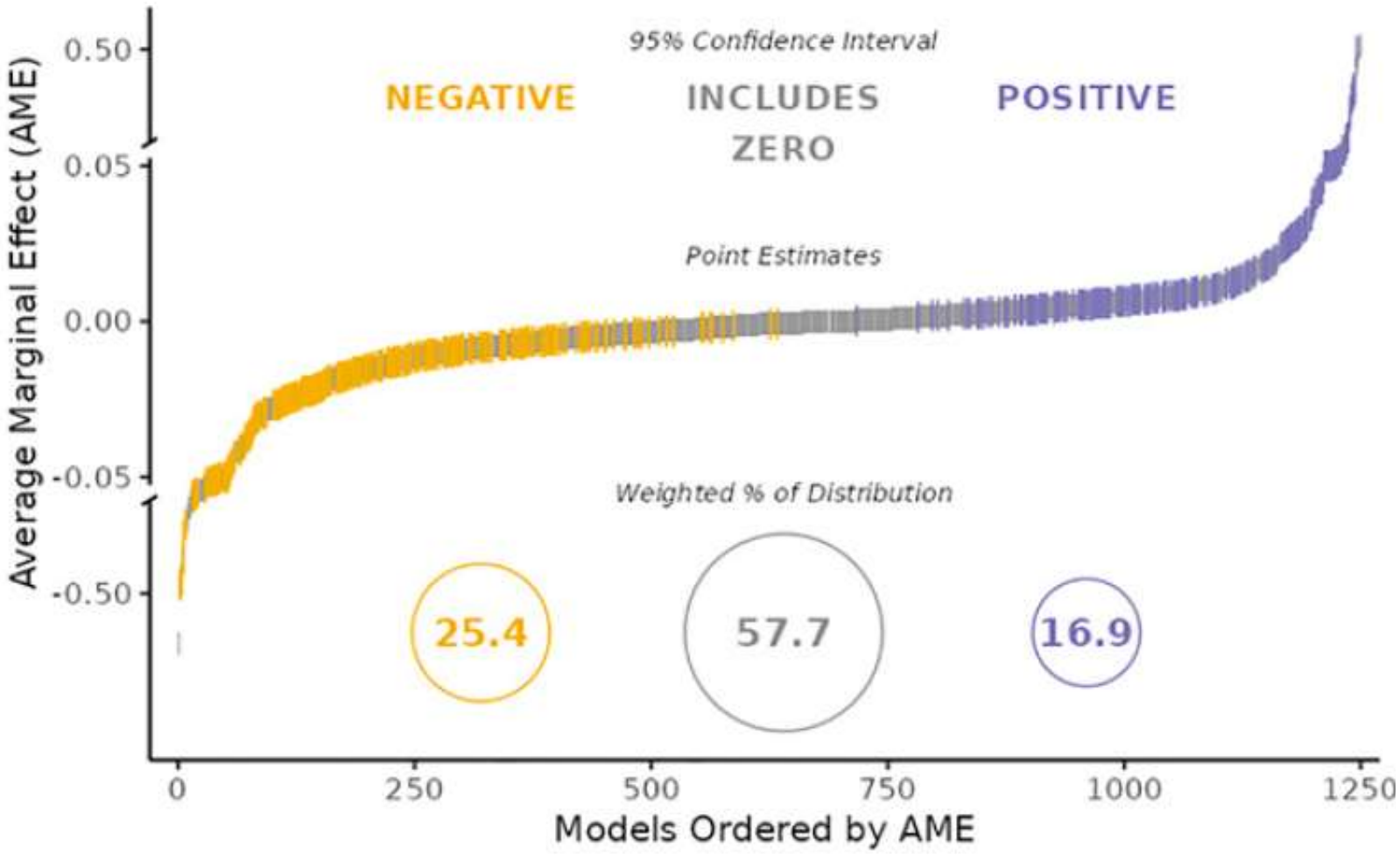
Andrew Gelman† and Eric Loken‡

14 Nov 2013

PNAS RESEARCH ARTICLE | SOCIAL SCIENCES OPEN

Observing many researchers using the same data and hypothesis reveals a hidden universe of uncertainty

Edited by Douglas Massey, Princeton University, Princeton, NJ; received March 6, 2022; accepted August 22, 2022



"Will different researchers [73 teams] converge on similar findings when analysing the same data?

…teams' results varied greatly, ranging from large negative to large positive effects"

PNAS RESEARCH ARTICLE | SOCIAL SCIENCES OPEN

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The political orientation of the analysts was found **not** to explain much of the variance

The modelling variables themselves were found to explain at most a few per cent of the variance of the results … Where **does the variance come from?**

https://www.istockphoto.com/

Simulate different paths using triggers

k_i	Variable	Description
1	*age*	Inclusion or non-inclusion of the covariates age and square age of participants
2	*all − ethnic*	Inclusion or non-inclusion of a covariate that takes into account all ethnic categories
3	*bootstrap*	Inclusion or non-inclusion of the bootstrap procedure
4	*cont − europe*	Inclusion or non-inclusion of continental Europe countries in the analysis
9	*income*	Inclusion or non-inclusion of the covariate related to the income
10	*pop − wb*	Inclusion or non-inclusion of the covariate related to the information about country-specific numerosity of population
11	*rich − dems*	Inclusion or non-inclusion of rich democracies in the analysis
12	*SE*	Inclusion or non-inclusion of clustered standard error
13	*socx − oecd*	Inclusion or non-inclusion of the covariate related to social expenditure
14	*X*1	Inclusion or non-inclusion of the covariates related to the migration indexes
15	*Y*	Choice of policy dependent variable

3 *bootstrap* Inclusion or non-inclusion of the bootstrap procedure
4 *cont − europe* Inclusion or non-inclusion of continental Europe countries in the analysis

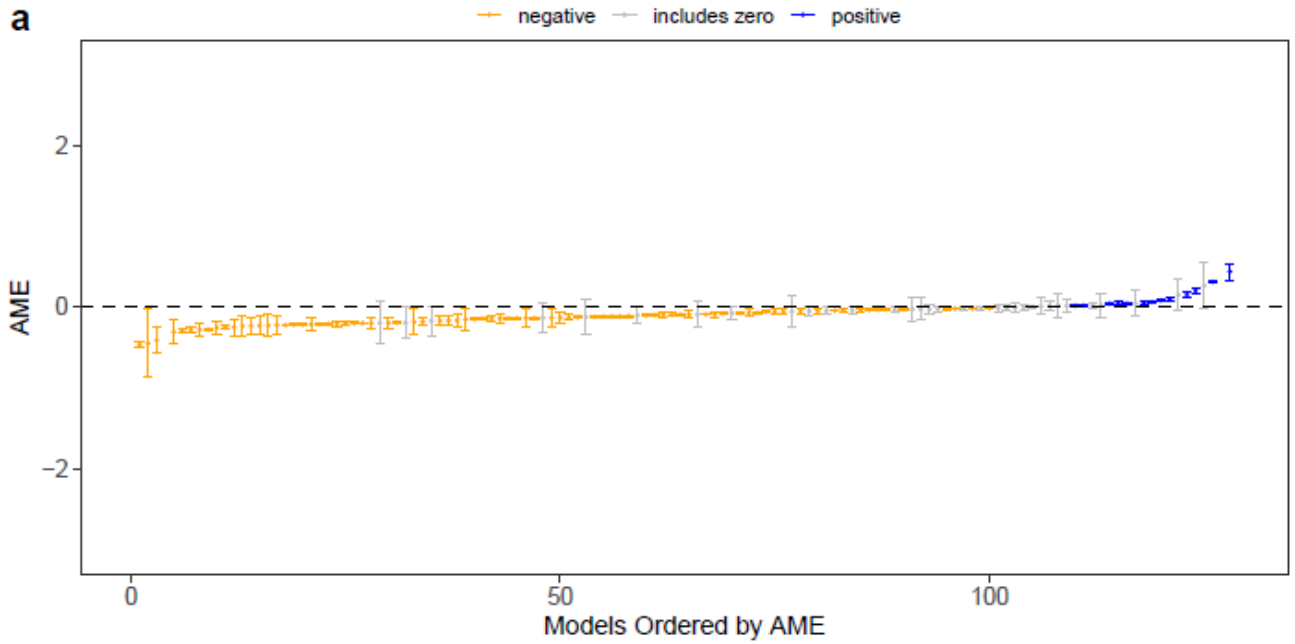
Table 1. Descriptions of variables included in the analysis.

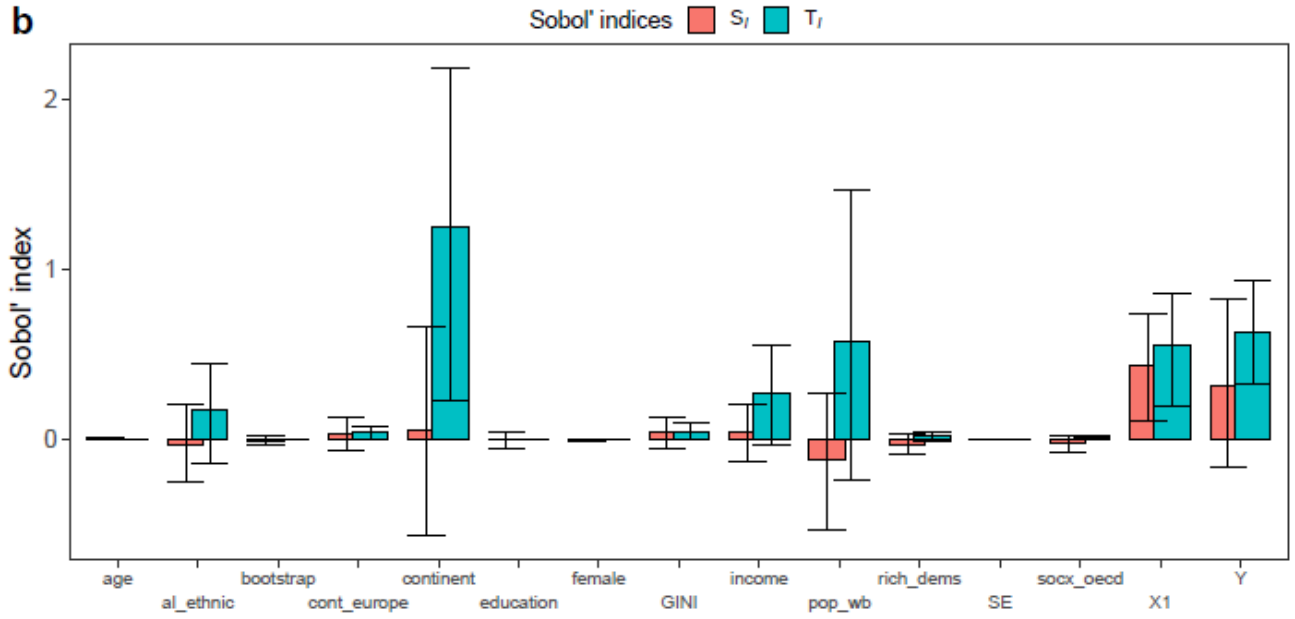
Leamer Reloaded: A Long-Neglected Suggestion Is Rediscovered To Apply Global Sensitivity Analysis To A Quantification Before Publishing It

Andrea Saltelli*[1,2], Alessio Lachi[3,4], Arnald Puy[5], and Nate Breznau[6]

OSF

https://osf.io/preprints/metaarxiv/sq34n_v1

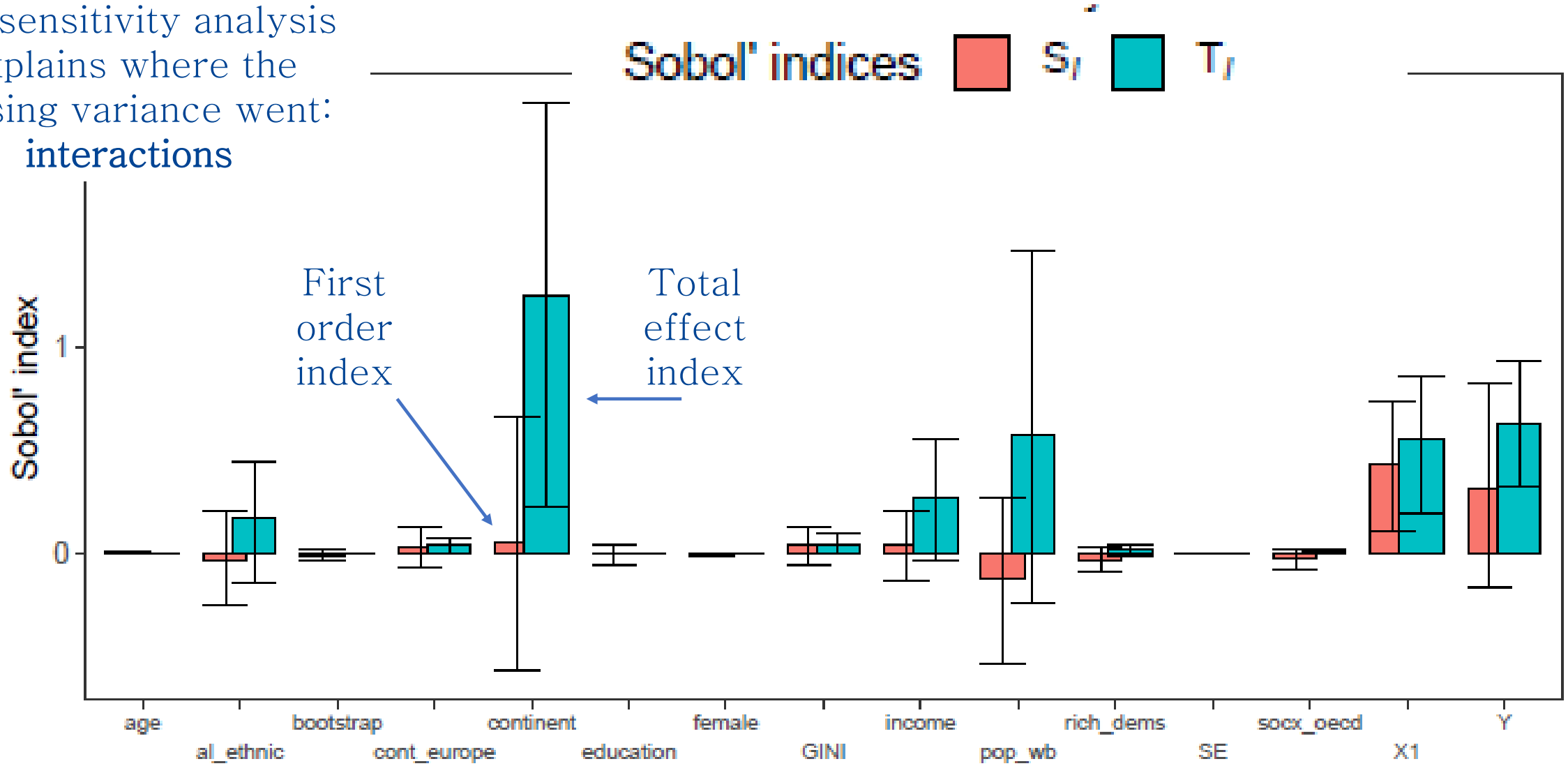




Our uncertainty analysis broadly reproduces the results of the multi-analyst experiment

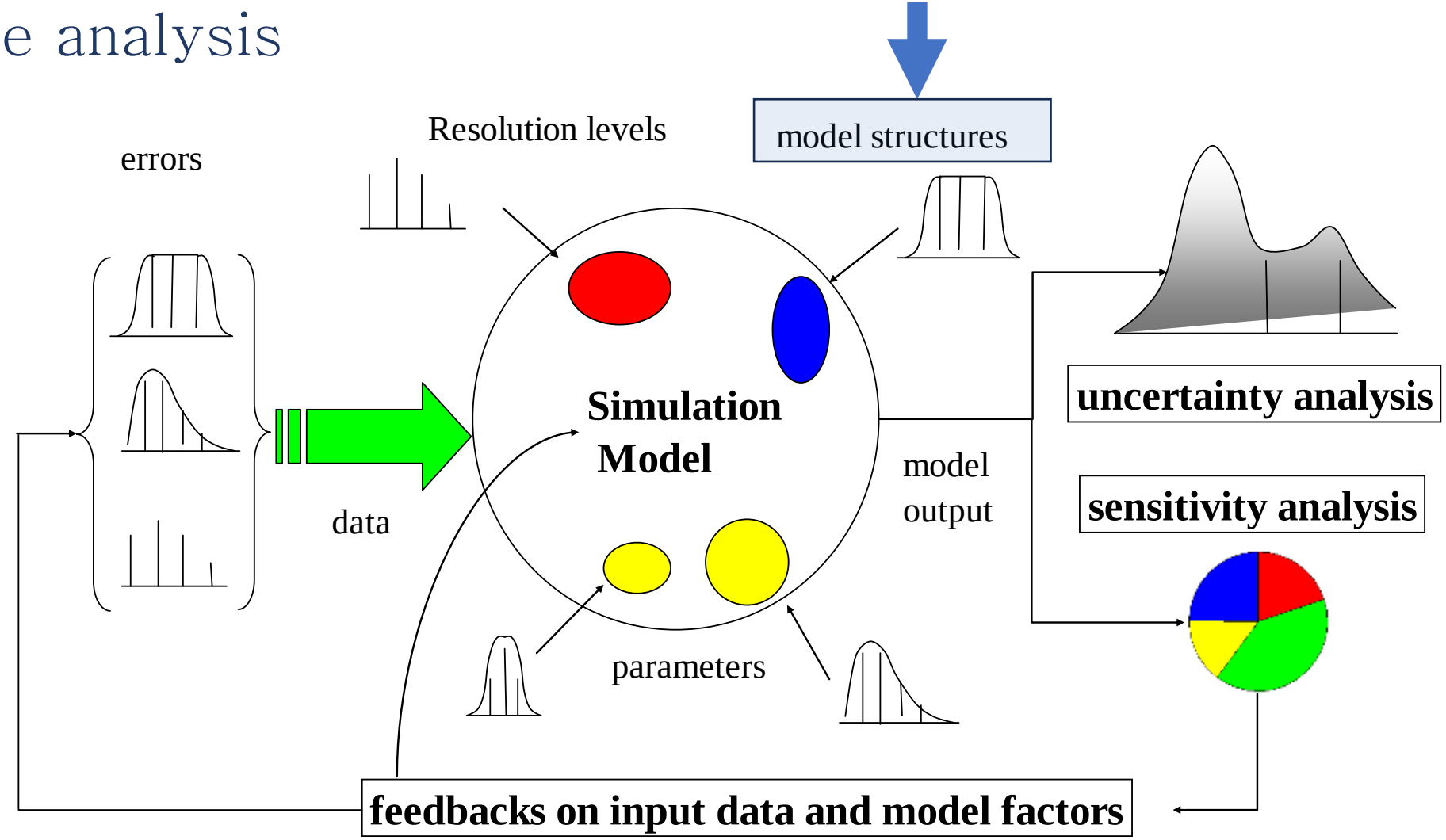
Our sensitivity analysis explains where the missing variance went: **interactions**

Our sensitivity analysis explains where the missing variance went: **interactions**



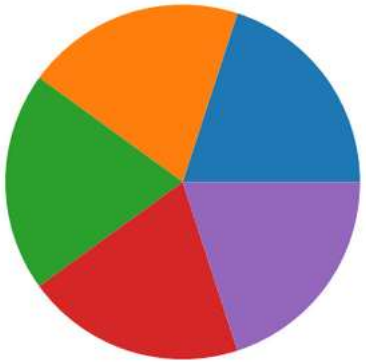
Part III GSA’s dos and don'ts

Sample modelling choices via ‘triggers’. Global sensitivity analysis becomes thus a modelling of the modelling process = multiverse analysis



Example of using triggers: an integer in [1-5] is used to select one out of 5 possible evapotranspiration formulae at each model run

Trigger=an integer variable, whose value is determined via 'Russian roulette' in Monte Carlo jargon



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The delusive accuracy of global irrigation water withdrawal estimates

Arnald Puy ✉, Razi Sheikholeslami, Hoshin V. Gupta, Jim W. Hall, Bruce Lankford, Samuele Lo Piano, Jonas Meier, Florian Pappenberger, Amilcare Porporato, Giulia Vico & Andrea Saltelli

Nature Communications **13**, Article number: 3183 (2022) | Cite this article

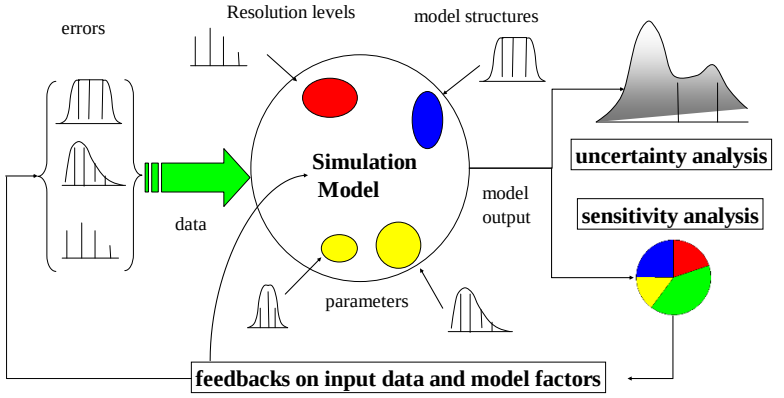
10k Accesses | **79** Citations | **93** Altmetric | Metrics

Russian roulette as depicted in the 1925 film The Night Club. Source: Wikipedia Commons

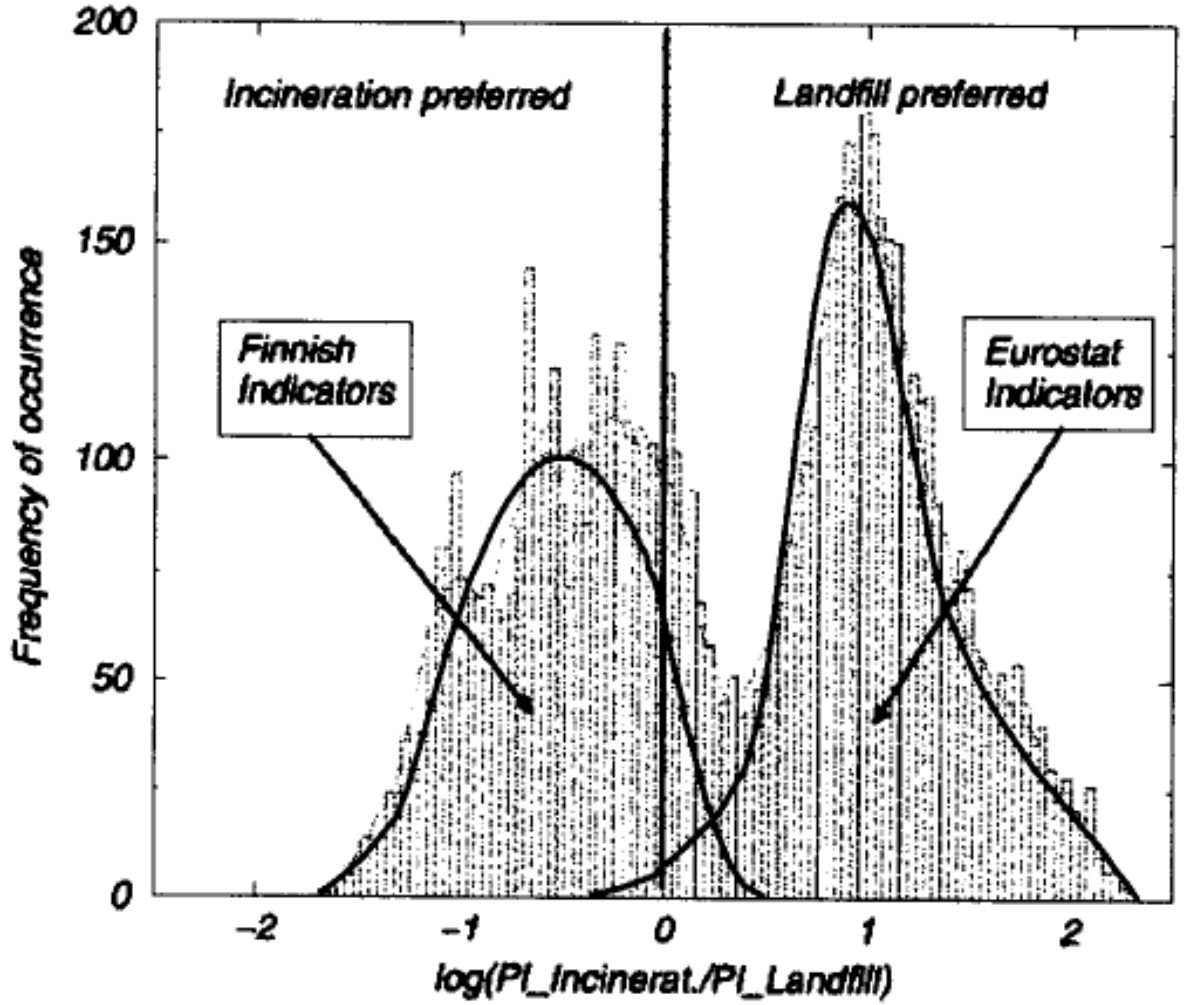
➔ Don't sample just parameters and boundary conditions: explore the space of assumptions thoroughly

One can sample more than just factors:

- modelling assumptions,
- alternative data sets,
- resolution levels,
- policies



Look at policy options versus existing uncertainties: e.g., test whether the choice of the model determines the choice of the policy



November 2000

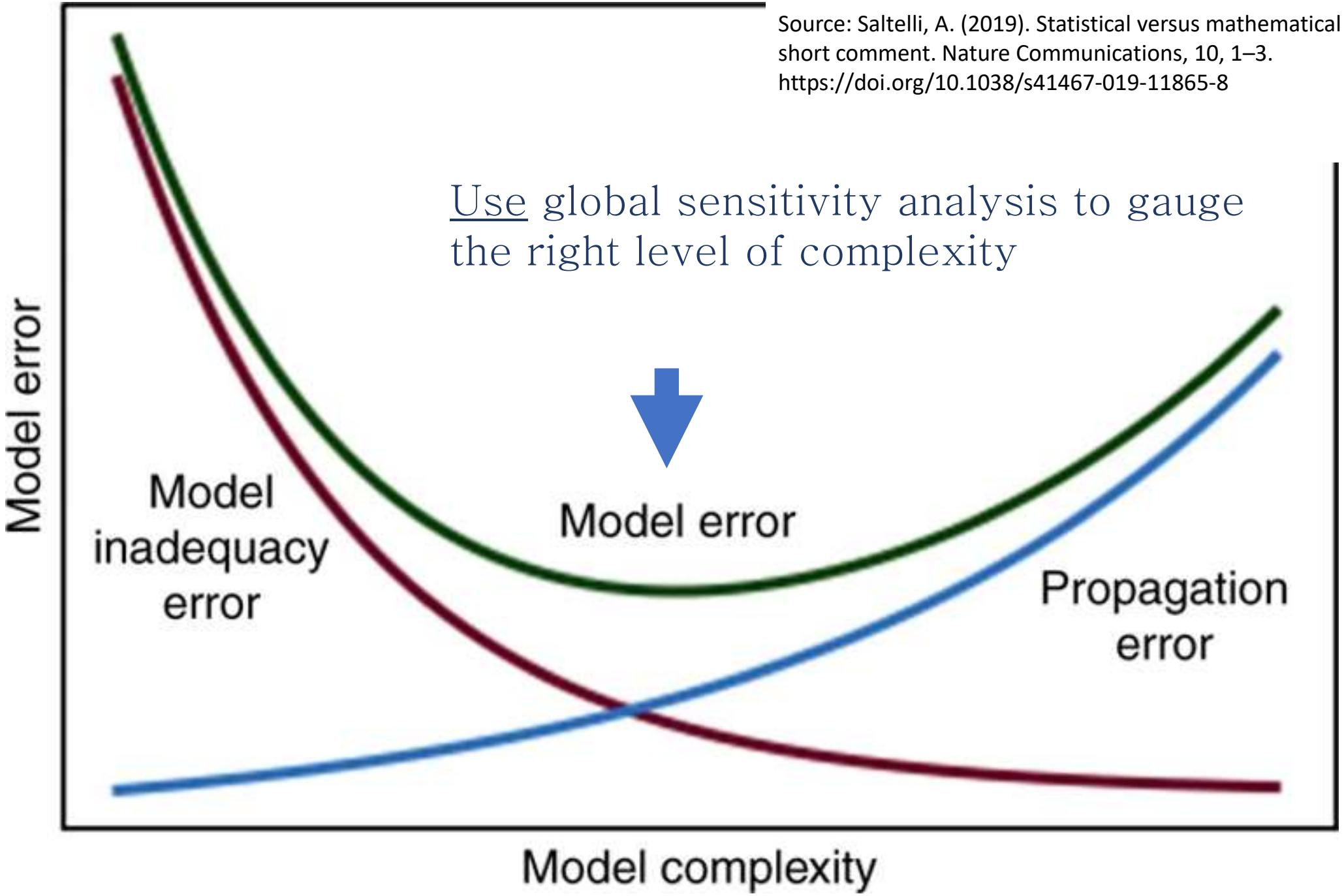
Sensitivity Anaysis as an Ingredient of Modeling

F. Campolongo, A. Saltelli, S. Tarantola

BARCELONA SCHOOL OF MANAGEMENT

Source: Saltelli, A. (2019). Statistical versus mathematical modelling: A short comment. Nature Communications, 10, 1–3. https://doi.org/10.1038/s41467-019-11865-8

Use global sensitivity analysis to gauge the right level of complexity

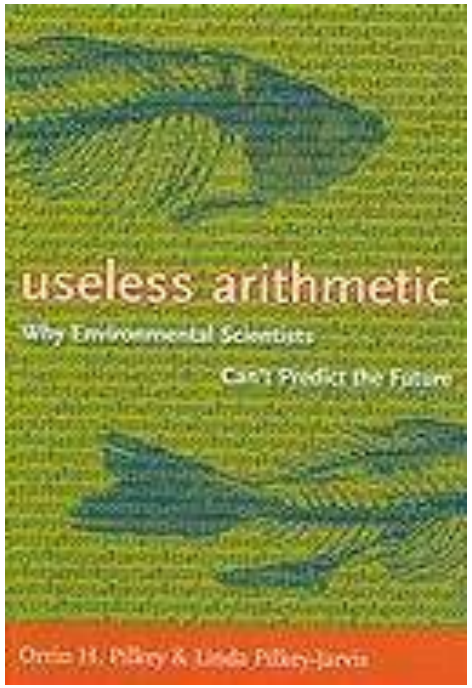


Don’t confuse the map with the territory

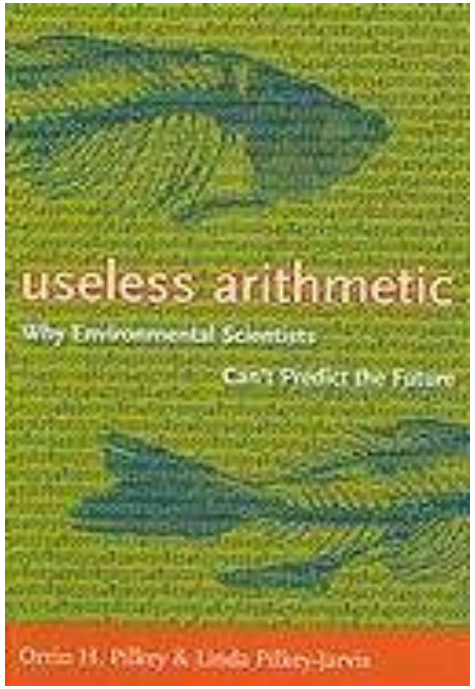
If you do, sensitivity analysis will not save you

<<It is important, however, to recognize that the sensitivity of the parameter in the equation is what is being determined, not the sensitivity of the parameter in nature>>

Orrin H. Pilkey



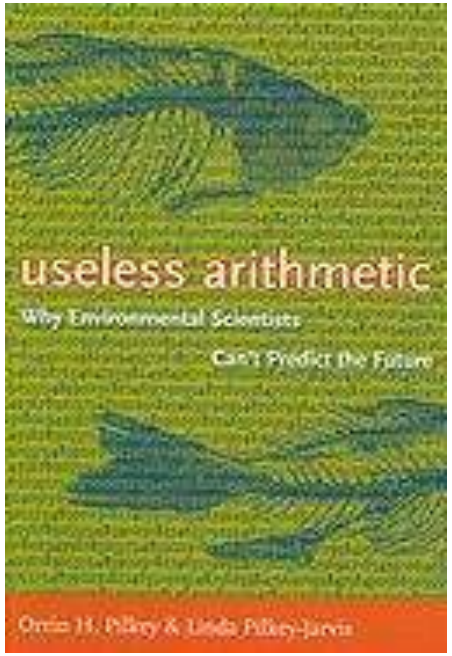
Useless Arithmetic: Why Environmental Scientists Can't Predict the Future
by Orrin H. Pilkey and Linda Pilkey-Jarvis, Columbia University Press, 2009.

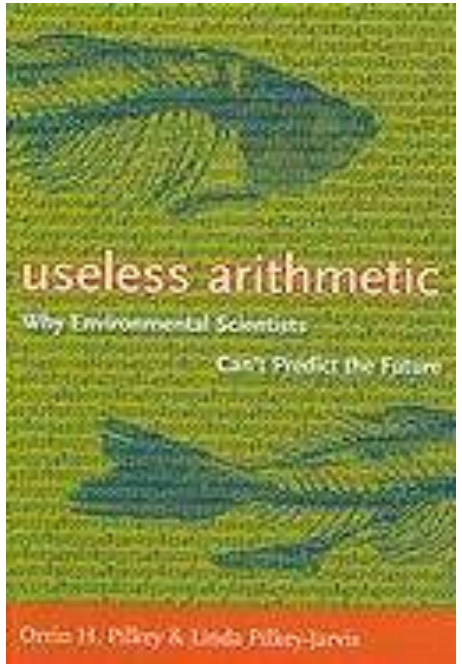


<<…If the model is wrong or if it is a poor representation of reality, determining the sensitivity of an individual parameter in the model is a meaningless pursuit>>

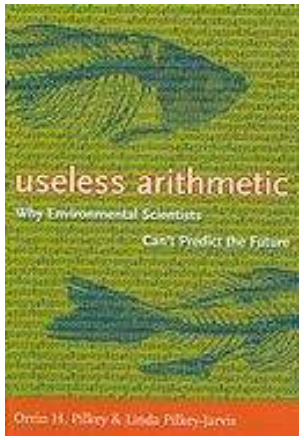
One of the examples discussed concerns the Yucca Mountain repository for radioactive waste. TSPA model (for total system performance assessment) for safety analysis.

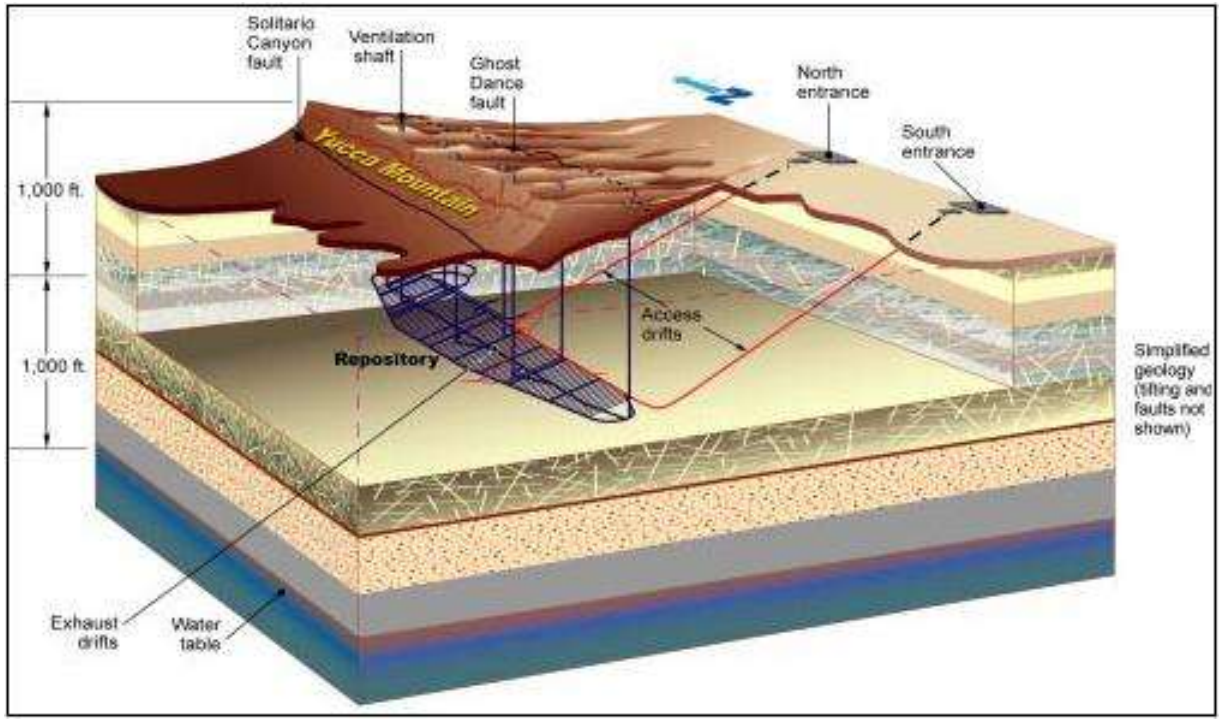
TSPA is Composed of 286 sub-models.





TSPA (like any other model) relies on assumptions → one is the low permeability of the geological formation → long time for the water to percolate from surface to disposal

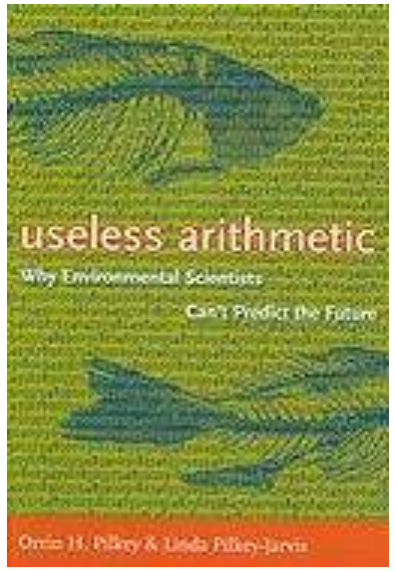




The confidence of the stakeholders in TSPA was not helped when evidence was produced which could lead to an upward revision of 4 orders of magnitude of this parameter
(the ^{36}Cl story)

In the case of TSPA (Yucca mountain) a range of 0.02 to 1 millimetre per year was used for percolation of flux rate.

→… SA useless if it is instead ~ 3,000 millimetres per year.



"Scientific mathematical modelling should involve constant efforts to falsify the model"

➔ Organized skepticism (as per CUDOS)

Communalism, Universalism, Disinterestedness, Organized Skepticism, from sociology of science, Robert K. Merton.

Don’t run the model just once

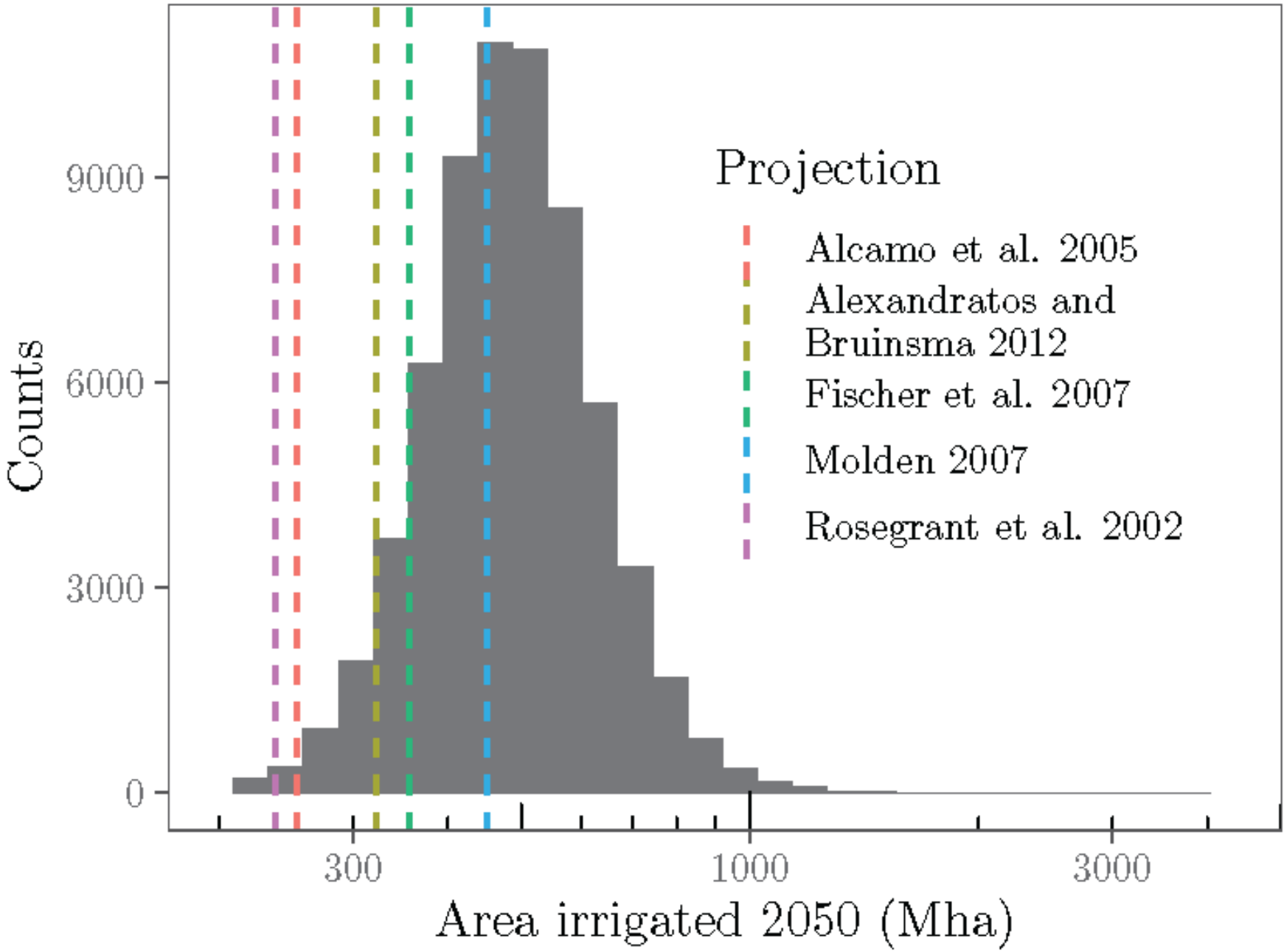
There is much to learn by running the model a few times, especially during model building

Lubarsky's Law of Cybernetic Entomology: there is always one more bug!

A model routinely used to produce point estimates may become non-conservative when the uncertainty is plugged in

Current Models Underestimate Future Irrigated Areas

- How much land will need to be irrigated by the year 2050?
- Here the dashed lines represent deterministic model predictions from different models and datasets (from FAO & others organizations);
- An uncertainty analysis (grey histogram) reveals that the models are non-conservative: the need might be much larger



Citation:
Puy, A., Lo Piano, S., & Saltelli, A. (2020). Current models underestimate future irrigated areas. *Geophysical Research Letters*, 47, e2020GL087360. https://doi.org/10.1029/2020GL087360

NEVER vary all factors by the same amount
Be it 5%, 10%, or 20%

New WHO estimates: Up to 190 000 people could die of COVID-19 in Africa if not controlled

07 May 2020

Brazzaville – Eighty-three thousand to 190 000 people in Africa could die of COVID-19 and 29 million to 44 million could get infected in the first year of the pandemic if containment measures fail, a new study by the World Health Organization (WHO) Regional Office for Africa finds. The research, which is based on prediction modelling, looks at 47 countries in the

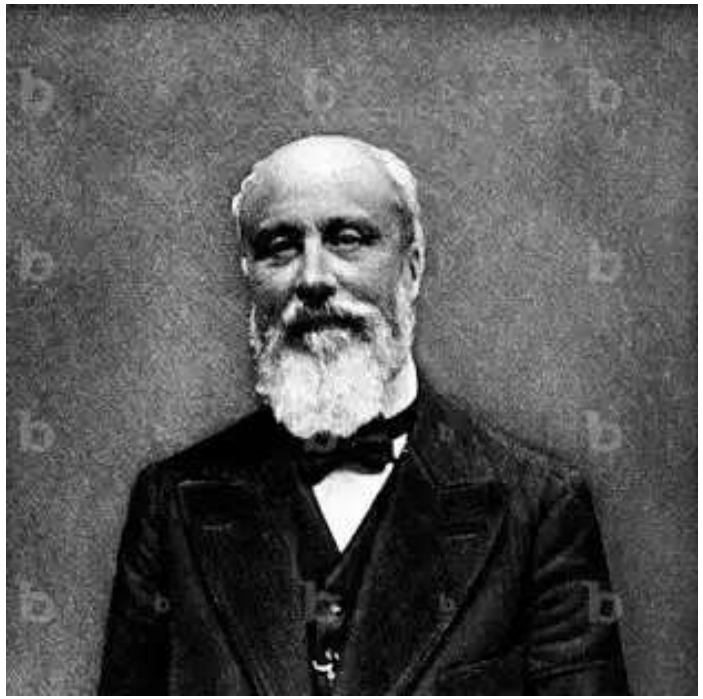
Speculative scenario in which ten uncertain input probabilities are varied by an arbitrary 10% — as if they were truly equally uncertain — with no theoretical or empirical basis for such a choice

World Health Organization
REGIONAL OFFICE FOR Africa

In a numerical experiment relating to a real-life application, the range of uncertainty of each input is a crucial input to the analysis, and often the most expensive to get

"… inferences from mathematical models of phenomena to real physical applications must also be demonstrated to be approximately correct when the assumptions of the model are only approximately true" [1]

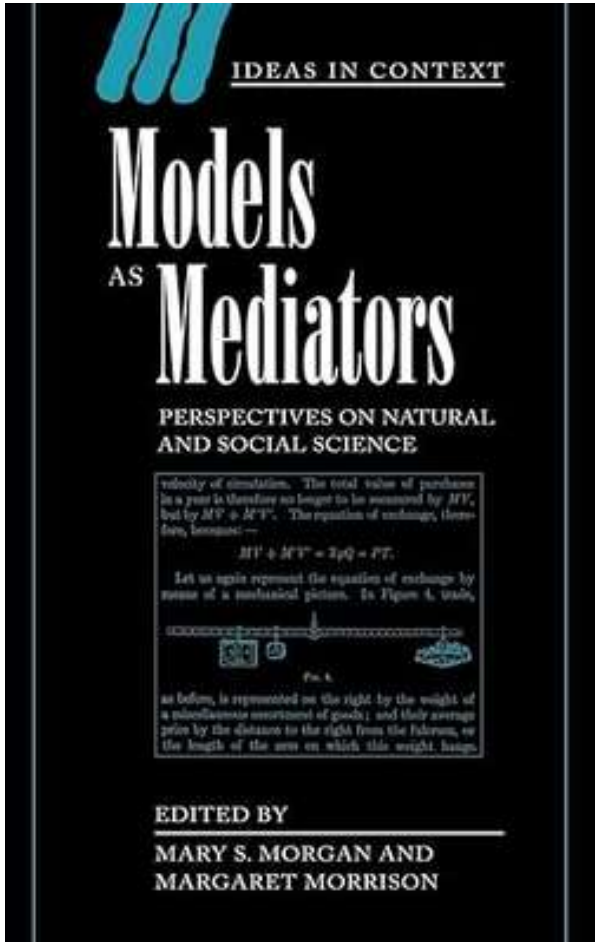
Pierre Duhem (1861–1916) and his 'Principle of stability' ~1906

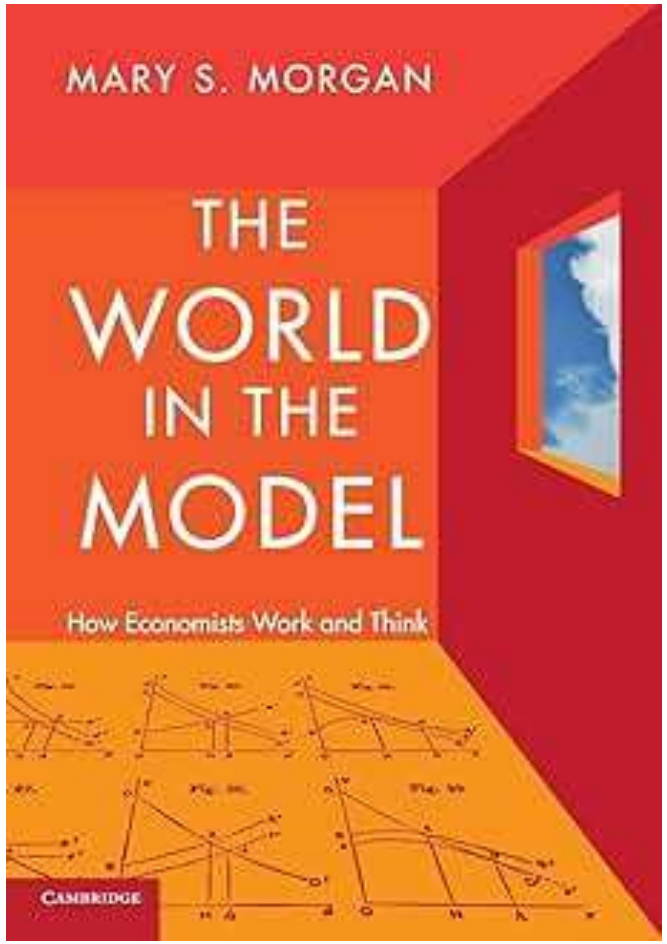


[1] See: S. C. Fletcher, 'The Principle of Stability', Philosopher's Imprint, vol. 20, no. 3, 2020, Accessed: Sep. 08, 2024. [Online].

Mary S. Morgan

Margaret Morrison

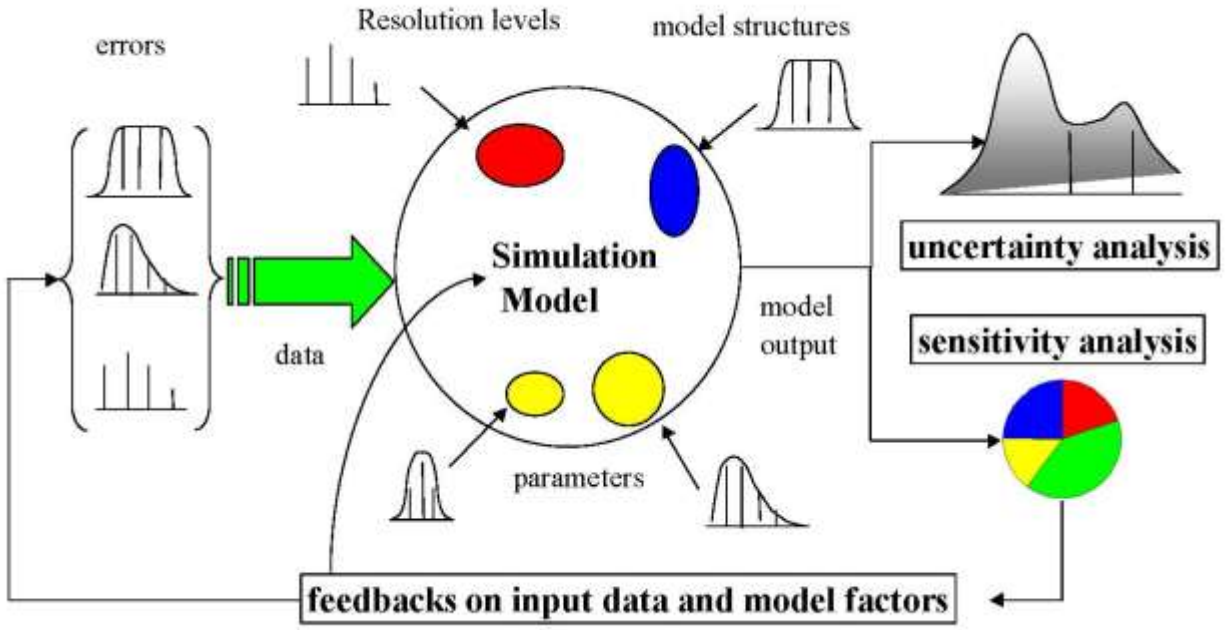


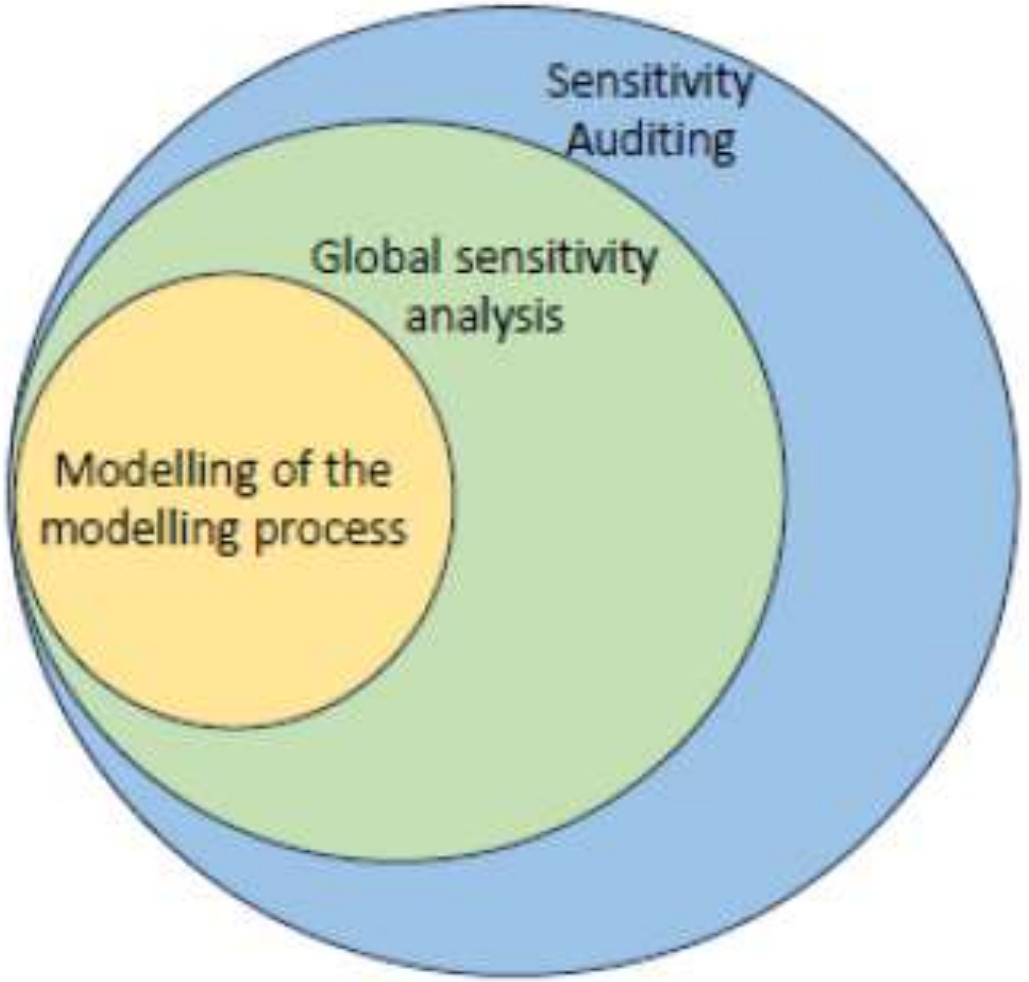


Models as mediators between theories and the world.

World in the model, model in the world

The End


errors
Resolution levels
model structures
Simulation Model
data
model output
uncertainty analysis
sensitivity analysis
parameters
feedbacks on input data and model factors


Sensitivity Auditing
Global sensitivity analysis
Modelling of the modelling process