RECKONING WITH UNCERTAINTY

SOCIAL SCIENCES LESSONS FOR MATHEMATICAL MODELING

The COVID-19 pandemic has brought mathematical modeling to the forefront of public attention and debate. Even the simplest of epidemiological models have played an essential role in informing decision-making and society at large. Vocabulary such as 'flattening the curve' has become part of the collective lexicon. But with popularity comes criticism and dissent, primarily when models are used to take unpopular decisions like containment policies. Models are mathematical constructs better understood by their developers than by users. So should the public trust models? The social sciences offer insights that can help society demand the quality it needs from modeling.

KEY MESSAGES

- ☑ Mathematical models can serve society well, as in the example of meteorological forecast models. But not all models are useful. Simple rules can benefit both models and their relationship with society.
- ☑ Model results are conditional on modeling assumptions. The potential outcomes that models project depend on the assumptions they make. Even the best models are affected by uncertainties that aren't always easy to recognize, understand, acknowledge, or communicate. Opacity about uncertainty damages trust.
- ☑ Modelers need to more effectively and transparently communicate the proper uses and limitations of their models to decision makers and the public. Likewise, modelers need to communicate an appreciation for, and the public needs to accept, what the numbers in those models really mean and do not mean.

Used appropriately, mathematical models serve society exceptionally well. Perhaps the best-known models are those used in weather forecasting, which provide critical data for transportation, travel, disaster prevention, and for simply planning outdoor picnics. Unfortunately, not all models are up to this same standard of societal effectiveness.

When social scientists look at mathematical models, they discover a multiverse, where each scientific discipline adopts its own styles of modeling and quality control. Very little in the way of 'user instructions' is available to those affected by modeling practices. In June 2020, a cross-disciplinary group of natural and social scientists published a manifesto in *Nature* that described what is urgently needed to ease

MIND THE ASSUMPTIONS

Uncertainty quantification and sensitivity analysis are complementary approaches to measuring the robustness of model predictions.

The usefulness of a model depends largely on the accuracy and credibility of its outputs. Yet, because model inputs are rarely precise, output values are always subject to some imprecision and uncertainty. Uncertainty analysis is the process of determining the uncertainty in the model output that is generated from uncertainty in parameter inputs. An essential complement to uncertainty quantification is a sensitivity analysis, which involves assessing how variations in model outputs can be apportioned to different input sources. Performing global uncertainty and sensitivity analyses is fundamentally critical to model quality. Conveying the uncertainty associated with model predictions can be as important to decision-making and policy development as the predictions themselves.

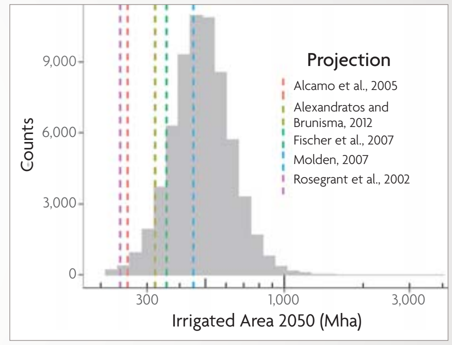
MIND THE HUBRIS

At their core, models are simplified representations of real systems or processes.

It's commonly held that simpler models are often preferable to complex ones. They're easier to understand and validate, and their predictions are typically more accurate. Increasing complexity comes at the cost of adding parameters, whose uncertainty propagates to the model outputs. But this is at odds with current trends that see increasingly complex and larger models. This attraction to complexity may reflect the justified ambition of modelers to achieve a more accurate representation of the study system. But no matter how big or complex the model is, it cannot reflect all of reality. If models are to fulfill their objectives, modelers must resist the urge of complexity as a goal and, instead, build models with an optimum trade-off between complexity and error.

EXAMPLE: MODELING FUTURE IRRIGATED AREAS

In these models, analysts were asked to predict how much irrigated land will be needed by the year 2050. The dashed vertical lines represent predictions from rather complex analyses, without uncertainties attached. The gray histogram represents an uncertainty analysis, where uncertainties from input variables and assumptions are propagated through the model to the output. Most predictions range between 240 and 450 million hectares (Mha), underestimating the potential expansion of irrigation by ignoring basic parametric and model uncertainties. When these are taken into account, the probability distribution of global irrigated land spans almost half an order of magnitude (300–800 Mha), yet higher values, up to 1,800 Mha, cannot be excluded. (*Figure adapted from Puy et al., 2020*).



MIND THE FRAMING

Framing refers to the different lenses, worldviews, or underlying assumptions that guide how individuals, groups, and societies perceive a particular issue.

Model results will at least partly reflect their creators' disciplinary orientations, interests, and biases. Critics of model predictions or policy implications will point to these biases to sow public distrust. How these results are framed and communicated can influence public opinion and steer one policy outcome over another. Modeling practitioners must develop models that are transparent and help model users understand their inner workings and outputs. Successful and transparent framing can support effective results communication and enhance trust with stakeholders.

MIND THE CONSEQUENCES

When appropriately executed, mathematical modeling helps society make smarter decisions. But when not done well, models can lead to wrong or simply unjustified choices.

Quantification can backfire. By helping to make complex financial products seem safe but failing to highlight the underlying assumptions clearly, models contributed to the breakdown of global financial markets in 2008. Society must collectively establish new social norms and ethics of quantification to ensure model predictions contribute to effective decision-making, Modelers must refrain from projecting a false sense of certainty, and decision-makers cannot offload accountability to models just because they fit a pre-established agenda.

MIND THE UNKNOWNS

Failure to acknowledge and communicate uncertainties can artificially limit policy options and open the door to unintended consequences.

Philosophers have long reflected on the virtue of knowing what is not known. German philosopher and mathematician Nicolas Cusa described this in *De Docta Ignorantia* — learned ignorance. Mathematical modeling often sins of excess precision. Too often, modelers are reluctant to acknowledge uncertainties, fearing candor undermines their credibility. In presenting their results, modelers must communicate how prediction uncertainties might change the conclusions. Being transparent about uncertainties strengthens public trust, both in the models and their sources.

the dialogue between models and society. The following five lessons summarize these best practices for responsible mathematical modeling.

CONCLUSIONS

Statistician George EP Box famously said, "Essentially, all models are wrong, but some are useful." Useful models foster understanding. When used appropriately, they make life better and safer in myriad ways. The five lessons above can help ensure mathematical models are responsibly produced and ultimately useful. Each of these lessons showcases the strengths and limits of model outputs and collectively will help preserve mathematical modeling as a valuable tool.

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