Uncertainty, Ignorance and Decision-Making: Looking Through the Lens of Modelling the Covid-19 Pandemic

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Abstract

A great deal of decision-making during crises is about coping with uncertainty. For rulemakers, this poses a fundamental challenge, as there has been a lack of a rigorous framework for understanding and analysing the nature and function of uncertainty in the context of rulemaking. In coping with crises, modelling has become a governance tool to navigate and tame uncertainty and justify decisions. This is because models, in particular mathematical models, can be useful to produce precise answers in numbers. This article examines the challenges rulemakers are facing in an uncertain world and argues that one of the most important challenges lies in rulemakers' failures to understand the nature of uncertainty and ignorance in the contested arena of science for decision-making. It focuses on the relationship between uncertainty, ignorance and decision-making through a case study of the interaction between modelling and rulemaking in the Covid-19 pandemic. In so doing, this article provides an alternative strategy to number- and model-based rulemaking in an uncertain world. It provokes a rethinking of using science to measure and govern human affairs and the impact of numbers and quantification on law.

Keywords: uncertainty; ignorance; decision-making; rulemaking; models; mathematical modelling; quantification; Covid-19.

1 The author would like to thank Roger Cotterrell, Monica Di Fiore, Theodore Konstadinides, Tim Murphy, Amanda Perry-Kessaris, Andrea Saltelli, Carl Stychin and Maurice Sunkin for their suggestions and comments on an earlier draft of this article. All remaining errors are my responsibility.

[A] INTRODUCTION

Risks and uncertainties have greatly increased in contemporary society and posed a fundamental challenge to decision-making;[2] the sudden outbreak of Covid-19 being one of the prominent examples. The novel coronavirus, SARS-COV-2—about which we knew very little when it emerged—quickly spread all over the world. 'Part of the considerable difficulty in managing this epidemic', a UK government health adviser wrote to Richard Horton, Editor-in-Chief of *The Lancet*, is that we 'have some major gaps in knowledge (especially around asymptomatic transmission by age)' (Horton 2020: 935). The scale of uncertainty and ignorance about Covid-19 is unnerving (Harford: 2020). Rulemakers need to make decisions on intervention measures. But they also need to minimize the negative impact of interventions on aspects of health, both physical and mental, as well as on wider social and economic life. As a result, rulemakers resort to modelling when making rules to prevent the spread of the epidemic.

Modelling has greatly influenced decision-making and mobilizing resources in managing the pandemic. Mathematical modelling has produced various sets of data on Covid-19, including the number of infections and fatalities etc. Countless rules made by the UK Government to prevent the spread of the epidemic, including maintaining social distance, isolation and lockdowns, are based on these data. The Imperial College team's model updated in March 2020, in particular 'Report 9' (Ferguson & Ors 2020), played a crucial role in changing the UK Government's policy on the pandemic (Adam 2020a: 318). Prior to the dramatic change in policy, the UK Government had hoped to rely on herd immunity—large

[2] The term 'decision-making' in this article primarily refers to 'rulemaking', although it encompasses 'law-making', which is also within the scope of this article. In the UK the term 'law-makers' is usually synonymous with 'Parliament' rather than 'government'. But the rules to deal with crises such as the pandemic are made by the Government. Indeed, the question of how much legislative scrutiny governmental decisions to deal with crises should receive (and how much opposition in systems where this is relevant) is itself a topic of active discussion. Related to this is the wide range of regulatory powers which modern governments have (the precise form depending on particular constitutional arrangements) which mean that parliaments are not central or even important to much rulemaking. For a discussion of legislation and rulemaking and the delegation of rulemaking functions to the government, see eg Baldwin (2003). I am aware that the term 'government' has a broad meaning, as Foucault (1982: 789-790) suggested:

> This word [government] must be allowed the very broad meaning it had in the sixteenth century. 'Government' did not refer only to political structures or to the management of states; rather, it designated the way in which the conduct of individuals or of groups might be directed: the government of children, of souls, of communities, of the sick ... To govern, in this sense, is to control the possible field of action of others.

When discussed in this article, the term 'government' refers to its narrow meaning, that is, 'the political structures or the management of states'. It is also mainly concerned with the UK Government.

proportions of the population getting ill first and then getting better and becoming immune to the virus (Boseley 2020).

Managing the Covid-19 pandemic has posed a fundamental challenge to the ways in which rules[3] and decisions are made and to what number- and model-based rulemaking can achieve. The UK's Coronavirus Act 2020, for example, has granted government emergency powers to respond to the pandemic. The Covid-19 pandemic has been subject to extensive rules, predominantly by national governments. Further, in an uncertain world such as during a global pandemic, rules need to be made under circumstances where 'facts are uncertain, values in dispute, stakes high and decisions urgent' (Funtowicz & Ravetz 1993: 744). In such an uncertain world rulemaking is being increasingly influenced by knowledge produced by experts across disciplines (see eg Murphy 1997)—the most pertinent example being the reliance by rulemakers upon mathematical models (primarily the officials in the Ministry of Health and the Treasury in the UK context). But the time horizons of epidemiologists and those of rulemakers may differ owing to their different orientations. For example, due to political short-termism, the pressure from business on the Johnson Government has led to a lifting of lockdown when it may not be epidemiologically justified. To what extent can rulemakers navigate and tame uncertainty through mathematical modelling? Or is their reliance on mathematical modelling increasing the uncertainty of rules?

The Covid-19 pandemic has provoked a need to rethink the nature and function of uncertainty in relation to rulemaking and to re-evaluate the relationship between uncertainty, ignorance and knowledge. However, there is lacking a proper taxonomy for understanding and assessing the degree of uncertainty as well as the uncertainty associated with the making of mathematical models. Further, in the UK and elsewhere, rulemakers have relied on models in communicating to the public around key decisions. But outside the relatively circumscribed community of sociologists studying the influence of quantification on governance and the intersection of numbers and power, there is a paucity of serious reflection on using modelling as a governance technique. These problems, if they remain unsolved, will undermine trust in public bodies and the accountability of rulemakers.

This article examines the challenges rulemakers are facing in an uncertain world and argues that one of the most important challenges

3 Rules discussed in this article include legislation and 'governmental' rules that aim to manage and control the Covid-19 pandemic. For a discussion of rule types, see eg Baldwin (2003).

lies in rulemakers' failures to understand the nature of uncertainty and ignorance in the contested arena of science for decision-making. It explores the interaction between mathematical modelling and rulemaking in managing the Covid-19 pandemic as a case study. It draws on interdisciplinary literature on the notions of uncertainty and ignorance, including economics, sociology and philosophy of science, and marks a significant step forward in extending the conceptual framework of understanding these concepts in the context of rulemaking. It also draws upon secondary sources, such as reports on Covid-19, to map the ways in which uncertainty and ignorance have been articulated, constructed and communicated through the interaction between modelling and rulemaking in the Covid-19 crisis. It removes barriers between traditional disciplines such as law and science and pushes the study of the interaction between modelling and rulemaking in fresh directions. First, however, it is necessary to define the scope of this article. Various kinds of modelling have been used in managing the Covid-19 pandemic, including mathematical modelling, financial and economic modelling, as well as social modelling (see the first section of this article for detailed discussion). But due to limited space, this article focuses on mathematical modelling. Likewise, it does not examine whether various techniques (using rules or discretionary powers) are, or are not, helpful to decision-makers when confronted with uncertain data but a need to act.[4] This important topic will be the subject of a further article. The study in this article also focuses on the interaction between mathematical modelling and rulemaking in the UK.

The first section of this article traces the origin of the influence of numbers and quantification on law to 'the Cartesian dream' (see eg Reinert & Ors 2021) and examines the nature of mathematical modelling. It argues that an examination of the interaction between mathematical modelling and decision-making in a global pandemic is not about finding the 'right numbers' for reducing uncertainties. Rather, it looks at a complex process whereby scientific, political and social factors are blended with the production of numbers to predict the future. This process requires us to look at not only the predictive outputs of models but also the inputs into models, including 'the theoretical underpinnings, the quality and quantity of the empirical data base, and the independence of the evidence supporting the model conceptualization' (Oreskes 2000: 37). The second section of this article argues that it is important to consider the extent of uncertainty both associated with mathematical modelling and embedded in crises. To achieve this goal, it dissects the typology and develops a

4 For a general overview of rules and discretion, see eg Harlow & Rawlings (2009: chapter 5).

taxonomy of uncertainty. The third section of this article explains the reason why the conventional views on the relationship between ignorance, uncertainty and knowledge are problematic and re-evaluates the relationship between ignorance and knowledge. The 'Conclusion' summarizes the main findings and provides an alternative strategy to number- and model-based rulemaking.

[B] TRACING THE ORIGIN: THE CARTESIAN DREAM VERSUS UNCERTAINTY EMBEDDED IN MATHEMATICAL MODELLING

Uncertainty and ignorance were under-researched topics in the human sciences for decades, as Smithson (1989: 1) argued. The neglect of uncertainty and ignorance is due to the Western intellectual mentality which has been obsessed with the pursuit of 'absolutely certain knowledge' (Smithson 1989: 1). The subsequent absence of a rigorous framework for studying these concepts in legal studies has made rulemaking in crises such as the Covid-19 pandemic difficult and challenging.

This section traces the origin of the failure to acknowledge the importance of studying uncertainty and ignorance to 'the Cartesian dream': an assumption deriving from René Descartes (1596–1650) that 'science can produce certain truths and absolute power' (Ravetz 2015: xvii). Mathematics and quantification are the key to this vision, as they enable prediction and control (Funtowitcz & Pereira 2015: 2). Within this paradigm, it is assumed that it is easy to tame uncertainty with mathematics and quantification, and ignorance is overcome (Ravetz 2015: xviii). Reinert & Ors (2021: 8) also argued that, in the Cartesian dream, 'uncertainty is to be evicted. It exists only in the form of "subtle" scientific inquiry, at the edge of scientific knowledge, and ignorance must be pushed beyond the research problem's boundaries' (see also Ravetz 1994).

Notions of indeterminacy and complexity in mathematics and physics, however, began to emerge at the beginning of the 20th century and cast doubt on beliefs in the absolute certainty of scientific knowledge and complete power of prediction and control (Funtowitcz & Pereira 2015: 2). That said, the emergence of these concepts has not challenged the institutional foundations of 'the Cartesian dream', which have been entrenched in 'national and international constitutional, legal and administrative arrangements' (Funtowitcz & Pereira 2015: 3).

The 1980s witnessed the dramatic increase in the use of quantification in governing social life, and this trend continues (Rottenburg & Ors 2015). Merry (2016: 1), for example, argued that 'quantification is seductive'. By quantification, she meant 'the use of numbers to describe social phenomena in countable and commensurable terms' (Merry 2016: 1). Quantification is seductive in the sense that it has the capacity of producing numbers which provide 'knowledge of a complex and murky world' (Merry 2016: 1). These numbers then formed a basis for decision-making which is also seen as 'scientific' and 'evidence-based' (Merry 2016: 4).[5] For instance, when unveiling plans to lift England's lockdown, Boris Johnson said that 'data will be used to inform "every step" of lifting restrictions' (BBC News 2021). Numbers generated by mathematical modelling, such as the reproduction number (R), contributed significantly to creating a public consciousness of the urgent need to control the pandemic: to bring the reproduction number below 1 (Nouvellet & Ors 2020). These numbers, however, could be flawed, misused and misleading. For example, a prestigious 2019 Global Health Security Index ranked the United States as the safest place to be in case of a pandemic (Johns Hopkins Center for Health Security 2019). Prediction based on these numbers clearly contrasts with what happened in the Covid-19 pandemic.

Numbers and quantification are exerting strong influence on law and governance (see eg Perry-Kessaris 2011a, 2011b, 2017; Nelken & Siems 2021). Supiot (2017) argued that human action has been increasingly governed by numbers and quantification rather than by law. Indeed, modelling has become a governance technique and has been heavily relied upon by rulemakers to navigate and tame the increasing uncertainty of social and economic life. Assumptions and outputs of models and policy recommendations by modellers have been embedded in law, regulation and policy. Rules informed by the research of the Imperial College team to suppress the spread of Covid-19, for example, which contained a combination of social distancing, home isolation of cases and household quarantine of their family members, have caused significant change to the ways in which social and economic life is organized in the pandemic. Jones (2020) pointed out that 'public attention should be devoted to the world-making effects of models'. Models are 'artifacts with politics', establishing and normalizing certain patterns of power and authority (Winner 1980: 134). However, 'the promise of control and prediction rooted in the Cartesian dream of rigorous technical models and precise scientific metrics in handling the uncertainties did not survive the test of a radically uncertain world' (Reinert & Ors 2021: 8; see also Scoones &

5 For a critique of 'evidence-based' policymaking, see also eg Funtowicz & Saltelli (2015).

Stirling 2020). Managing the Covid-19 pandemic provides an important lens through which we can assess the challenges posed by the interaction between modelling and rulemaking and, more broadly, on the effect of numbers and quantification on governance and the rule of law.

Models function as one of the critical instruments in many disciplines, including science and economics, mediating between theories and the real world. Models can serve many purposes. They are used for the examination and elaboration of theories; for the exploration of the processes and consequences of applying theories; for the measurement of risks; for giving precise answers in numbers; and for the justification of intervention measures. The use of models also has limits, especially under circumstances where modelling is based on a paucity of data and a significant degree of abstraction and uncertainty is involved (Spiegelhalter 2019). Models are by no means neutral: they are shaped by the modellers' disciplinary orientations, made in a particular context, and embody the modellers' interests, assumptions and biases (Saltelli & Ors 2020). 'Different contexts—different markets, social settings, countries, time periods and so on—require different models' (Rodrik 2015: 11).[6] For example, using models out of their context fuelled the financial crisis (Reinert 2009)[7] and delayed action on Covid-19.

Modelling, in particular mathematical modelling, has dominated experiences of and controversies surrounding the Covid-19 pandemic (Jewell & Ors 2020: 1893). In addition to mathematical modelling, various kinds of modelling have been used in estimating the impact of Covid-19, including financial and economic modelling and social modelling. For example, the Organisation for Economic Co-operation and Development (OECD) (2020) provided an economic assessment of the impact of Covid-19, using NiGEM, a global macro-econometric policy model, maintained by the National Institute of Economic and Social Research in the UK. The economic assessment focused on the adverse impact of Covid-19 on particular areas, including financial markets, the travel sector and supply chains, rather than the underlying, structural features of the economy, such as inequality and the uneven distribution of access to healthcare for those suffering from the effects of Covid-19 (Jones 2020). In the pandemic, individuals bear the burden of restrictions on individual rights unequally (people with or without disability or people living in a densely populated area or not, for instance). But financial and economic modelling does not usually take these factors into account. Examples

6 For a discussion of studying economics while ignoring the context, see eg McCloskey (2002).

7 For critiques of how financiers respond to uncertainty around the possibility of a financial crisis, see eg Taleb (2010).

of social modelling include the 'Singapore model' (see eg Bowie 2020) or the 'Swedish model' (see eg Mann 2020), depicting different national responses to Covid-19. The Swedish model caused much controversy surrounding whether it could effectively build up herd immunity and help balance competing priorities of coping with the health crisis and mitigating the adverse economic impacts of Covid-19. Social modelling suggests a 'getting something off the shelf' approach to making policy recommendations (Jones 2020).

Mathematical modelling describes 'our beliefs about how the world functions', using mathematical concepts and languages (Lawson & Marion 2008: 1). Mathematical models, enabled by computer simulations, have been used by rulemakers to communicate with the public and to establish rules on various interventions (Adam 2020a: 316). But, instead of justifying the certainty of the rules, estimates from mathematical models about Covid-19 can lead to uncertainty and anxiety, for example, when these models estimate tens of thousands of deaths (Jewell & Ors 2020: 1893). Inaccurate assumptions can be made because of the poor quality of data on infections, deaths and tests. Decisions made based on the outputs of models may mislead. This was evidenced at the early stage of the Covid-19 pandemic when detection was limited and reporting was delayed (Jewell & Ors 2020: 1893).

Mathematical models are imbued with uncertainty: to predict Covid-19 transmission rates, models rely on hundreds of parameters (Adam 2020b: 533), which are poorly understood (Holmdahl & Buckee 2020). Mathematical models can only 'estimate the relative effect of various interventions in reducing disease burden rather than to produce precise quantitative predictions about extent or duration of disease burdens' (Jewell & Ors 2020: 1893; see also Whitty 2015: 4). Nevertheless, 'consumers' of mathematical models, including rulemakers, the media and the public, 'often focus on the quantitative predictions of infections and mortality estimates' (Jewell & Ors 2020: 1893). The resulting model uncertainty is not always properly communicated to the public (Holmdahl & Buckee 2020).

[C] DEVELOPING A TAXONOMY OF UNCERTAINTY

From the above analysis, we know that uncertainty is associated with the making of mathematical modelling and that decisions based on the outputs of models are often made under conditions of uncertainty in crises. It is necessary to dissect this typology by developing a taxonomy of uncertainty to ascertain the nature and degree of uncertainty in modelling and rulemaking in crises. Uncertainty in the broad sense means that 'given current knowledge, there are multiple possible future states of nature' (Stewart 2000: 41). Uncertainty is also defined as 'the result of our incomplete knowledge of the world, or about the connection between our present actions and their future outcomes' (Kay & King 2020:13). The degree of the connection between current human actions and their future consequences varies, giving rise to different types of uncertainty. But how can we gauge the extent of their connection?

The conventional measure of uncertainty is probability. Probability theory as a discipline originated in the 17th century and was discussed precisely for the first time by Pierre Simon Laplace (1749–1827) in his *Essai philosophique des probabilités* (von Mises 1957 [1928]: vii). Probability can be divided into two categories: frequentist and subjectivist views of probabilities (Stewart 2000: 41; see also Morgan & Henrion 1990). Frequentist probability is based on 'long-run observations of the occurrence of an event', while subjective probability is determined by one's belief on whether an event will occur (Steward 2000: 41). The frequentist approach to probability was proposed by von Mises (1957 [1928]). He argued that a quantitative probability concept 'must be defined in terms of potentially unlimited sequences of observations or experiments' (ibid: viii). He also argued that 'the relative frequency of the repetition is the "measure" of probability, just as the length of a column of mercury is the "measure" of temperature' (ibid). The essence of the frequentist interpretation of probability is to explain how often a phenomenon occurs. For example, in the management of the Covid-19 pandemic, data on infection rates, hospital admission rates and fatalities are based on the frequentist approach to probability.

Uncertainty can also be categorized as aleatory or epistemic. Aleatory uncertainty refers to random processes which can still be quantified or can be 'statistically characterizable' (Stewart 2000: 41). For example, we know that a fair dice has six sides and that each of the faces has the same probability of landing facing up. But we cannot reduce the uncertainty about which face will next land facing up (Stewart 2000: 41). Aleatory uncertainty can still be measured by the frequentist approach to probability, while epistemic uncertainty arises from our 'incomplete knowledge of processes that influence events' (Stewart 2000: 42). The result of epistemic uncertainty, for instance, is that mathematical modelling may omit important factors which should have been considered in its production. 'Total uncertainty, either subjective or frequentist, is the sum of epistemic and aleatory uncertainty' (Stewart 2000: 42).

Making decisions to cope with uncertainty brought about by the Covid-19 epidemic cannot rely on the frequentist approach to probability, although the collection of various sets of data on Covid-19 can do so. For example, in preventing the spread of Covid-19, too strict isolation measures may cause serious economic problems and may also squeeze the space for treatment of other diseases. Rulemakers need to balance the costs and benefits of adopting prevention and control measures. For instance, the fatality rate caused by Covid-19 infections may decrease, but the fatality rate caused by other diseases may increase (see eg Katz & Sanger-Katz 2021). Further, epistemic uncertainty is unavoidable in making decisions under the Covid-19 pandemic. Rulemakers need to make holistic decisions based on both different sets of data and non-data-based criteria such as public acceptability, but their incomplete knowledge of processes that influence managing the Covid-19 pandemic is profound. We have witnessed the difficulty in coping with epistemic uncertainty in the Covid-19 pandemic due to incomplete information on the virus and misunderstanding of the processes of its spread. As a result, experts leaned towards the wrong answer.

Since World War II, the application of modern probability theory has arisen in several major fields where humans interact with complex technologies, including economics, management science, computer science and artificial intelligence (Smithson 1989: 3). The popularity of modern probability theory constitutes a major response to the increasing complexity of technologies and organizations and provides an alternative to deterministic, mechanical approaches to dealing with complexity and uncertainty embedded in these systems (Smithson 1989: 3).

Probability theory has been applied to solving legal problems. In fact, 'Leibniz' [Gottfried Wilhelm (von) Leibniz, 1646–1716] early formulations of probability theory were motivated by problems of legal inference' (Smithson 1989: 24). However, there are challenges to applying probability theory in the legal field. Judges and juries make decisions based on evidence, which is primarily qualitative rather than quantitative and cannot be easily measured by probability. Judges deal with imperfect information, unreliable witnesses and doubtful 'facts' (Smithson 1989: 23). Their judgments may also be influenced by socio-economic and political factors. The law is subject to interpretations and revisions. As Endicott (2000: 1) argued, 'vagueness, and resultant indeterminacies, are essential features of law. Although not all laws are vague, legal systems necessarily include vague laws'.[8] Legal problems cannot easily be formulated by probabilistic language. A misunderstanding of probability in judgments may even turn

8 For a discussion of vagueness in law, see also Asgeirsson (2020).

on the 'prosecutor's fallacy'; a fallacy that uses statistical reasoning to test an occurrence. Prominent examples include the rape conviction of Andrew Deen in 1990 based on DNA evidence and the heart-breaking case of Sally Clark in 1999 (Chivers 2021).[9]

From the above analysis, we can see that the study of uncertainty deals with probability and other concepts such as vagueness which cannot be explained in probabilistic language. To decipher the complexity of uncertainty under which rules are made in managing the Covid-19 pandemic, it is important to evaluate different kinds of uncertainty. This can be divided into at least two types according to the degree of connection between current human actions and their future consequences, namely, external risk (resolvable uncertainty) and manufactured risk (radical uncertainty, with ignorance as one important dimension).[10] In developing this taxonomy of uncertainty, it is important to bear in mind that we cannot 'apply probabilities to every instance of our imperfect knowledge of the future' (Kay & King 2020: 12).

Analysis of risk and the risk society figure prominently in the writings of some preeminent sociologists researching modernity, in particular Ulrich Beck and Anthony Giddens. For example, Beck's definition of risk, which differs from danger, is closely associated with reflexive modernization. He argued that risk may be defined as '*a systematic way of dealing with hazards and insecurities induced and introduced by modernization itself*' (Beck 1992: 21, italics original). By 'reflexive modernization', Beck meant that modernization 'is becoming its own theme':

> Questions of the development and employment of technologies (in the realms of nature, society and the personality) are being eclipsed by questions of the political and economic 'management' of the risks of actually or potentially utilized technologies — discovering, administering, acknowledging, avoiding or concealing such hazards with respect to specially defined horizons of relevance (Beck 1992: 19-20).

Giddens (1999: 3) also pointed out that risk differs from hazard or danger, but he emphasized that 'the idea of risk is bound up with the aspiration to control and particularly with the idea of controlling the future'. The term

9 In 1990 Andrew Deen was convicted of rape. His conviction was partly based on DNA evidence and a statement from an expert witness that 'the chance that the DNA came from someone else was just one in 3m' (Chivers 2021). In 1999, Sally Clark was convicted of murdering her two children. Her conviction was again partly based on an expert witness statement that 'the chance of two babies dying of sudden infant death syndrome (Sids) in one family was one in 73m'. Her conviction was overturned in 2003 for not taking into account 'the prior probability—that is, the likelihood that someone was a double murderer, which is, mercifully, even rarer than Sids' (Chivers 2021).

10 For the difference between external and manufactured risk, see Giddens (1999). For the difference between resolvable uncertainty and radical uncertainty, see Kay & King (2020).

'risk society' was coined in the 1980s and became a popular topic in the 1990s. Risk society refers to 'a society increasingly preoccupied with the future (and also with safety), which generates the notion of risk' (Giddens & Pierson 1998: 209). The reason why a risk society is preoccupied with the future, as Giddens further explained in his Chorley Lecture,[11] is that 'we increasingly live on a high technological frontier which absolutely no one completely understands and which generates a diversity of possible futures' (Giddens 1999: 3).

The analysis of uncertainty and risk so far has shown that these two concepts are closely related, as both are the result of our incomplete knowledge of the world and its connections with possible futures. That said, there are differences between risk and uncertainty. Economists (used to) highlight the distinction between risk and uncertainty: risk refers to 'unknowns which could be described with probabilities', while uncertainty means unknowns which could not be described with probabilities (Kay & King 2020: 12). Frank Knight (1885–1972) and John Maynard Keynes (1883–1946) were the two key figures in economics who argued for the continued importance of the distinction. Knight (1921: 20), for example, argued that risk is 'measurable' and that we should 'restrict the term "uncertainty" to cases of the non-quantitative type'. Keynes (1937: 214) pointed out that for uncertainty 'there is no scientific basis on which to form any calculable probability whatever'. Keynes (1937: 222) also argued that 'the hypothesis of a calculable future leads to … an underestimation of the concealed factors of utter doubt, precariousness, hope and fear'. These factors are ubiquitous in decision-making in managing crises such as the Covid-19 pandemic but are easily concealed by the illusion of truth and control generated by mathematical modelling.[12] This is despite flaws in the theoretical underpinnings and the quality and quantity of data, as well as biases and human fallibility in making mathematical models. The distinction between risk and uncertainty has been sidelined by mainstream economics over the last century through applying 'probabilities to every instance of our imperfect knowledge of the future' (Kay & King 2020: 12).

Given the differences and overlaps between risk and uncertainty, attempts have been made to specify various categories of risk and uncertainty to make sense of the distinction, reveal the overlaps, and illuminate better approaches to their similarities and differences. Giddens (1999: 4) made a distinction between 'external and manufactured risk'. External risk is 'risk of events that may strike individuals unexpectedly

[11] The lecture was delivered at the London School of Economics on 27 May 1998.

[12] See eg Drechsler (2011: 50) arguing that it is wrong to assume that the use of mathematics necessarily leads to 'truth'.

(from the outside, as it were) but that happen regularly enough and often enough in a whole population of people to be broadly predictable, and so insurable' (Giddens 1999: 4). Manufactured risk refers to 'new risk environments for which history provides us with very little previous experience. We often don't really know what the risks are, let alone how to calculate them accurately in terms of probability tables' (Giddens 1999: 4). The Covid-19 pandemic, for example, provides a new risk environment where we can rely little on experience with previous epidemics. It is a noteworthy example of manufactured risk. Kay & King have chosen to replace the distinction between risk and uncertainty with a distinction between 'resolvable and radical uncertainty':

> Resolvable uncertainty is uncertainty which can be removed by looking something up (I am uncertain which city is the capital of Pennsylvania) or which can be represented by a known probability distribution of outcomes (the spin of a roulette wheel). With radical uncertainty, however, there is no similar means of resolving the uncertainty – we simply do not know. Radical uncertainty has many dimensions: obscurity; ignorance; vagueness; ambiguity; ill-defined problems; and a lack of information that in some cases but not all we might hope to rectify at a future date (Kay & King 2020: 14).

The distinction between external and manufactured risk made by Giddens, and the distinction between resolvable and radical uncertainty drawn by Kay and King, both help us develop a taxonomy of uncertainty. External risk has overlaps with resolvable uncertainty, while manufactured risk comes close to radical uncertainty. Most challenges to decision-making in managing the Covid-19 pandemic come from manufactured risk or radical uncertainty. Further, radical uncertainty cannot be described in terms of well-defined, numerical probabilities (Kay & King 2020). Increasing radical uncertainty has led to more complexity in decision-making. The key questions that rulemakers need to reflect upon include: is uncertainty something to overcome in rulemaking? Should rulemakers eliminate uncertainty in rulemaking? Scoones & Stirling (2020: 12), for example, argued that claims to be able to control uncertainty seem to 'underpin the securing of authority, justification, legitimacy, trust and wider public acceptance'. But for rulemakers, if they simply make these claims without awareness of the nature of risk and uncertainty, and the importance of communicating 'the unknown' to the public, their accountability will be undermined.

[D] RE-EVALUATING THE RELATIONSHIP BETWEEN IGNORANCE, UNCERTAINTY AND KNOWLEDGE

This section continues to examine one important dimension of radical uncertainty, that is, ignorance, as well as the ways in which rulemakers should deal with it. It focuses on the notion and function of 'ignorance' and the dynamism between ignorance and knowledge in the context of rulemaking. It also examines the nature and significance of ignorance for reassessing the role of mathematical modelling in rulemaking and for finding an alternative strategy to number- and model-based rulemaking.

Under conditions of radical uncertainty, ignorance is unavoidable. As discussed in the first section of this article, within Western intellectual culture which can trace its origin to 'the Cartesian dream', ignorance is often regarded as 'either the absence or the distortion of "true" knowledge' (Smithson 1989: 1). The conventional approach to ignorance is therefore to eliminate or tame it by using some kind of 'scientific method' (Smithson 1989: 1). The ways in which ignorance has been tamed by mathematical modelling through probabilistic judgments in the context of rulemaking in the Covid-19 pandemic is one of the noteworthy examples of exercising this conventional approach. The key problem in managing the Covid-19 pandemic, echoing Friedman's observation of the nature of ignorance (2005: xiv), however, is not just gaps in our knowledge about the virus. Rather, the central problem is that the information presented by experts to rulemakers, even if supported by mathematical models, only provides a veneer of certainty and may mislead.

Ignorance is 'socially constructed and negotiated' and 'multiple' (Smithson 1989: 6). Acknowledging this reminds us of the famous quote from Rumsfeld on 'known unknowns' and 'unknown unknowns':

> There are known unknowns. That is to say there are things that we now know we don't know. But there are also unknown unknowns. There are things we don't know we don't know.[13]

There are other instances of ignorance which have been overlooked by Rumsfeld such as 'what we don't know we know' (Rayner 2012). Accordingly, there are various ways that rulemakers try to cope with ignorance, such as taming it with a technical solution.

[13] Rayner (2012: 107-108), quoting former US Secretary for Defence, Donald Rumsfeld, NATO Headquarters, 6 June 2002.

Taming ignorance in rulemaking leads to several consequences. Rulemakers fail to understand that uncertainties are 'conditions of knowledge itself' (Scoones & Stirling 2020: 4). The ways in which we 'understand, frame and construct possible futures' are 'hard-wired into "objective" situations' (Scoones & Stirling 2020: 4), including the application of probabilities to every kind of uncertainty. Rulemakers may tend to use models to justify predetermined agendas and to undermine the importance of communicating what is not known (Saltelli & Ors 2020). Rulemakers may also offload accountability to the models they choose (Saltelli & Ors 2020).[14] Thus, in managing the Covid-19 pandemic, the UK Government's claim that it is 'following the science' has been criticized by scientists as a way to 'abdicate responsibility for political decisions' (Devlin & Boseley 2020).

In some disciplines, including philosophy, sociology and economics, there have been challenges to the conventional way we approach the nature and function of ignorance. After all, 'learned ignorance' (*docta ignorantia*), or self-awareness of ignorance, was regarded as a virtue for most of the history of Western philosophy (Ravetz 2015). Popper (1985: 55) argued that:

> the more we learn about the world, and the deeper our learning, the more conscious, specific, and articulate will be our knowledge of what we do not know, our knowledge of our ignorance. For this, indeed, is the main source of our ignorance – the fact that our knowledge can only be finite, while our ignorance must necessarily be infinite.

Hayek (1945), as well as Knight and Keynes discussed above, questioned the nature of 'perfect knowledge' and warned us of the dangers of projecting excessive certainty about the future (Davies & McGoey 2012: 76). However, the virtue of learned ignorance has been neglected in contemporary society. Rather, it is a common assumption that modern society is based on the accumulation of reliable and calculable knowledge. Yet, past crises such as the financial crisis 2007–2008 have taught us important lessons. In contrast to the common assumption, many institutions that survived the financial crisis are not those which had a firm faith in the reliability of credit-rating agencies. Rather, they were those 'most able to suggest risks were unknowable or not predictable in advance' (Davies & McGoey 2012: 65). The financial crisis thus was not only an economic crisis but also an epistemological and scientific one (Davies & McGoey 2012: 66; see also Best 2010). These lessons, however, have not been taken seriously by rulemakers in the UK in coping with the Covid-19 pandemic.

[14] See also Snow (2021). Please note that experts such as modellers may oversell their predictions and tend to offload accountability to a technical solution like rulemakers.

Ignorance and knowledge are not antithetical, as Nietzsche argued (2003 [1973]: 24; see also Ravetz 1987: 100). Rather, ignorance should be regarded as the 'refinement' of knowledge. Ignorance can serve as 'a productive force' and 'the twin and not the opposite of knowledge' (McGoey 2012). This does not mean that there is value in knowing what we don't know as opposed to not knowing what we don't know. 'Knowing what we don't know' is productive in the sense that it generates a constant need for solutions to crises that experts and rulemakers failed to identify earlier (Davies & McCoey 2012: 79). We need to 'lean into the reality of not knowing' (Snow 2021) and even embrace uncertainty (Scoone & Stirling 2020: 11):

> In embracing uncertainty in modelling practice, the emphasis must therefore shift towards active advocacy of qualities of doubt (rather than certainty), scepticism (rather than credulity) and dissent (rather than conformity) – and so towards creative care rather than calculative control. With indeterminacy thus embraced and irreducible plurality accepted, non-control and ignorance emerge as positive values in any attempt to create narratives for policy under conditions of uncertainty.

[E] CONCLUSION

A great deal of decision-making during crises is about coping with uncertainty. For rulemakers, this poses a fundamental challenge, as there has been a lack of a rigorous framework for understanding and analysing the nature and function of uncertainty in the context of rulemaking. Although in some disciplines, including philosophy, sociology and economics, there have been new studies of and reflection on the way we approach uncertainty and ignorance, responses from legal studies have been slow. Rulemakers rely heavily on numbers and quantification, trying to give precise answers and assert control when making decisions in crises. Drawing on interdisciplinary literature on uncertainty and ignorance and a case study of the interaction between mathematical modelling and rulemaking in the Covid-19 pandemic, this article sets out three steps to analyse the challenges posed by reliance on mathematical modelling by rulemakers under conditions of uncertainty.

The first step examines the nature of mathematical modelling and traces the origin of rulemakers' tendency to rely on numbers and quantification in decision-making to the 'Cartesian dream', which involved the firm belief in absolute certainty of scientific knowledge and its complete power of prediction and control. The discussion of this article, however, shows that mathematical modelling is closely associated with uncertainty.

Mathematical models are also by no means neutral: they are shaped by the modellers' disciplinary orientations, made in a particular context, and embody the modellers' interests and biases.

The second step develops a taxonomy of uncertainty and helps establish a framework for rulemakers to understand and analyse the kinds of uncertainty with which they are coping. This taxonomy clarifies different kinds of risks and uncertainty associated with mathematical modelling and embedded in crises. Although mathematical models can minimize the complexity of the real world and give precise answers in numbers, their role is limited under conditions of uncertainty, as not all kinds of uncertainty can be described as well-defined, numerical probabilities. If rulemakers approach mathematical modelling as 'truth' and manipulate it as 'evidence' to support predetermined agendas under conditions of radical uncertainty, their approach is flawed, and the public cannot really know what works and how to effectively address the challenge. Reliance on mathematical models may also downplay other sources of knowledge and expertise. For example, experts argued that in coping with the Covid-19 pandemic, the UK Government gave too much weight to the views of modellers while overlooking the views of public health experts (Devlin & Boseley 2020).

The third step re-evaluates the nature and function of ignorance and its relationship to uncertainty and knowledge. It supports the view that ignorance is a condition of knowledge. It argues that, rather than eliminating uncertainty or hiding ignorance behind their expertise, rulemakers should instead embrace untruth, uncertainty and even ignorance. Embracing 'what we don't know' is productive in that it prompts rulemakers to seek solutions to crises that they failed to identify earlier, which may then form a positive component in managing the Covid-19 pandemic. In so doing, rulemakers will be able to find an alternative strategy to number- and model-based rulemaking so that they can improve their accountability in an uncertain world.

The new strategy includes three essential aspects, corresponding to the three steps set out in this article. First, rulemakers need to reflect on the uncertainty embedded in mathematical modelling, including how data is gathered and how information is captured. They should ask: what data is missing? What factors are not considered? What assumptions are made behind the making of mathematical modelling? Second, rulemakers should assess the kind of uncertainty embedded in the crisis with which they are coping. Third, rulemakers need to communicate the unknown in decision-making. 'Communicating the unknown' means that rulemakers should not conceal fear, doubt and dissent behind claims of truth and absolute control made through the outputs of mathematical modelling. Instead, rulemakers should embrace and work with uncertainty, acknowledging that our ignorance is infinite. Recognizing the virtue of self-awareness of ignorance encourages rulemakers to find missing data and listen to unheard voices that they and other experts failed to identify earlier. Learned ignorance pushes rulemakers to find solutions to crises but also to accept that not all is knowable. Developing an alternative strategy to number- and model-based rulemaking will also provoke a rethinking of the impact of numbers and quantification on governance and the rule of law.

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