



Citation for published version:

Pagel, C & Yates, CA 2022, 'Role of mathematical modelling in future pandemic response policy', *BMJ (Clinical research ed.)*, vol. 378, e070615. <https://doi.org/10.1136/bmj-2022-070615>

DOI:

[10.1136/bmj-2022-070615](https://doi.org/10.1136/bmj-2022-070615)

Publication date:

2022

Document Version

Peer reviewed version

[Link to publication](#)

This article has been accepted for publication in the BMJ, 2022 following peer review, and the Version of Record can be accessed online at <https://doi.org/10.1136/bmj-2022-070615> © Authors (or their employer(s)) 2022.

University of Bath

Alternative formats

If you require this document in an alternative format, please contact:
openaccess@bath.ac.uk

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

UK Inquiry collection: four key questions to consider for the role of mathematical modelling in future pandemic response policy

Christina Pagel¹ and Christian A. Yates²

1. Clinical Operational Research Unit, University College London, London, UK
2. University of Bath, Bath, UK

Mathematical modelling is a crucial contributor to any country's pandemic response, but its usefulness can be hindered by lack of interdisciplinarity, lack of data sharing, poor or absent communication, and modelling over unrealistically long timeframes.

4299 words exc references

Introduction

The UK Inquiry into the Covid-19 pandemic published its draft terms of reference in March 2022 (1). Part of the aims of the Inquiry is to examine how decisions were made and communicated; intergovernmental decision-making and the availability and use of data and evidence. Mathematical modelling underpinned much of the advice that the Scientific Advisory Group for Emergencies (SAGE) (and others) provided to government and as such should be a focus of the Inquiry.

The Scientific Pandemic Influenza Group on Modelling (SPI-M) gives expert advice to the Department of Health and Social Care and wider UK government on emerging human infectious disease threats. During the pandemic, SPI-M has reported to SAGE. The membership of the group is drawn from a range of UK institutions and their advice is based on infectious disease modelling and epidemiology. A detailed review of how SPI-M feeds into policy via SAGE was published in 2021 (2). Its modelling has been influential throughout, particularly during the first eighteen months of the pandemic.

For instance, the Imperial College "Report 9" (3) was an important trigger which pushed the UK government to implement a lockdown in March 2020. The same modelling group later suggested that delays in taking action cost tens of thousands of lives in the UK (4). In July 2020, modelling was used to project the number of deaths that might have been expected over the winter of 2020/2021 in a reasonable worst-case scenario. The prediction, at the time largely reported as being overly fatalistic (5), was of 85,000 deaths between July 2020 and March 2021 (6). In actuality, between 1 July 2020 and 31 March 2021 almost 100,000 deaths with Covid-19 on the death certificate were recorded in the UK (7). Projections from multiple independent modelling teams informed the UK's "Roadmap" (8) for release from lockdown in February 2021 and implementation of "Plan B" measures in December 2021 (9). Modelling (10) determined the vaccine priority groups in December 2020, which played a significant role in the UK's successful vaccine rollout and consequently saving thousands of lives over the first half of 2021. SPI-M's work has also been important in evaluating the relative impact of different interventions, such as the importance of home working in reducing transmission in 2021 (11).

46 Throughout the pandemic, official modelling efforts have been subjected to criticism from
47 many different quarters. No doubt some of that criticism has been understandable – a result
48 of highly publicised projections that never came to pass. Some of these missteps have
49 derived directly from failures of the modelling process to capture reality – mistakes in model
50 parameterisation from uncertain data, misunderstanding or misinterpretation of the key
51 features of the situations being modelled and a fundamental inability to capture important
52 facets of human behaviour. However, much of the criticism modellers have received has
53 been misplaced, a result of fundamental misunderstandings of the purpose of mathematical
54 modelling, what it is capable of – and how its results should be interpreted. In turn, the
55 misunderstandings result, in part, from failures in communication.

56 This has been seen most recently in sustained criticism of SPI-M models on the impact of
57 Omicron in the UK in December 2021 (12–16). The models turned out to be too pessimistic
58 due to a combination of uncertainty about Omicron’s severity and uncertainty about how the
59 public would react to growing cases. In the end, Omicron proved to be somewhat less
60 severe than Delta, the boosters more effective, and - for the first Omicron wave - the public
61 voluntarily restricted their contacts and took up rapid antigen testing much more than
62 expected, which all combined to reduce the wave’s severity (17–19). The model
63 assumptions were clear within the reports (20–22), but the attacks expanded to cover the
64 whole of SPI-M’s contribution (23,24). However, what was not anticipated in the modelling,
65 or in policy, was a second (and just as large) Omicron wave just three months after the first.
66 In fact, the combined stress of two waves in short succession contributed to the worst waits
67 for emergency care (25) since data collection began and high levels of sick leave in the NHS
68 (26).

69 In this paper, we cover briefly how epidemiological modelling can be used to inform policy
70 before posing four key questions for the upcoming UK Inquiry around the role of
71 mathematical modelling in supporting policy. Firstly, where can greater interdisciplinarity
72 improve the usefulness of models? Secondly, how can data be generated and shared more
73 within and between different modelling groups to sustain a more egalitarian and robust
74 modelling environment? Thirdly, would better public communication of modelling processes
75 as well as the underlying assumptions improve usefulness of the models, and if so, how can
76 this be supported? Fourthly, how helpful were pandemic projections looking a year or more
77 ahead?

78
79 We note that SAGE were not charged with the economic modelling of policy options and that
80 this is beyond the remit of this paper. The Inquiry might like to separately consider whether
81 and how economic modelling could have been part of the SAGE remit.

82 83 **How mathematical modelling is used to inform policy**

84 Mathematical modelling provides a framework in which we can formalise our assumptions
85 about the processes we are trying to capture (e.g. disease spread and impact), build them
86 into a simplified representation of reality and simulate forwards in time in order to suggest
87 what might happen in the future under different policy options (27,28). Modelling is also
88 extremely useful in understanding the underlying situation where we have incomplete or
89 missing data (29,30), and indeed can shed light on what has happened in the past where the
90 picture is murky, such as the impact of different public health mitigations (29). A detailed

91 review of how SPI-M was formed and how its work feeds into government policy via SAGE
92 was published in 2021 (2).

93

94 Epidemiological modelling is much more akin to science than it is to pure mathematics. The
95 process involves iteratively building models, making predictions, comparing these
96 predictions to observations, and then refining the models. Through this repetitive process
97 modellers can build accurate, detailed, and robust representations of reality, which can then
98 be used to speculate what will happen in hitherto unseen scenarios. Most applications of
99 mathematical modelling allow for many repeats of this cycle over periods of weeks, months
100 or even years. In contrast, synthesising appropriate data to populate and fine-tune models in
101 real time during an epidemic is an almost unique challenge in applied mathematics and one
102 which only a few mathematicians ever experience (2).

103

104 Any modelling comes with various uncertainties and assumptions that need to be thought
105 through, examined and explained (31). Significant errors in any area can derail the
106 usefulness of the model, and, if not understood and recognised, cause harm. In the context
107 of a rapidly evolving pandemic this is even more important. Good mathematical modelling
108 must be transparent about all the sources of uncertainty (Figure 1) and provide sufficient
109 detail to outsiders (including policymakers) to assess the model outputs.

110

111 SPI-M modelling has been admirably transparent about key assumptions and parameter
112 estimates and have typically encompassed a range of scenarios. They have incorporated
113 inherent variability and caveated many of the problems associated with unknown future
114 events. Structural details of the SPI-M modelling are usually available in academic papers
115 but are not easily accessible to a non-academic audience. Nonetheless, these efforts have
116 not been sufficient to prevent mistakes or criticism. What then are key questions around the
117 role of modelling that the Inquiry should address?

118

119 **Questions for the Inquiry**

120 Q1. Who was invited to contribute to the design of the models and estimation of the
121 parameters?

122

123 As described above, model building is iterative. The structure of the model and its input
124 parameters are continuously refined in light of the latest evidence and understanding about
125 the dynamics of the disease and its spread. Perhaps the biggest threat to the usefulness of
126 the models appears when important information/knowledge relating to the dynamics is held
127 by experts who are not connected to the modelling community. The modelling of care homes
128 during the Covid-19 pandemic represents perhaps the most important cautionary tale.

129

130 It was known early on that older and sicker populations were at much higher risk of severe
131 illness and death from Covid-19. Modellers on SPI-M quickly understood that the elderly,
132 and particularly those in care-homes were at significant risk should they catch coronavirus.
133 The need for protection of care home residents was also well appreciated, yet surprisingly
134 care homes only appear twice (32) in the minutes of the Scientific Advisory Group for
135 Emergencies (SAGE) during the first five months of the pandemic. Modellers had extensive
136 access to excellent hospital surveillance data set up rapidly at the start of the pandemic_(33),
137 but the domain specific knowledge allowing models of social care settings to be

138 appropriately represented and thereby care-homes to be properly protected was not well
139 understood. The intersecting factors of an extremely vulnerable population living in shared
140 accommodation, frequent contact with friends and relatives in the community, the discharge
141 of potentially sick patients from hospitals, lack of personal protective equipment and low-paid
142 staff (with little access to sick pay, working across multiple homes as agency workers and
143 more likely to live in multi-occupancy poor housing) were all identified by industry
144 practitioners as particular system vulnerabilities. Many of these issues, however, did not
145 seem to be anticipated or explicitly taken into account by the modellers.

146
147 While it is not reasonable to expect mathematical modellers to have a prior understanding of
148 the details of the social care sector and the interacting features of vulnerable populations
149 and staff, it is reasonable to expect that modellers should anticipate there may be important
150 unknown factors on which they should canvas domain-specific expertise. To domain experts,
151 the vulnerabilities in the system were both knowable and known. The apparent shortfall on
152 the part of the modellers was in not realising that there was a knowledge gap and
153 subsequently failing to identify and gain knowledge from those with the requisite expertise.
154 Once the vulnerability of care homes became clearer to modellers, their specific features
155 were successfully incorporated into models which then (albeit with hindsight) highlighted the
156 high numbers of deaths if mitigations were not adequate. In England and Wales there were
157 more than 27,000 deaths in care homes during the first wave of the pandemic.

158
159 Government-convened modelling subgroups should incorporate as much diverse expertise
160 as possible – an aspect also considered by the Parliamentary Committee on Science and
161 Technology (34). Learning could be drawn from published literature on interdisciplinary
162 working (35) in disaster response (36–38) and adapted to the UK situation. The mechanisms
163 for ensuring interdisciplinary working must be in place and documented before a pandemic
164 hits and should be agnostic to the nature of the pandemic or to the lead experts at the time:
165 that is, incorporating other perspectives should not depend on the experience or personal
166 network of the expert leads. This recommendation in fact goes beyond the role of modelling
167 in the UK response and applies to the overall structure of SAGE with its relatively siloed
168 working groups feeding independently into decision making.

169
170 Q2. Could data have been shared more widely?

171
172 The information used to build, refine and characterise models of infectious disease might
173 include raw data on the spread of the disease (e.g. case numbers, hospitalisation numbers,
174 deaths etc), data on the parameters which feed into models (e.g. transmissibility, severity,
175 incubation period, etc) assumptions underlying model structure (e.g. is there a significant
176 pre-infectious “exposed period” etc) and the outputs of models (e.g. predictions of case
177 numbers, hospitalisations etc). Retrospectively, a problem with data accessibility (particularly
178 the raw data and parameterisation data) within SPI-M was identified by some of its
179 members. Some groups had access to better quality data that was not shared with all
180 modelling groups. It was regarded by the chair of SPI-M that these disparities in data
181 availability were “inevitable” and that some groups would necessarily have a “head start”
182 because of the effort they had put in to create those networks through which the data was
183 being shared (39). As a result of the paucity of available data, some researchers on SPI-M
184 were forced to resort to dredging Wikipedia early on in the pandemic, citing the fact it was
185 the only data stream that was publicly available at the time (40). Some modellers described

186 the data that was publicly available as being of extremely poor quality. Initially, there was
187 only limited data sharing across countries – reducing the learning possible from others’
188 earlier experience. The importance of international data sharing has been shown repeatedly
189 via, for example, the genomic data on new variants disseminated via GISAID (41).

190

191 It is possible that the initial lack of data sharing contributed to mistakes made early on in the
192 pandemic. Groups with access to poorer quality data did not feel able to challenge the
193 conclusions of groups with access to better quality data. There have been stark examples of
194 situations in which this data disparity has led to poor modelling outcomes. In March 2020 the
195 doubling time in the UK epidemic was overestimated by SPI-M. Estimates of a doubling time
196 of 5-7 days made their way to SAGE (42) and thence to policymakers. The true doubling
197 time was more likely to be around three days. As a result of the incorrect doubling time,
198 Patrick Vallance would claim we were “maybe four weeks or so behind [Italy] in terms of the
199 scale of the outbreak” when in fact the UK was more like two weeks behind (43). This
200 incorrect calculation may have provided a false sense of security which in turn might have
201 contributed to the UK’s disastrous delay in taking measures to suppress the epidemic (44),
202 which resulted in the avoidable loss of tens of thousands of lives (45,46).

203

204 SPI-M have since instituted better methods of model-averaging, which have been used, for
205 example, to come up with consensus views on estimates of the reproduction number and
206 growth rates of the disease. However, it is not clear that issues pertaining to the sharing of
207 other data sources required to construct effective models have been resolved (for instance
208 individual-level data on infections, hospitalisations, and deaths; international data). More
209 comprehensive and timely sharing of other data sources might reduce uncertainty and
210 increase accuracy in models, improving their usefulness. A range of better parameterised,
211 but structurally different, models would additionally reduce the impact of structural
212 uncertainty (Fig 1).

213

214 Q3. Who should have been responsible for communicating the modelling and resourcing its
215 communication?

216

217 Open and clear communication of the outputs of disease transmission models (and indeed
218 the entire modelling process) is vital in supporting policymaker decisions and in increasing
219 the public’s understanding of, and desire to abide by, rules that are informed by such
220 models. Indeed, one of the main critiques surrounding mathematical modelling during the
221 pandemic has been the lack of clear and consistent communication (47). Unfortunately,
222 outputs of complex models do not speak for themselves - they need to be explained. This
223 does not necessarily mean that modellers should advocate for specific policies, but they do
224 need to explain what the models can and can’t be used for, and why. Some SPI-M scientists
225 recognised the importance of public communication, but reasonably explained that they did
226 not themselves have the time to engage fully, given that their energies were devoted to
227 refining and running models (34).

228

229 As a simple example, the inability to correctly recognise and interpret exponential growth,
230 has been shown to act as a significant impediment to the ability of governments to
231 implement effective strategies to control infectious disease (48). The lower the levels of
232 understanding of exponential growth, the lower the levels of compliance with anti-covid
233 measures, including the use of face coverings and social distancing. People who find it hard

234 to accurately estimate the speed of disease spread also find it difficult to see the importance
235 of disease control mitigations and are less likely to implement or observe them. When
236 people better understand the true rate of growth of the epidemic their perception of risk is
237 adjusted accordingly, and they are more likely to comply with suggested protective
238 behaviours.

239

240 That said, communication must also involve listening – and different people listen differently
241 and from different perspectives. Smith and Stewart (49) highlight that modelling results may
242 be seized upon by policymakers to support pre-existing policy-goals – a kind of policy-based
243 evidence selection rather than true evidence-based policy. They present further evidence
244 that policy actors may not engage with or understand the process underlying the modelling
245 results they choose to base policy on. Indeed, it may be the case that, in the eyes of
246 policymakers, the complexity of the modelling process provides the model outputs with an
247 ‘illusion of certainty’, rendering the results difficult to question (50). Excellent communication
248 is necessary but not sufficient for models to appropriately inform policy.

249

250 Pandemic policy making differs significantly from normal-time policy making in a number of
251 ways. Firstly, the short timescale over which policies must be determined leaves less time
252 for a proper assessment of the available evidence, adding uncertainty to the modelling and
253 making it hard to communicate the nuances behind modelling results to policymakers.
254 Conversely, the high visibility of much of the scientific evidence during the covid pandemic
255 may have meant policymakers felt under increased scrutiny and under greater pressure
256 therefore to make evidence-based decisions on as a result of this greater public
257 accountability.

258

259 Another challenge is that the lack of context surrounding model results means they are open
260 to misinterpretation by the media or exploitation by bad-faith actors. As discussed above,
261 uncertainties in key parameter values and variability mean that good modelling practice is to
262 present a range of different scenarios for different combinations of parameter values
263 alongside prediction intervals which can help to express uncertainty. In particular, the
264 development of reasonable worst-case scenarios follows the public health modelling mantra
265 “plan for the worst, but hope for the best”. These worst-case scenarios often generate the
266 most startling projections and consequently capture the news headlines. This, particularly if
267 policy action is taken to avoid the worst outcomes, can lead to accusations of doom-
268 mongering and distrust in future model predictions when these scenarios do not then play
269 out in reality.

270 A third problem presented by inadequate communication surrounding official modelling efforts
271 is that it leaves a media vacuum, which will necessarily be filled by other academic or amateur
272 modelling efforts. While there is certainly room for different modelling perspectives to the
273 SAGE ones, it does mean that those modellers who present their findings in the most media
274 friendly manner tend to dominate the public perception of modelling. For example, just over a
275 week after the Imperial College modelling group published their report 9 (3), a group of
276 modellers at the University of Oxford published their own pre-print (51). Using a simplistic
277 model, they proposed the UK’s epidemic has “already led to the accumulation of significant
278 levels of herd immunity”. The article was distributed to the media through a third-party PR firm.
279 Unusually for academic papers, the same PR firm was the only contact listed on the preprint.

280 As a result of their successful media strategy, the “Oxford model” was presented with the same
281 credibility as the Imperial model (52), despite the very different quality of the modelling
282 undertaken. Although many scientists openly challenged the headline results from the Oxford
283 model (53), their voices were largely drowned out in the media furor. Even without the official
284 sanction of peer review, the press surrounding the modelling had the effect of catapulting the
285 authors to a prominent position from which they were able to influence government policy.
286 Their advice, which went directly to the top of government, may have influenced the decision
287 to delay lockdown in the autumn of 2020.

288 Communication of modelling is challenging at the best of times and made harder in a
289 pandemic. But this does not mean modellers should not try. Ideally, the authoritative voice
290 on the work should come from the modellers themselves. We need to better train modellers
291 to convey the nuances of the model results and their assumptions to a general audience.
292 Modellers cannot and should not try to completely control the media narrative around their
293 work. Rather we are suggesting that models are accompanied by suitable lay summaries
294 and that either the modellers themselves or well-briefed intermediaries actively engage with
295 journalists about their work to reduce the chances of misrepresentation.
296

297 The additional work of communication must be adequately resourced. Funding must be
298 available for modelling teams to have the time and access to the expertise to undertake this
299 communication, or else for this communication to be undertaken by domain experts within
300 government (such as the UK Health Security Agency or the Civil Service, both of which
301 employ many excellent modellers) or outsourced to an independent expert body such as the
302 Royal Statistical Society or the Royal Society of Public Health. Expert communication must
303 also be tailored to each audience and use an appropriate amount of detail (often less than
304 modellers might wish). Decision makers too should receive basic training into how
305 mathematical models inform policy, what questions to ask of modellers and what the
306 potential pitfalls are. Making explicit provision for communication is not an optional extra, but
307 a key part of maximising the benefit of modelling to inform policy and minimising the risk of
308 misuse.
309

310 Finally, in order to sustain trust, modelling undertaken for the government should be made
311 publicly available as soon as possible so that the results and the underlying assumptions of
312 the models can be appropriately scrutinised. It is also important that modellers – alongside
313 the interdisciplinary team assembled as discussed in Q1 - should have input into the
314 scenarios they choose to model. In particular, they should not feel restricted to model only
315 those scenarios suggested to them by the government, which risks not taking full advantage
316 of the expertise contained within SAGE. We note though, that even if models were
317 communicated perfectly, their utilisation by other parties is not wholly (or often even largely)
318 within the modellers’ control.
319

320 Q4. Were modellers asked to project their models too far into the future?

321
322 Currently many SPI-M projections extend 4 to 6 months (54) and some projections (55) go
323 up to a year ahead or more. Fundamental shifts in the dynamics of the pandemic within that
324 time frame can render the projections redundant, as we have seen several times for
325 example with the emergence of new variants or with changes in government policy. For
326 instance, the projections in February 2021 (55) that went up to April 2022, assumed no new

327 variants and no vaccine waning. In fact, four new dominant variants have arisen since then
328 (Delta and Omicron BA.1, BA.2 and BA.4/5) and vaccine waning has been an important
329 factor in determining the trajectory of the pandemic and new vaccine policies.

330
331 Whilst there should be no prohibition on delivering long-term forecasts of what a pandemic
332 might look like, and while SPI-M have been transparent about the assumptions made (e.g.
333 no new variants emerging), the results of such projections can nonetheless mislead because
334 the likelihood of such fundamental shifts in pandemic dynamics is poorly understood by both
335 policymakers and the public.

336
337 The problem in presenting projections over such a long timeframe is that they can instil a
338 false sense of certainty and complacency, because they do not acknowledge the likelihood
339 (which has proven to be high with SARS-CoV-2) of such fundamental changes occurring.
340 Moving to a shorter timeframe might also encourage policymakers to incorporate more
341 uncertainty and anticipated reassessments into their plans and communication.

342
343 There are established methods in other disciplines such as Operational Research or
344 Financial Risk Management that can incorporate the risk of rare but potentially momentous
345 events into decision making (e.g. Conditional Value at Risk strategies (56)). One approach
346 would be to incorporate these into the long-term modelling framework. Another approach
347 would be to use a shorter planning horizon for modelling of no longer than four months or so.
348 Such an approach would recognise that it may be better not to provide projections at all
349 under assumptions that are almost certain to be wrong in several months' time than to
350 provide not just uncertain, but fundamentally inaccurate, projections over a longer timeframe.
351 Of course, there may be modelling scenarios which are unlikely to be impacted by these
352 trajectory-changing events and for which longer timeframes are suitable. Care should be
353 taken to explain why longer projections are likely to be valid and therefore justified in these
354 instances.

355 356 **Conclusions**

357 Epidemiological modelling is vital to both understanding the current state of the pandemic
358 and also to predicting what might happen in the future under a range of different scenarios.
359 No doubt, modelling has provided valuable input into the policies designed to tackle
360 coronavirus. No more so is this true than the case of the modelling carried out in March
361 2020, which is widely regarded to have precipitated the lockdown that was introduced a
362 week later. On the other hand, modelling projections have not always influenced
363 policymakers. A prime example is when the government decided not to impose stricter
364 measures in September 2020 despite SAGE's suggestions that doing so could halt the early
365 exponential growth in cases (57).

366
367 We have suggested four key questions for the UK Inquiry to ask about the input of modelling
368 into government Covid policy. We believe that improvement is necessary in each area:
369 designing processes to ensure that appropriate interdisciplinary expertise informs the
370 modelling; committing to sharing data nationally and internationally, enabling more effective
371 collaboration and reducing over-reliance on any one modelling group; investing in supporting
372 clear communication surrounding the key results of, and assumptions underlying, the
373 modelling; recognising the inherent limitation of any model and using shorter timeframes for

374 modelling. We suggest that with better communication, more openness to dialogue with
375 other communities as well as improved data sharing, epidemiological modelling could more
376 successfully support the UK response to this and future pandemics.

377

378 **Authors**

379 Christina Pagel is Professor of Operational Research at University College London with over
380 15 years of experience in developing mathematical and statistical models to inform policy.

381 Christian (Kit) Yates is a Senior Lecturer in Mathematics at University of Bath, where his
382 research concentrates on combining different mathematical modelling paradigms in order to
383 understand biological processes including epidemics. Both are members of Independent
384 SAGE and have been active in helping explain mathematical models and their role in policy
385 to the public during the pandemic. Both authors contributed equally to this paper and
386 Christina Pagel stands as guarantor.

387

388 *The Corresponding Author has the right to grant on behalf of all authors and does grant on*
389 *behalf of all authors, an exclusive licence (or non exclusive for government employees) on a*
390 *worldwide basis to the BMJ Publishing Group Ltd ("BMJ"), and its Licensees to permit this*
391 *article (if accepted) to be published in The BMJ's editions and any other BMJ products and to*
392 *exploit all subsidiary rights, as set out in [our licence](#).*

393

394 **Patient and Public Involvement**

395 We have not involved patients or the public in this article, but its content has been informed
396 by extensive public communication during the pandemic across Social, Print and Broadcast
397 Media.

398

399 **References**

400

- 401 1. UK COVID-19 Inquiry: draft terms of reference (HTML) [Internet]. GOV.UK. [cited 2022
402 Mar 10]. Available from: [https://www.gov.uk/government/publications/uk-covid-19-](https://www.gov.uk/government/publications/uk-covid-19-inquiry-draft-terms-of-reference/uk-covid-19-inquiry-draft-terms-of-reference-html)
403 [inquiry-draft-terms-of-reference/uk-covid-19-inquiry-draft-terms-of-reference-html](https://www.gov.uk/government/publications/uk-covid-19-inquiry-draft-terms-of-reference/uk-covid-19-inquiry-draft-terms-of-reference-html)
- 404 2. Brooks-Pollock E, Danon L, Jombart T, Pellis L. Modelling that shaped the early COVID-
405 19 pandemic response in the UK. *Philos Trans R Soc B Biol Sci*. 2021 Jul
406 19;376(1829):20210001.
- 407 3. Report 9 - Impact of non-pharmaceutical interventions (NPIs) to reduce COVID-19
408 mortality and healthcare demand [Internet]. Imperial College London. [cited 2021 Dec 8].
409 Available from: [http://www.imperial.ac.uk/medicine/departments/school-public-](http://www.imperial.ac.uk/medicine/departments/school-public-health/infectious-disease-epidemiology/mrc-global-infectious-disease-analysis/covid-19/report-9-impact-of-npis-on-covid-19/)
410 [health/infectious-disease-epidemiology/mrc-global-infectious-disease-analysis/covid-](http://www.imperial.ac.uk/medicine/departments/school-public-health/infectious-disease-epidemiology/mrc-global-infectious-disease-analysis/covid-19/report-9-impact-of-npis-on-covid-19/)
411 [19/report-9-impact-of-npis-on-covid-19/](http://www.imperial.ac.uk/medicine/departments/school-public-health/infectious-disease-epidemiology/mrc-global-infectious-disease-analysis/covid-19/report-9-impact-of-npis-on-covid-19/)
- 412 4. Stewart H, Sample I. Coronavirus: enforcing UK lockdown one week earlier 'could have
413 saved 20,000 lives'. *The Guardian* [Internet]. 2020 Jun 11 [cited 2021 Dec 8]; Available
414 from: [https://www.theguardian.com/world/2020/jun/10/uk-coronavirus-lockdown-20000-](https://www.theguardian.com/world/2020/jun/10/uk-coronavirus-lockdown-20000-lives-boris-johnson-neil-ferguson)
415 [lives-boris-johnson-neil-ferguson](https://www.theguardian.com/world/2020/jun/10/uk-coronavirus-lockdown-20000-lives-boris-johnson-neil-ferguson)
- 416 5. Coronavirus: Winter plans revealed in leaked Sage report. *BBC News* [Internet]. 2020
417 Aug 29 [cited 2021 Dec 8]; Available from: <https://www.bbc.com/news/uk-53954492>

- 418 6. S0663_SPI-M-O_Reasonable_worst-case_planning_scenario.pdf [Internet]. [cited 2021
419 Dec 8]. Available from:
420 [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/958746/S0663_SPI-M-O_Reasonable_worst-case_planning_scenario.pdf)
421 [_data/file/958746/S0663_SPI-M-O_Reasonable_worst-case_planning_scenario.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/958746/S0663_SPI-M-O_Reasonable_worst-case_planning_scenario.pdf)
- 422 7. Deaths in the UK | Coronavirus in the UK [Internet]. [cited 2021 Dec 8]. Available from:
423 [https://coronavirus.data.gov.uk/details/deaths?areaType=overview&areaName=United%](https://coronavirus.data.gov.uk/details/deaths?areaType=overview&areaName=United%20Kingdom)
424 [20Kingdom](https://coronavirus.data.gov.uk/details/deaths?areaType=overview&areaName=United%20Kingdom)
- 425 8. COVID-19 Response - Spring 2021 [Internet]. GOV.UK. [cited 2021 Dec 8]. Available
426 from: [https://www.gov.uk/government/publications/covid-19-response-spring-2021/covid-](https://www.gov.uk/government/publications/covid-19-response-spring-2021/covid-19-response-spring-2021)
427 [19-response-spring-2021](https://www.gov.uk/government/publications/covid-19-response-spring-2021/covid-19-response-spring-2021)
- 428 9. Prime Minister confirms move to Plan B in England [Internet]. GOV.UK. [cited 2022 Jun
429 6]. Available from: [https://www.gov.uk/government/news/prime-minister-confirms-move-](https://www.gov.uk/government/news/prime-minister-confirms-move-to-plan-b-in-england)
430 [to-plan-b-in-england](https://www.gov.uk/government/news/prime-minister-confirms-move-to-plan-b-in-england)
- 431 10. Moore S, Hill EM, Dyson L, Tildesley MJ, Keeling MJ. Modelling optimal vaccination
432 strategy for SARS-CoV-2 in the UK. PLOS Comput Biol. 2021 May 6;17(5):e1008849.
- 433 11. S1376_SPI-M-O_Consensus_Statement.pdf [Internet]. [cited 2021 Dec 8]. Available
434 from:
435 [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1017129/S1376_SPI-M-O_Consensus_Statement.pdf)
436 [_data/file/1017129/S1376_SPI-M-O_Consensus_Statement.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1017129/S1376_SPI-M-O_Consensus_Statement.pdf)
- 437 12. Evans-Pritchard A. Prof Lockdown's 'apocalyptic' omicron claims undermine faith in
438 vaccines and have fuelled unnecessary shutdowns. The Telegraph [Internet]. 2021 Dec
439 23 [cited 2022 Feb 15]; Available from:
440 [https://www.telegraph.co.uk/business/2021/12/23/prof-lockdowns-apocalyptic-omicron-](https://www.telegraph.co.uk/business/2021/12/23/prof-lockdowns-apocalyptic-omicron-claims-undermine-faith-vaccines/)
441 [claims-undermine-faith-vaccines/](https://www.telegraph.co.uk/business/2021/12/23/prof-lockdowns-apocalyptic-omicron-claims-undermine-faith-vaccines/)
- 442 13. Clark A. In charts: How omicron modelling of 10k hospitalisations was wildly off the
443 mark. The Telegraph [Internet]. 2022 Jan 19 [cited 2022 Feb 15]; Available from:
444 [https://www.telegraph.co.uk/news/2022/01/19/omicron-sage-lockdown-model-vs-real-](https://www.telegraph.co.uk/news/2022/01/19/omicron-sage-lockdown-model-vs-real-data/)
445 [data/](https://www.telegraph.co.uk/news/2022/01/19/omicron-sage-lockdown-model-vs-real-data/)
- 446 14. 'It's not an exact science': In defence of the Covid-19 modellers [Internet]. The
447 Independent. 2022 [cited 2022 Feb 15]. Available from:
448 [https://www.independent.co.uk/news/science/covid-omicron-modelling-cases-uk-latest-](https://www.independent.co.uk/news/science/covid-omicron-modelling-cases-uk-latest-b1997414.html)
449 [b1997414.html](https://www.independent.co.uk/news/science/covid-omicron-modelling-cases-uk-latest-b1997414.html)
- 450 15. Attacks against modellers undermine future pandemic response, say Sage scientists
451 [Internet]. The Independent. 2022 [cited 2022 Feb 15]. Available from:
452 [https://www.independent.co.uk/news/science/covid-modelling-latest-sage-omicron-](https://www.independent.co.uk/news/science/covid-modelling-latest-sage-omicron-b1996446.html)
453 [b1996446.html](https://www.independent.co.uk/news/science/covid-modelling-latest-sage-omicron-b1996446.html)
- 454 16. Boris Johnson ignores scientists' pleas for Covid restrictions before Christmas | Daily
455 Mail Online [Internet]. [cited 2022 Feb 15]. Available from:
456 [https://www.dailymail.co.uk/news/article-10325299/Boris-Johnson-ignores-scientists-](https://www.dailymail.co.uk/news/article-10325299/Boris-Johnson-ignores-scientists-pleas-Covid-restrictions-Christmas.html)
457 [pleas-Covid-restrictions-Christmas.html](https://www.dailymail.co.uk/news/article-10325299/Boris-Johnson-ignores-scientists-pleas-Covid-restrictions-Christmas.html)
- 458 17. S1498_220119_SPI-M-O_consensus_statement.pdf [Internet]. [cited 2022 Feb 15].
459 Available from:
460 [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1052426/S1498_220119_SPI-M-O_consensus_statement.pdf)
461 [_data/file/1052426/S1498_220119_SPI-M-O_consensus_statement.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1052426/S1498_220119_SPI-M-O_consensus_statement.pdf)

- 462 18. SPI-M-O Consensus Statement on COVID-19. :3.
- 463 19. Brooks-Pollock E, Northstone K, Pellis L, Scarabel F, Thomas A, Matthews DA, et al.
464 Impact of voluntary risk-mitigation behaviour on the magnitude of a COVID-19 Omicron
465 variant wave in England. :15.
- 466 20. Modelling the potential consequences of the Omicron SARS-CoV-2 variant in England
467 [Internet]. CMMID Repository. 2021 [cited 2022 Feb 15]. Available from:
468 <https://cmmid.github.io/topics/covid19/omicron-england.html>
- 469 21. SPI-M-O: Consensus statement on COVID-19, 8 December 2021 [Internet]. GOV.UK.
470 [cited 2022 Feb 15]. Available from: <https://www.gov.uk/government/publications/spi-m-o-consensus-statement-on-covid-19-8-december-2021/spi-m-o-consensus-statement-on-covid-19-8-december-2021>
- 473 22. SAGE99_S1441_Warwick_Omicron_for_release_v2.0.pdf [Internet]. [cited 2022 Feb
474 15]. Available from:
475 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1042228/SAGE99_S1441_Warwick_Omicron_for_release_v2.0.pdf
476
- 477 23. Knapton S. 'Wildly incorrect' Covid modelling bounced Boris Johnson into second
478 lockdown, MPs told. The Telegraph [Internet]. 2022 Jan 18 [cited 2022 Feb 15];
479 Available from: <https://www.telegraph.co.uk/politics/2022/01/18/wildly-incorrect-covid-modelling-caused-boris-johnson-bounce/>
480
- 481 24. Lesh M. The Covid modelling industry is biased towards doom. The Telegraph [Internet].
482 2021 Dec 21 [cited 2022 Feb 15]; Available from:
483 <https://www.telegraph.co.uk/news/2021/12/21/covid-modelling-industry-biased-towards-doom/>
484
- 485 25. A&E waiting times [Internet]. The Nuffield Trust. 2018 [cited 2022 Jun 15]. Available
486 from: <https://www.nuffieldtrust.org.uk/resource/a-e-waiting-times>
- 487 26. Covid UK: NHS staff absences due to virus hit 10-week high [Internet]. The Independent.
488 2022 [cited 2022 Jun 15]. Available from:
489 <https://www.independent.co.uk/news/health/covid-nhs-staff-sick-leave-uk-b2052783.html>
- 490 27. Gog JR, Hollingsworth TD. Epidemic interventions: insights from classic results. *Philos*
491 *Trans R Soc B Biol Sci.* 2021 Jul 19;376(1829):20200263.
- 492 28. Morgan ALK, Woolhouse MEJ, Medley GF, van Bunnik BAD. Optimizing time-limited
493 non-pharmaceutical interventions for COVID-19 outbreak control. *Philos Trans R Soc B*
494 *Biol Sci.* 2021 Jul 19;376(1829):20200282.
- 495 29. Birrell P, Blake J, van Leeuwen E, Gent N, De Angelis D. Real-time nowcasting and
496 forecasting of COVID-19 dynamics in England: the first wave. *Philos Trans R Soc B Biol*
497 *Sci.* 2021 Jul 19;376(1829):20200279.
- 498 30. Challen R, Tsaneva-Atanasova K, Pitt M, Edwards T, Gompels L, Lacasa L, et al.
499 Estimates of regional infectivity of COVID-19 in the United Kingdom following imposition
500 of social distancing measures. *Philos Trans R Soc B Biol Sci.* 2021 Jul
501 19;376(1829):20200280.
- 502 31. Basu S, Andrews J. Complexity in Mathematical Models of Public Health Policies: A
503 Guide for Consumers of Models. *PLOS Med.* 2013 Oct 29;10(10):e1001540.

- 504 32. Care homes mentioned only twice in five months of Sage minutes [Internet]. The
505 Independent. 2020 [cited 2021 Dec 8]. Available from:
506 [https://www.independent.co.uk/news/health/coronavirus-sage-meetings-care-homes-](https://www.independent.co.uk/news/health/coronavirus-sage-meetings-care-homes-a9541321.html)
507 [a9541321.html](https://www.independent.co.uk/news/health/coronavirus-sage-meetings-care-homes-a9541321.html)
- 508 33. Parliamentary committee evidence [Internet]. [cited 2021 Dec 8]. Available from:
509 <https://committees.parliament.uk/writtenevidence/10928/html>
- 510 34. The UK response to covid-19: use of scientific advice - Science and Technology
511 Committee - House of Commons [Internet]. [cited 2022 Feb 15]. Available from:
512 <https://publications.parliament.uk/pa/cm5801/cmselect/cmsctech/136/13608.htm>
- 513 35. Crowe S, Brown K, Tregay J, Wray J, Knowles R, Ridout DA, et al. Combining qualitative
514 and quantitative operational research methods to inform quality improvement in
515 pathways that span multiple settings. *BMJ Qual Saf.* 2017 Aug 1;26(8):641–52.
- 516 36. Lahiri S, Snowden B, Gu J, Krishnan N, Yellin H, Ndiaye K. Multidisciplinary team
517 processes parallel natural disaster preparedness and response: A qualitative case study.
518 *Int J Disaster Risk Reduct.* 2021 Jul 1;61:102369.
- 519 37. Cruz-Vega F, Sun C, Brink B, Bugslag R (Bob), Castillo BGD, Hastings P, et al. Theme
520 6. Multidisciplinary Team Interaction: Summary and Action Plan. *Prehospital Disaster*
521 *Med.* 2001 Mar;16(1):39–41.
- 522 38. Ge Y “Gurt”, Zobel CW, Murray-Tuite P, Nateghi R, Wang H. Building an Interdisciplinary
523 Team for Disaster Response Research: A Data-Driven Approach. *Risk Anal.*
524 2021;41(7):1145–51.
- 525 39. Lockdown 1.0 - Following the Science? [Internet]. BBC2; 2020 [cited 2022 Feb 16].
526 Available from:
527 [https://eur01.safelinks.protection.outlook.com/?url=https%3A%2F%2Flearningonscreen.
528 ac.uk%2Fondemand%2Findex.php%2Fclip%2F213637%3Fbcast%3D133406777&data
529 =04%7C01%7Ccc.page1%40ucl.ac.uk%7C1bf13e8094774ec2d61a08d9f12bfdad%7C1faf
530 88fea9984c5b93c9210a11d9a5c2%7C0%7C0%7C637805993504862725%7CUnknown
531 %7CTWFpbGZsb3d8eyJWljoIMC4wLjAwMDAiLCJQIjoiV2luMzliLCJBTiI6IjEhaWwiLCJ
532 XVCi6Mn0%3D%7C3000&sdata=YlqWwNcVX%2BISRg2vXPAYeW8KbVx0%2F4sQx
533 AQaDxu38%3D&reserved=0](https://eur01.safelinks.protection.outlook.com/?url=https%3A%2F%2Flearningonscreen.ac.uk%2Fondemand%2Findex.php%2Fclip%2F213637%3Fbcast%3D133406777&data=04%7C01%7Ccc.page1%40ucl.ac.uk%7C1bf13e8094774ec2d61a08d9f12bfdad%7C1faf88fea9984c5b93c9210a11d9a5c2%7C0%7C0%7C637805993504862725%7CUnknown%7CTWFpbGZsb3d8eyJWljoIMC4wLjAwMDAiLCJQIjoiV2luMzliLCJBTiI6IjEhaWwiLCJXVCi6Mn0%3D%7C3000&sdata=YlqWwNcVX%2BISRg2vXPAYeW8KbVx0%2F4sQxAQaDxu38%3D&reserved=0)
- 534 40. Donnelly L. Sage advisers used Wikipedia entries to model first Covid lockdown. *The*
535 *Telegraph* [Internet]. 2020 Nov 19 [cited 2022 Feb 16]; Available from:
536 [https://www.telegraph.co.uk/news/2020/11/19/sage-advisers-used-wikipedia-entries-](https://www.telegraph.co.uk/news/2020/11/19/sage-advisers-used-wikipedia-entries-model-first-covid-lockdown/)
537 [model-first-covid-lockdown/](https://www.telegraph.co.uk/news/2020/11/19/sage-advisers-used-wikipedia-entries-model-first-covid-lockdown/)
- 538 41. GISAIID - hCov19 Variants [Internet]. [cited 2022 Jun 7]. Available from:
539 <https://www.gisaid.org/hcov19-variants/>
- 540 42. 23-london-lockdown-18032020.pdf [Internet]. [cited 2021 Dec 8]. Available from:
541 [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/882720/23-london-lockdown-18032020.pdf)
542 [_data/file/882720/23-london-lockdown-18032020.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/882720/23-london-lockdown-18032020.pdf)
- 543 43. Coronavirus: Three reasons why the UK might not look like Italy. *BBC News* [Internet].
544 2020 Mar 13 [cited 2022 Feb 16]; Available from: [https://www.bbc.com/news/uk-](https://www.bbc.com/news/uk-51858987)
545 [51858987](https://www.bbc.com/news/uk-51858987)

- 546 44. Yong E. The U.K.'s Coronavirus 'Herd Immunity' Debacle [Internet]. The Atlantic. 2020
547 [cited 2022 Feb 16]. Available from:
548 [https://www.theatlantic.com/health/archive/2020/03/coronavirus-pandemic-herd-](https://www.theatlantic.com/health/archive/2020/03/coronavirus-pandemic-herd-immunity-uk-boris-johnson/608065/)
549 [immunity-uk-boris-johnson/608065/](https://www.theatlantic.com/health/archive/2020/03/coronavirus-pandemic-herd-immunity-uk-boris-johnson/608065/)
- 550 45. Opinion: Why Didn't The UK Lockdown Sooner And Prevent Thousands Of Deaths?
551 [Internet]. HuffPost UK. 2020 [cited 2022 Feb 16]. Available from:
552 [https://www.huffingtonpost.co.uk/entry/lockdown-uk-](https://www.huffingtonpost.co.uk/entry/lockdown-uk-deaths_uk_5ec6efd8c5b68038a74a50ad)
553 [deaths_uk_5ec6efd8c5b68038a74a50ad](https://www.huffingtonpost.co.uk/entry/lockdown-uk-deaths_uk_5ec6efd8c5b68038a74a50ad)
- 554 46. Locking Down One Week Earlier Could Have Avoided Thousands Of UK Deaths,
555 Scientists Say [Internet]. HuffPost UK. 2020 [cited 2022 Feb 16]. Available from:
556 [https://www.huffingtonpost.co.uk/entry/uk-lockdown-coronavirus-deaths-](https://www.huffingtonpost.co.uk/entry/uk-lockdown-coronavirus-deaths-avoided_uk_5ec76ad1c5b66686597a8129)
557 [avoided_uk_5ec76ad1c5b66686597a8129](https://www.huffingtonpost.co.uk/entry/uk-lockdown-coronavirus-deaths-avoided_uk_5ec76ad1c5b66686597a8129)
- 558 47. science-advice-crisis_0.pdf [Internet]. [cited 2022 Feb 15]. Available from:
559 [https://www.instituteforgovernment.org.uk/sites/default/files/publications/science-advice-](https://www.instituteforgovernment.org.uk/sites/default/files/publications/science-advice-crisis_0.pdf)
560 [crisis_0.pdf](https://www.instituteforgovernment.org.uk/sites/default/files/publications/science-advice-crisis_0.pdf)
- 561 48. Banerjee R, Bhattacharya J, Majumdar P. Exponential-growth prediction bias and
562 compliance with safety measures related to COVID-19. *Soc Sci Med* 1982. 2021
563 Jan;268:113473.
- 564 49. Smith KE, Stewart E. 'Black magic' and 'gold dust': the epistemic and political uses of
565 evidence tools in public health policy making. *Evid Policy*. 2015 Aug 1;11(3):415–37.
- 566 50. Gigerenzer G, Gaissmaier W, Kurz-Milcke E, Schwartz LM, Woloshin S. Helping Doctors
567 and Patients Make Sense of Health Statistics. *Psychol Sci Public Interest*. 2007 Nov
568 1;8(2):53–96.
- 569 51. Lourenço J, Paton R, Ghafari M, Kraemer M, Thompson C, Simmonds P, et al.
570 Fundamental principles of epidemic spread highlight the immediate need for large-scale
571 serological surveys to assess the stage of the SARS-CoV-2 epidemic [Internet]. 2020
572 Mar [cited 2021 Dec 8] p. 2020.03.24.20042291. Available from:
573 <https://www.medrxiv.org/content/10.1101/2020.03.24.20042291v1>
- 574 52. Panovska-Griffiths J. Coronavirus: we've had 'Imperial', 'Oxford' and many more models
575 – but none can have all the answers [Internet]. The Conversation. [cited 2022 Feb 16].
576 Available from: [http://theconversation.com/coronavirus-weve-had-imperial-oxford-and-](http://theconversation.com/coronavirus-weve-had-imperial-oxford-and-many-more-models-but-none-can-have-all-the-answers-135137)
577 [many-more-models-but-none-can-have-all-the-answers-135137](http://theconversation.com/coronavirus-weve-had-imperial-oxford-and-many-more-models-but-none-can-have-all-the-answers-135137)
- 578 53. Sayburn A. Covid-19: experts question analysis suggesting half UK population has been
579 infected. *BMJ*. 2020 Mar 25;368:m1216.
- 580 54. s0976-spi-m-o-medium-term-projections-161220.pdf [Internet]. [cited 2021 Dec 8].
581 Available from:
582 [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/952733/s0976-spi-m-o-medium-term-projections-161220.pdf)
583 [_data/file/952733/s0976-spi-m-o-medium-term-projections-161220.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/952733/s0976-spi-m-o-medium-term-projections-161220.pdf)
- 584 55. S1075_SPI-M-O_summary_of_modelling_on_easing_restrictions__1_.pdf [Internet].
585 [cited 2021 Dec 8]. Available from:
586 [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/963504/S1075_SPI-M-)
587 [_data/file/963504/S1075_SPI-M-](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/963504/S1075_SPI-M-)
588 [O_summary_of_modelling_on_easing_restrictions__1_.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/963504/S1075_SPI-M-O_summary_of_modelling_on_easing_restrictions__1_.pdf)

589 56. Zhu S, Fukushima M. Worst-Case Conditional Value-at-Risk with Application to Robust
590 Portfolio Management. *Oper Res.* 2009 Oct 1;57(5):1155–68.

591 57. SAGE 58 minutes: Coronavirus (COVID-19) response, 21 September 2020 [Internet].
592 GOV.UK. [cited 2022 Feb 16]. Available from:
593 [https://www.gov.uk/government/publications/fifty-eighth-sage-meeting-on-covid-19-21-](https://www.gov.uk/government/publications/fifty-eighth-sage-meeting-on-covid-19-21-september-2020/sage-58-minutes-coronavirus-covid-19-response-21-september-2020)
594 [september-2020/sage-58-minutes-coronavirus-covid-19-response-21-september-2020](https://www.gov.uk/government/publications/fifty-eighth-sage-meeting-on-covid-19-21-september-2020/sage-58-minutes-coronavirus-covid-19-response-21-september-2020)

595

Sources of uncertainty that affect accuracy of modelling scenarios.

Features of the epidemiological models

Features of real life

Model structure

Does model accurately capture key dynamics of disease spread? e.g.

- age differences
- regional differences
- vaccination differences#
- hospital/school/care home spread
- Symptomatic/asymptomatic spread
- Incubation period

Structure is often refined as more is known about the disease.

Secondly, how does the model capture public behaviour? Current models do not really do this well. Instead, the impact of interventions is often incorporated as blanket reduction in exposure.

Model parameters

This includes estimates of things are measurable but very uncertain early in a pandemic (or a new variant) such as:

- Transmissibility; severity; likelihood of showing symptoms
- Effectiveness of vaccines in preventing infection and severe illness

It also includes elements that are inherently much more uncertain such as:

- Effectiveness of interventions (masks, working from home, social distancing)
- Public behaviour over and above any public health measures (e.g. cancelling plans, reducing contacts)

Inherent randomness

Even if a model is perfectly structured and parameterised, the future is not determined.

For instance, a chance event might lead to a superspreading event or no onward infections. At a larger scale, unexpected events (e.g. weather disasters, political protests) might create conditions for a superspreading event accelerating spread or, conversely reduce transmission (e.g. a long period of good weather)

Teams normally deal with this uncertainty by running stochastic models thousands of times and reporting the central outcome and the range of possible outcomes seen in different realisations.

Context fundamentally changes

Slightly different to inherent randomness, is if the situation fundamentally changes over the timescale of prediction.

For instance, projections are run for 6 months with best current knowledge, but a new variant emerges and spreads, or new policy is brought in or measures are dropped. Any such even that fundamentally changes the context of the disease will render previous predictions invalid.

Modellers try to deal with this (and uncertainties within the model) by considering various scenarios (different policies, different variants, different behaviour), but reality usually does something different again.

Figure 1 - Sources of uncertainty that affect the accuracy of modelling scenarios. These need to be communicated – and more than once - to policymakers and the public.