Response to the Examiners’ Joint Report

Navigating Uncertainty - Evaluating Human and Model-Based Forecasting of COVID-19

PhD thesis by Nikos Ioannis Bosse

Dear Professor Diggle,
Dear Professor Höhle,

I would like to express my heartfelt gratitude to you for the time and attention you dedicated to reviewing my thesis, for your thoughtful comments, and for the interesting and enjoyable conversation during the viva. It was a pleasure and an honour to discuss my work with you.

Please find below my responses to your comments.

Yours sincerely,

Nikos Bosse

Chapter 1
Section 1.2 (page 10) states (correctly) that the thesis will equate “model-based” with “mathematical model-based.” Nothing wrong with that, but it ignores a third, and very widely used, approach to forecasting , namely statistical modelling of time series data. We would like the candidate to add a paragraph on this third approach, citing key references that interested readers can follow up for themselves; for example, Box and Jenkins (1970), West and Harrison (1997), Hyndman and Athanasopoulos (2021).

The comment refers to the following paragraph on page 10, which I updated slightly (addition in bold):

> Analyse the role of human judgement in forecasting COVID-19 in Germany and Poland. Compare human judgement forecasts against model-based predictions and analyse the added benefit of human input over mathematical **and statistical** modelling (Paper 2, see Chapter 4).

This change now more accurately conveys that paper 2 (Chapter 4) compares human forecasts not only against mechanistic models, but against a broader category of model-based predictions. On the one hand, we compare the human forecasts against the (semi-)mechanistic EpiNow2 model directly, aiming to analyse the added benefit of human input over mathematical modelling in detail. On the other hand, we also compare them against the Forecast Hub ensemble, which comprises both mechanistic and statistical models.

To discuss this distinction in more detail and give readers a chance to learn more about the topic, I added the following paragraph on page 13/14 (additions in bold):

> **Mathematical models (see e.g. Frauenthal, 1980; Kretzschmar and Wallinga, 2009), as described above, are often also referred to as 'mechanistic models'. Mechanistic models, such as compartmental models (see e.g. Shah and Mittal, 2021) or agent-based models (see e.g. Hunter et al., 2017) explicitly model the underlying infectious disease process, encoding our understanding of infectious disease dynamics. There exists a second broad category of models that are commonly used to make forecasts in epidemiology: 'statistical models'. Statistical models derive their predictive power from the statistical relationships between different observable variables. They usually do not rely on an understanding of the underlying processes, although they often make distributional assumptions about relevant variables. For an extensive overview of statistical time series models and their use in forecasting, see e.g. Box and Jenkins (1970); West and Harrison (1997), and Hyndman, Rob J and Athanasopoulos, George(2021). In practice, the distinction between mechanistic and statistical models is not always clear-cut. Models that make use of statistical estimation while at the same time constraining parameters based on mechanistic assumptions are common in epidemiology, and are often referred to as 'semi-mechanistic' models (see e.g. Bhatt et al., 2023, for a recent example).**

Chapter 2
Section 2.2.2.3 (page 18) introduces the weighted interval score (WIS) without any reference to its origin. Furthermore, on p. 20 a statement about convergence of the WIS towards CRPS is given without neither a proof nor a reference to a proof. We would like the candidate to correct these omissions.

To address this comment, I updated the following sentence on page 20 (previously page 18, additions in bold)

> A proper scoring rule that is well suited to evaluate forecasts in such a quantile format is the weighted interval score **(**WIS**, see e.g. Bracher et al., 2021a; Gneiting and Raftery, 2007; Winkler, 1972, and references therein)**.

And the following sentence on page 20 (additions in bold)

> When the weights are set to $w_k = \frac{\alpha_k}{2}$ and $w_0 = 0.5$, then the WIS converges to the CRPS for an increasing number of equally spaced quantiles **(for a proof see e.g Bracher et al., 2021a)**.

References:

Bhatt, S., Ferguson, N., Flaxman, S., Gandy, A., Mishra, S., and Scott, J. A. (2023). Semi-mechanistic Bayesian modelling of COVID-19 with renewal processes. *Journal of the Royal Statistical Society Series A: Statistics in Society*, 186(4):601–615

Box, G.E.P. and Jenkins, G.M. (1970). Time Series Analysis, Forecasting and Control. San Francisco : Holden-Day.

Bracher, J., Ray, E. L., Gneiting, T., and Reich, N. G. (2021a). Evaluating epidemic forecasts in an interval format. *PLoS computational biology*, 17(2):e1008618.

Frauenthal, J. C. (1980). *Mathematical Modeling in Epidemiology*. Universitext. Springer,Berlin, Heidelberg.

Gneiting, T., Balabdaoui, F., and Raftery, A. E. (2007). Probabilistic forecasts, calibration and sharpness. *Journal of the Royal Statistical Society: Series B (Statistical Methodology)*, 69(2):243–268.

Hunter, E., Mac Namee, B., and Kelleher, J. D. (2017). A Taxonomy for Agent-BasedModels in Human Infectious Disease Epidemiology. *Journal of Artificial Societies and Social Simulation*, 20(3):2

Hyndman, R. and Athanasopoulos G. (2021). Forecasting: Principles and Practice (3rd ed), OTexts: Melbourne, Australia. https://OTexts.com/fpp3

Kretzschmar, M. and Wallinga, J. (2009). Mathematical Models in Infectious Disease Epidemiology. *Modern Infectious Disease Epidemiology*, pages 209–221.

Shah, N. H. and Mittal, M. (2021). Introduction to Compartmental Models in Epidemiology.In Shah, N. H. and Mittal, M., editors, *Mathematical Analysis for Transmission of COVID-19*, pages 1–20, Singapore. Springer.

West, M. and Harrison, J. (1997). Bayesian Forecasting and Dynamic Models. New York: Springer.

Winkler, R. L. (1972). A Decision-Theoretic Approach to Interval Estimation. *Journal of the American Statistical Association*, 67(337):187–191.