Institution: Brunel University London		
Unit of Assessment: 11 – Computer Science and Informatics		
Title of case study: Supporting decision making in West London NHS trusts during the COVID-19 pandemic.		
Period when the underpinning research was undertaken: 2015-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Dr. Derek Groen	Senior Lecturer	09/2015-present
Dr. David Bell	Reader	09/2006-present
Dr. Hamid Arabnejad	Research Fellow	12/2018-present
Dr. Imran Mahmood	Research Fellow	10/2019-present
Dr. Alan Serrano	Reader	05/2002-present
Dr. Anastasia Anagnostou	Lecturer	03/2012-present
Dr. Isabel Sassoon	Lecturer	03/2020-present
Dr. Alaa Marshan	Lecturer (Teaching only contract)	03/2014-present
Dr. Diana Suleimenova	Research Fellow	09/2016-present
Prof. Simon Taylor	Professor	01/1995-present
Prof. Panos Louvieris	Professor	03/2010-present
Period when the claimed impact occurred: April 2020 - December 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact (indicative maximum 100 words)

Brunel's research was incorporated into a toolkit that directly informed planning decisions for 2 NHS trusts (LNWH and Hillingdon), including 6 hospitals serving 1,290,000 citizens. LNWH used the simulations to plan COVID-19 capacity and service recovery, informing the pace and scale of health service provision and capacity expansion in response to pandemic waves, benefitting approximately 4,000 COVID-19 patients and improving the well-being and working conditions for approximately 2,600 hospital staff. This led to the trusts being able to treat 2.3 times more COVID-19 patients in their hospitals at the end of 2020, compared to the first wave capacity, and helped prevent medical services in West London being overwhelmed. The toolkit was also applied to analyse CovidSim on behalf of the Royal Society, with the findings contributing towards a shift by SAGE away from reliance on single codes.

2. Underpinning research (indicative maximum 500 words)

Brunel researchers created an epidemiological simulation toolkit for large-scale COVID-19 forecast analysis. The toolkit relies on a combination of agent-based modelling algorithms to reproduce individual behaviours, ensemble simulations to efficiently account for statistical noise and counterfactuals and automated access to large supercomputers (such as the Eagle supercomputer in Poznan (PL), and the SuperMUC-NG computer in Garching (DE)) to facilitate the rapid and reliable execution of these complex workflows. The research work performed to establish the toolkit comprises two main themes: one concerning the Flu And Coronavirus

Simulator (FACS) and one concerning the VECMA toolkit for facilitating robust and reproducible simulations on the high end computing scale.

The FACS code **[REF1]** has been developed from the ground up, and uses an agent-based modelling algorithm with people represented as individual agents in conjunction with local mapping data, demographic information and disease information. FACS serves to forecast the spread of Covid-19 in a local environment, such as a borough in London or a different city or region in the UK. The code has been validated against hospitalisation data of the first wave of COVID-19 from two NHS Trusts: London North West University Healthcare (LNWH) and Hillingdon Hospitals, and has shown good agreement with that validation data. The code also supports a wide range of public health interventions, such as social distancing, mask wearing and the closing of locations by type. To run FACS robustly, we perform ensemble simulations that cater for a large number of intervention scenarios, while also testing the sensitivity of key assumptions in specific forecasts, and accounting for the aleatory uncertainty in the code **[REF6]**. The FACS code has been developed in collaboration with the HiDALGO Centre of Excellence project (https://hidalgo-project.eu) and is currently applied to simulate COVID-19 spread in Madrid as part of that project.

The VECMA toolkit **[REF2]**, co-developed by Groen and the VECMA Consortium, facilitates rapid and robust verification, validation, uncertainty quantification and sensitivity analysis for a wide range of scientific applications. It is used by researchers across 8 different application domains, and it enables the team at Brunel to quickly run large ensembles of simulations using remote supercomputers (using the FabSim component **[REF4]**), and enables them to rapidly identify key uncertainties in the simulations, and parameters to which the simulations outcomes are most sensitive (using the EasyVVUQ component **[REF3]**). We also used the ensemble execution approach in VECMAtk to analyse the sensitivities and limitations of the CovidSim code **[REF5]**, which has been consulted for policy decision making by the UK government through the Scientific Advisory Group for Emergencies (SAGE). We found that the code derives 70% of its sensitivity from only 4 out of the 940 parameters and that the model's validation errors cannot be fully attributed, in a probabilistic sense, to lack of knowledge about the correct values of these 940 parameters. We highlight important omitted factors, such as the modelling of care homes and medical facilities, and the effect of using face masks, that could be the reason for this discrepancy.

3. References to the research (indicative maximum of six references)

REF1: Mahmood, I., Arabnejad, H., Suleimenova, D., Sassoon, I., Marshan, A., Serrano, A., Louvieris, P., Anagnostou, A., Taylor, S., Bell, D. and Groen, D., 2020. FACS: A geospatial agent-based simulator for analyzing COVID-19 spread and public health measures on local regions. Journal of Simulation, pp. 1-19, doi:10.1080/17477778.2020.1800422.

REF2: Groen, D., Richardson, R.A., Wright, D.W., Jancauskas, V., Sinclair, R., Karlshoefer, P., Vassaux, M., Arabnejad, H., Piontek, T., Kopta, P. and Bosak, B., 2019, June. Introducing VECMAtk - Verification, Validation and Uncertainty Quantification for Multiscale and HPC Simulations. In International Conference on Computational Science (pp. 479-492). Springer, Cham. doi:10.1007/978-3-030-22747-0_36.

REF3: Wright, D.W., Richardson, R.A., Edeling, W., Lakhlili, J., Sinclair, R.C., Jancauskas, V., Suleimenova, D., Bosak, B., Kulczewski, M., Piontek, T., Kopta, P., Chirca, I., Arabnejad, H., Luk, O.O., Hoenen, O., Węglarz, J., Crommelin, D., Groen, D. and Coveney, P.V. (2020), Building Confidence in Simulation: Applications of EasyVVUQ. Adv. Theory Simul.. doi:10.1002/adts.201900246.

REF4: Groen, D., Bhati, A.P., Suter, J., Hetherington, J., Zasada, S.J. and Coveney, P.V., 2016. FabSim: facilitating computational research through automation on large-scale and distributed e-infrastructures. Computer Physics Communications, 207, pp.375-385. Doi: 10.1016/j.cpc.2016.05.020.

REF5: Edeling, W., Arabnejad, H., Sinclair, R.C., Suleimenova, D., Gopalakrishnan, K., Bosak, B., Groen, D., Mahmood, I. Crommelin, D., Coveney, P.V..The Impact of Uncertainty on Predictions of the CovidSim Epidemiological Code. Nature Computational Science. doi:10.21203/rs.3.rs-82122/v3.

REF6: Groen, D., Arabnejad, H. et al. VECMAtk: A Scalable Verification, Validation and Uncertainty Quantification toolkit for Scientific Simulations. Phil. Trans. R. Soc. A (in press, preprint available at: https://arxiv.org/abs/2010.03923).

GRANT 1: Dr. Derek Groen, Verified Exascale Computing for Multiscale Simulations, European Commission Horizon 2020 Programme, June 2018 - June2021, EUR4,000,000 (EUR429,000 allocated to Brunel, equivalent to GBP379,643 [01-2021]).

GRANT 2: Dr. Derek Groen, HPC and Big Data Technologies for Global Systems, European Commission Horizon 2020 Programme, December 2018 - November 2021, EUR8,000,000 (EUR647,000 allocated to Brunel, equivalent to GBP572,562 [01-2021])

4. Details of the impact (indicative maximum 750 words)

NHS planning is typically driven by a mix of historical data and trend analysis. COVID-19 (a novel virus), lacking such data, required rapid evidence analysis, synthesis, and simulation to provide actionable local insight. Senior NHS managers (CIOs and direct reports) from West London with Bell planned a collaboration strategy in March 2020. Brunel was then able to rapidly assemble academic teams deploying their research on evidence sifting (for model inputs), COVID-19 transmission and bed utilisation modelling. Research outputs were subsequently disseminated to the NHS through the delivery, presentation and discussion of 15 written forecast reports between April and December 2020, directly feeding into operational planning decisions of 2 NHS trusts, the London North West University Healthcare (LNWH) Trust and the Hillingdon Hospitals (HH) Trust, which together are responsible for the healthcare provision for 1,290,000 citizens. Scenarios were co-designed with the NHS as research was developed and validated. Forecasts were then disseminated to NHS analytics groups to further support short-term, elective and social care planning and transformation.

The epidemiological simulation toolkit has been used repeatedly from early in the first wave of the pandemic **[E8 and E9]** to provide long term forecasts of COVID-19 spread to LNWH, and was used during the second wave and after to provide forecasts for HH. This supported healthcare delivery across West London in three different ways:

First, it informed the trusts' operational response during subsequent waves of the pandemic **[E1]**, which led to LNWH arranging capacity in advance that benefited approximately 4,000

COVID-19 hospital patients during this period **[E3]**. Planning the zoning and repurposing of wards was undertaken using a range of forecasted scenarios which included key decision or trigger points. This was required as patient admission ranged from several per day to approximately 1 per 10 minutes. As the pandemic progressed, models were refined and adapted to better support general and acute (G&A) and intensive care unit (ICU) bed planning (including surge capacity and stand-down points). This enabled the flexing of bed capacity throughout 2020 from no COVID-19 beds up to 54 additional ICU beds and 44 acute respiratory beds. The capacity increase also was aligned with the wider planning with local councils, such that sufficient care home support and intermediate recovery beds were prepared for the surge capacity scenario.

Second, it influenced the assumptions underlying the scenarios the trusts developed to help them plan their non-COVID elective service recovery **[E1]**. Brunel's forecasts provided early warnings for new peaks which subsequently occurred, and quieter periods that occurred in between. Both COVID-19 and elective service recovery planning affects the work pressure level and well-being of approximately 2,600 relevant hospital staff (healthcare assistants plus medical) and affects the care provisioning for approximately 1,600 elective inpatient and day case admissions per week **[E4]**. In addition, the research helped LNWH to understand the potential interplay of different factors in driving COVID19 admissions demand variations **[E1]**.

Third, forecasts indicated the scale and pace at which capacity needs to be expanded and whether it can be returned towards other health and care needs **[E1]**. The preparatory efforts, informed by Brunel's research, of both NHS trusts enabled them to facilitate more COVID-19 patients in their hospitals (629 beds occupied) during the peak of the third wave as compared to the peak of the first wave (268 beds occupied) **[E3]**.

The Brunel team was also requested by the Rapid Assistance In Modelling the Pandemic (RAMP) initiative, which is coordinated by the Royal Society, to analyse the sensitivities and limitations of the CovidSim code **[REF5]** using the VECMA sensitivity analysis and ensemble simulation toolkit **[REF6]**. The results from Arabnejad, Groen, and others in the VECMA consortium were fed back to RAMP in a report **[E7]** and contributed towards a shift in SAGE away from sole reliance on the CovidSim model **[E10]**. The results are also published on the Science Museum web page for educational purposes to the general public **[E6]**.

5. Sources to corroborate the impact (indicative maximum of 10 references)

E 1: Testimonial and contact details of the NHS planning and transformation directors for the LNWH NHS Trust.
E 2: Contact details of the NHS planning and transformation directors for the Hillingdon NHS Trust.
E 3: Information on COVID-19 cases and hospitalisations in England: https://www.england.nhs.uk/statistics/wp-content/uploads/sites/2/2021/01/Covid-Publication-14-01-2021.xlsx
E 4: Annual Report on LNWH Trust: https://www.england.nhs.uk/wp-content/uploads/2019/10/London_North_West_University_Healthcare_NHS_Trust_Annual_Report_and_Accounts_2018-19.pdf
E 5: LNWH Trust Wiki page: https://en.wikipedia.org/wiki/London_North_West_University_Healthcare_NHS_Trust
E 6: Science Museum blog on Virtual Pandemics:

https://www.sciencemuseumgroup.org.uk/blog/coronavirus-virtual-pandemics/
E 7: Sensitivity Analysis and Uncertainty Quantification for the covid-sim Epidemiological Code [26th June 2020]
E 8: Correspondence with LNWH on 13-04-2020.
E 9: Correspondence with LNWH on 24-04-2020.
E 10: Evidence of modelling presentation shift in SAGE away from reliance of single transmission models, relative to the direct CovidSim forecasts presented by the government in March. Attached and available at: https://www.gov.uk/government/publications/spi-m-o-covid-19-short-term-forecasts-5-august-2020