Report 36: Modelling ICU capacity under different epidemiological scenarios of the COVID-19 pandemic in three western European countries

Ruth McCabe[1,2]*, Mara D. Kont[1]*, Nora Schmit[1]*, Charles Whittaker[1], Alessandra Løchen[1], Marc Baguelin[1], Edward Knock[1], Lilith Whittles[1], John Lees[1], Patrick G. T. Walker[1], Azra C. Ghani[1], Neil M. Ferguson[1], Peter J. White[1], Christl A. Donnelly[1,2], Katharina Hauck[1], Oliver Watson[1^]

* Contributed equally
^Correspondence: o.watson15@imperial.ac.uk

[1] MRC Centre for Global Infectious Disease Analysis & WHO Collaborating Centre for Infectious Disease Modelling, Abdul Latif Jameel Institute for Disease and Emergency Analytics, Imperial College London
[2] Department of Statistics, University of Oxford

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Summary

The coronavirus disease 2019 (COVID-19) pandemic has placed enormous strain on healthcare systems, particularly intensive care units (ICUs), with COVID-19 patient care being a key concern of healthcare system planning for winter 2020/21. Ensuring that all patients who require intensive care, irrespective of COVID-19 status, can access it during this time is essential.

This study uses an integrated model of hospital capacity planning and epidemiological projections of COVID-19 patients to estimate the spare capacity of key ICU resources under different epidemic scenarios in France, Germany and Italy across the winter period of 2020/21. In particular, we examine the effect of implementing suppression strategies of varying effectiveness, triggered by different numbers of COVID-19 patients in ICU. The use of a 'dual-demand' (COVID-19 and non-COVID-19) patient model and the consideration of multiple ICU resources that determine capacity (beds, doctors, nurses and ventilators) and the interdependencies between them, provides a detailed insight into potential capacity constraints this winter.

Without sufficient mitigation, we estimate that COVID-19 ICU patient numbers will exceed those seen in the first peak, resulting in substantial capacity deficits, with beds being consistently found to be the most constrained resource across countries. Lockdowns triggered based on ICU capacity could lead to large improvements in spare capacity during the winter season, with pressure being most effectively alleviated when lockdown is triggered early and implemented at a higher level of suppression. In many cases, maximum deficits are reduced to lower levels which can then be managed by expanding supply-side hospital capacity, to ensure that all patients can receive treatment. The success of such interventions also depends on baseline ICU bed numbers and average non-COVID-19 patient occupancy. We find that lockdowns of longer duration reduce the total number of days in deficit, but triggering lockdown earlier when COVID-19 ICU occupancy is lower is more effective in minimising deficits. Our results highlight the dependencies between different metrics, suggesting that absolute benefits of different strategies must be weighed against the feasibility and drawbacks of different amounts of time spent in lockdown.

1. Introduction

National healthcare systems have been placed under extreme pressure due to the coronavirus disease (COVID-19) pandemic. To avoid hospitals being overwhelmed at the beginning of the pandemic, countries implemented stringent non-pharmaceutical interventions (NPIs) including physical-distancing measures and lockdowns of essential services to reduce incidence. While effective in reducing transmission, the high economic and social costs of such interventions cast doubt on their long-term tenability [1]. At the same time, countries also took measures to increase hospital capacity to treat COVID-19 patients, such as the opening of field hospitals, reorganisation of health services and the cancellation of elective surgery. Nonetheless, many European countries still reported severe strains on intensive care unit (ICU) resources owing to a surge in demand [2–4], with care sometimes having to be prioritised among those who would benefit most.

The demand on healthcare systems is greatest during autumn and winter in most countries [5]. Healthcare systems must be prepared to deal with these pressures in addition to responding to likely increases in numbers of COVID-19 patients requiring hospitalisation due to a second wave [6–8]. The dynamics of the number of patients in ICU will be heavily dependent on population behaviour and the effectiveness of NPIs. However, few studies to date have linked forecasts of COVID-19 healthcare demand under NPIs to national-level estimates of hospital capacity and utilisation (for example, [9]).

Here, we integrate a previously developed hospital capacity framework [10,11] with epidemiological projections of COVID-19 patients requiring ICU treatment [12] in three European countries that have been heavily affected by the pandemic. We present a scenario-based analysis of estimated spare capacity of ICU beds, ventilators and staff in France, Germany and Italy over the winter period between late October 2020-March 2021 under a ‘dual-demand’ (COVID-19 and non-COVID-19) patient model. We examine the effect of suppression strategies of varying effectiveness which are triggered based on the number of COVID-19 patients surpassing ICU capacity thresholds. We conclude with a discussion of key strategies to address possible capacity deficits: lockdown to control the number of COVID-19 patients, policies to reduce the number of non-COVID-19 patients, and supply-side interventions to increase hospital capacity, and discuss the trade-offs inherent to each.

2. Methods

In this paper we estimate the spare capacity, defined as the difference between the provision of, and demand for, four key ICU resources, namely beds, nurses, doctors and ventilators in France, Germany and Italy.

2.1 Estimating pre-pandemic baseline capacity

Baseline national capacity of ICU resources were estimated based on pre-pandemic hospital capacity. Data were derived from the most recent official publications from the Ministries of Health and the OECD, where available [13–16]. In all three countries, baseline estimates include both public and private resources within official reports. However, exact definitions and measurement methods of the extracted values depend on the country-specific healthcare organisation. For example, estimates of ICU doctors vary between countries, with some countries only reporting doctors who have completed their training [14,16,17]. Staff values are given as full-time equivalents (FTEs).

Baseline occupancy of non-COVID-19 patients was determined using pre-pandemic average annual occupancy of ICU beds. While admissions are often seasonal with rises in winter months, this year it is unclear if this will occur due to physical distancing measures to reduce SARS-CoV-2 transmission also reducing the spread of other respiratory infections. Furthermore, the pandemic has reduced the number of non-COVID-19 patients seeking hospital care [18,19]. Therefore, figures for the average annual ICU occupancy of non-COVID-19 patients were considered the upper bound for this variable, but alternative scenarios were also explored (see *Methods: Modelled Scenarios*).

2.2 Parameterising the capacity model

The capacity framework includes a 'dual-demand' model of care requirements incorporating demand from both COVID-19 and non-COVID-19 cohorts. The former is projected under different epidemiological scenarios while the latter is estimated using average annual occupancy figures in each country. The requirements of each resource are calculated on a per-patient basis, with a variety of data sources being used to parameterise the model (Table 1) [20–30].

There is a one-to-one relationship between patients and beds. The relationship between patients and required staff and ventilators is more nuanced. First, not all ICU patients require mechanical ventilation, with an average of 42% of non-COVID-19 and 68% of COVID-19 patients receiving this treatment [22,23]. These are not assumed to vary by country. Second, for consistency, we determined optimal ratios of nurse and doctor FTEs per occupied bed informed by recommended staff-to-patient ratios [24–29] and applied the same staff ratios uniformly across all three countries. Maxima of 2.5 ICU beds per nurse and 8 ICU beds per doctor were assigned. Staff availability is reduced using a staff sickness rate to account for the impact of the virus, including self-isolation, on the workforce. These were calculated for each country using recent population infection rates and a modified hazard rate for healthcare workers, before being applied to the FTE values. This rate remains constant throughout the projection period and assumes effective personal protective equipment (PPE) to avoid nosocomial transmission.

Model equations and an illustration of the relationship between bed demand and deficits are provided in the Supplementary Material (Supplementary Figure 1).

2.3 Epidemiological models

Epidemiological projections were performed by country using a previously published stochastic compartmental age-structured SEIR model of SARS-CoV-2 transmission [12]. The model estimates the number of cases going through different severity pathways of COVID-19 disease over time. The model is fit to daily reported COVID-19 deaths from the European Centre for Disease Prevention and Control (ECDC) [31] in a Bayesian framework that has previously been described [32]. We provide a brief overview of the model fitting process for context here, before detailing model changes made in order to tailor the model to the three European countries explored. In overview, when fitting the model, we consider the time series of deaths, D_t, as a partially-observed Markov process, which is given by:

$$D_t = NB(\mu, \sigma)$$

where NB is the Negative Binomial distribution, with mean μ and standard deviation σ. σ can be expressed as $\sqrt{(\mu + \mu^2/r)}$, where r is the dispersion parameter and assumed to be equal to 2 to account for overdispersion. The model is fit to D_t by allowing 4 parameters to vary: the start date of the epidemic, t_0; the initial reproduction number in the absence of interventions, R_0; the effect size of mobility sourced from the Google Mobility Reports [33], on transmission, Mα; and the effect size of mobility on transmission after mobility increases from its minimum, Mω, which acts on increases in mobility relative to this minimum. In addition, we include pseudo-random walk parameters to reflect changes in human behaviour over time, which are introduced one week after the minimum in mobility, which serve to capture changes in transmission that are independent to mobility. We fit the model to the data using a Metropolis-Hastings Markov Chain Monte Carlo (MCMC)-based sampling scheme. Model projections were subsequently created by drawing 100 parameter sets from the posterior parameter space from model fitting. For all analysis conducted, the package *squire* v0.4.34 was used [34].

In order to better capture both the dynamics in mortality and ICU demand, the following changes were made to the default model parameters. When fitting the model to the epidemic in France, we used the age dependent infection fatality ratio (IFR), probability of hospitalisation and probability of requiring an ICU bed given hospitalisation estimated in a previous analysis of the first epidemic wave in France [35]. For Italy, we use the same parameters as for France, however, we incorporate a higher IFR as recently estimated from seroprevalence surveys [36]. For the model fitting in Germany, no changes were made from the default model parameters, which sufficiently captured the dynamics in mortality and ICU demand. For all countries, we observed significant triaging practices in order to ensure that ICU bed demand did not exceed capacity during the first peak in transmission, which we captured in the model by fitting a shorter duration of ICU stay during the first peak. The epidemiological models were assessed according to their fit to both official COVID-19 death data [37] and official ICU demand data [22,37].

2.4 Modelled scenarios

The calibrated model was used to project ICU demand from COVID-19 patients under different epidemic scenarios from 25th October 2020 to 1st March 2021, assuming no substantial impact from potential vaccines in this period. The spare capacity of each resource was then calculated under each of the 100 model simulations for every day of the projection period.

COVID-19 ICU demand, and by extension spare capacity, was modelled both under an unmitigated (no intervention) scenario and under a series of lockdown scenarios, where the use of a lockdown is designed to capture a period of increased suppression on transmission. We investigated a trigger-based approach to the initiation of lockdown. Lockdowns were initiated when the number of ICU beds required by COVID-19 patients exceeded a proportion of total baseline ICU bed provision (either 1/5, 1/4, 1/3 or 1/2). The length of each triggered lockdown was varied between 2, 3, 4, 5 and 6 weeks and under two levels of suppression, captured by a reduction in the effective reproduction number, R_t. First, it was assumed that subsequent lockdowns were as effective as the initial lockdown of Spring 2020 in each country, defined as the lowest R_t estimated during this period. We refer to these as lockdowns; however, this simply refers to a sustained period in which a reduction in R_t is observed. Second, given the uncertainty in the reduction in R_t likely to be observed in future lockdowns, we also explore a higher R_t=0.8 during lockdowns, which may reflect the lighter suppression measures implemented. During periods of no lockdown, R_t is assumed to return to the estimated value of R_t on the 25th October 2020. Lastly, we explored the impact of lockdowns being implemented in a non-reactive strategy, instead being introduced at the beginning of November for 2, 4 or 6 weeks before being lifted and reimplemented after 4 or 6 weeks. These were performed under the same two suppression R_t values as above.

Deficits in capacity occur when demand exceeds capacity. Under the baseline parameterisation of non-COVID-19 patient ICU occupancy, the deficit threshold is defined by spare capacity falling below zero. Reductions in this threshold, corresponding to an increase in spare capacity, owing to possible decreases in non-COVID-19 occupancy were evaluated in sensitivity analyses. Both a 30% reduction in baseline bed occupancy representing the cancellation of elective surgery [11,38], and the removal of all non-COVID-19 patients were considered. These alternative thresholds equate to a reduction of the baseline threshold and were calculated by subtracting the number of each resource freed under these occupancy levels from zero (the baseline threshold). Estimates of spare capacity over time and maximum deficits are presented as the median and 95% credible intervals (2.5th and 97.5th centiles) from the 100 spare capacity curves. Lastly, to characterise the impact of different lockdown triggers and length of lockdowns we compare the overall mean spare capacity of beds throughout the projection period, the mean number of days with bed deficits and the mean total time spent in lockdown from the same 100 spare capacity curves.

3. Results

3.1 Baseline capacity

The required baseline ICU capacity data were publicly available from official government publications, the OECD or academic papers, with the most recent data being from 2017-2018 (Table 1). The total number of baseline beds alongside annual average pre-pandemic non-COVID-19 occupancy is illustrated in Figure 1A.

3.2 COVID-19 ICU Demand

The calibrated epidemiological models accurately reproduced patterns of national counts of COVID-19 deaths and patients receiving ICU care to date in France, Germany and Italy [22,37] (Supplementary Figure 2). In each country, the unmitigated scenarios suggest that the number of COVID-19 patient numbers in ICU would overtake those seen during the first epidemic wave observed in each country between March-June 2020 (Supplementary Figure 3). France and Italy are estimated to observe a second peak ahead of Germany, which is partly due to the greater number of confirmed cases and deaths in France and Italy in recent months (Figures 1C and 1D).

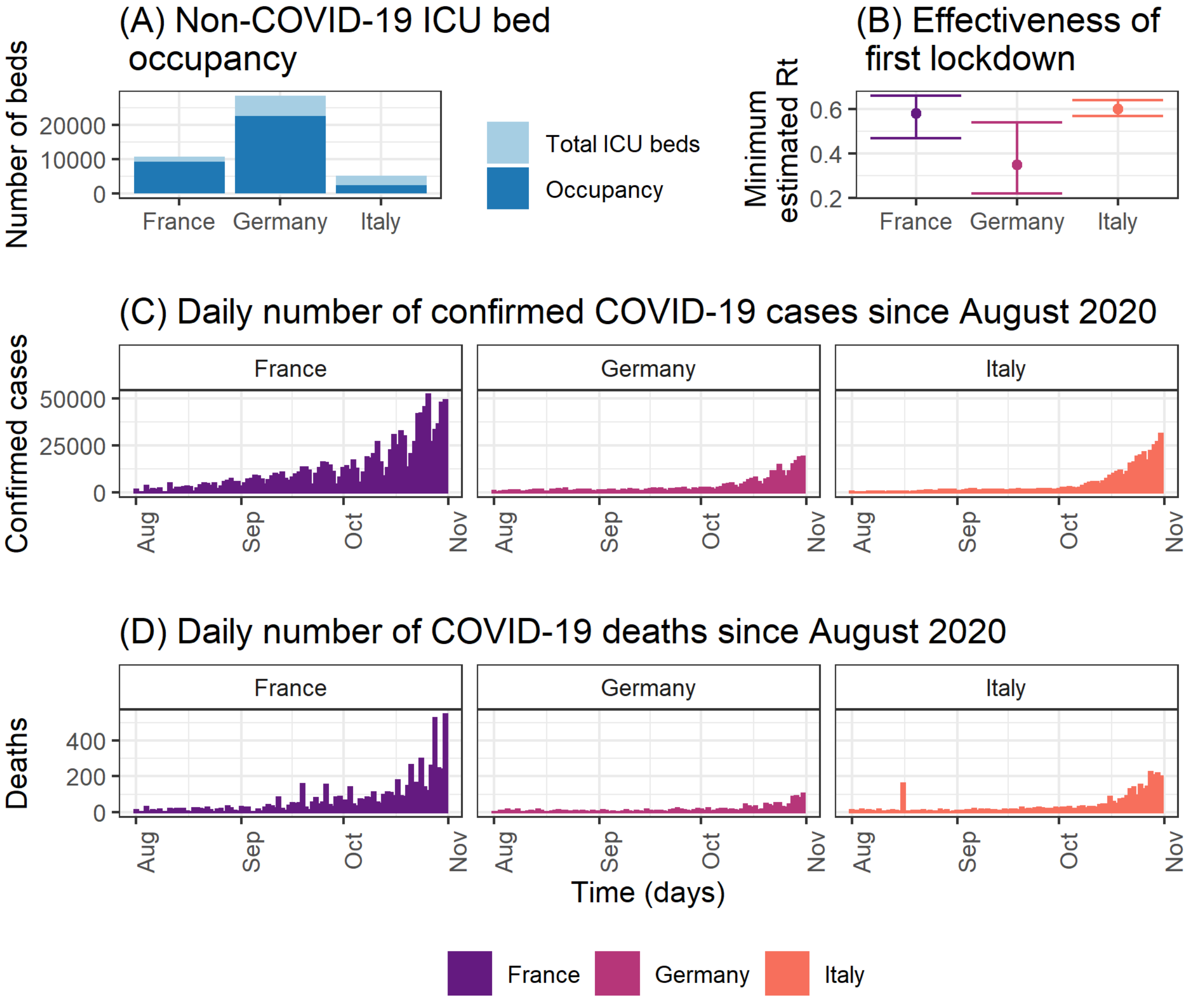

Figure 1: Drivers of the differences of spare capacity estimates in France, Germany and Italy. (A) The number of ICU beds and average annual non-COVID-19 patient occupancy at baseline. (B) The estimated minimum value of R_t from the implementation of the first national lockdown (occurring in March 2020 in Italy; May 2020 in France and Germany) with 95% credible intervals. (C) The daily number of confirmed COVID-19 cases across August to November 2020. (D) The daily number of COVID-19 registered deaths across August to November 2020.

Table 1: Baseline capacity of ICU resources in France, Germany and Italy and parameters of the capacity model with sources.

Country	Variable	Value	Year of estimate	Details	Source
France	Total beds	10640	2018	Beds per 100,000 population applied to 2020 population size.	OECD Intensive Care Beds Capacity [13]; Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat [39]
	Bed occupancy (%)*	87%	2011		Published country-wide study of ICU wards [40]
	Total doctors (FTE)	2047	2018	Data represent annual average FTEs of doctors of various specialties working in ICU. Excludes doctors who are still in training (“internes”).	Ministry of Health Annual Statistic of Health Establishments [14]
	Total nurses (FTE)	12332	2018	Data represent annual average FTEs of all nurses working in ICU (irrespective of their employer). Includes nurses with and without specialisation.	Ministry of Health SAE [14]
	Total ventilators	7241	2009	Estimated by applying ratio of ventilators per ICU bed reported in 2009 to the 2018 number of ICU beds. Data represent (fixed and mobile) ventilators in ICU units only.	Survey by the Ministry of Health [41]
Germany	Total beds	28403	2017	Beds per 100,000 population applied to 2020 population size.	OECD Intensive Care Beds Capacity [13]; Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat [39]
	Bed occupancy (%)*	79%	2017		Federal Statistical Office [15]
	Total doctors (FTE)	15944	2015	Estimated by applying average ICU doctor FTE per hospital to the total number of hospitals in 2015 and scaled to 2017 assuming same increase as for ICU beds between 2015 and 2017. It is unclear whether this estimate includes junior doctors.	Report from the German Hospital Institute [17]
	Total nurses (FTE)	58206	2015	Estimated by applying the ratio of ICU nurse FTEs per ICU beds reported in 2015 to the 2017 number of beds.	Report from the German Hospital Institute [17]
	Total ventilators	25000	2020	Represents number of ventilators before the COVID-19 pandemic.	COVID-19 Health Systems Response Monitor, citing Ministry of Health [3]
Italy	Total beds	5200	2020	Beds per 100,000 population applied to 2020 population size.	OECD Intensive Care Beds Capacity [13]; Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat [39]
	Bed occupancy (%)*	48%	2017		Ministry of Health [16]
	Total doctors (FTE)	2415	2017	Data on doctors employed in ICU were not directly available. An estimate of the headcount of ICU doctors was derived by applying the proportion of hospital doctors	Ministry of Health [16]

Country	**Variable**	**Value**	**Year of estimate**	**Details**	**Source**
				working in ICU from Spain (2.9%) to the total doctors employed in hospital in Italy. Converted to FTE using the multiplier derived from OECD physician dataset.[†]	
	Total nurses (FTE)	5841	2017	Data on nurses employed in ICU were not directly available. An estimate of the headcount of ICU nurses was derived by applying the proportion of hospital doctors working in ICU from Spain (2.9%) to the total nurses employed in hospital in Italy. Converted to FTE using the multiplier derived from OECD nurse dataset.[†]	Ministry of Health [16]
	Total ventilators	17011	2017		Ministry of Health [16]
Hospital capacity model parameters					
France	Staff sickness	14.6%	2020	The daily population infection risk was determined using ECDC 14-day cumulative number of COVID-19 cases per 100,000 and country population estimates. This risk was inflated for healthcare workers, who are estimated to be 3.4 times more likely to be infected than the general population.	ECDC COVID-19 data [20]; Nguyen et al. [21]
Germany	Staff sickness	3.3%	2020		
Italy	Staff sickness	6.9%	2020		
All	Proportion of COVID-19 patients requiring ventilation	68%		The mean daily proportion of COVID-19 ICU patients using a ventilator was calculated from daily situation reports published between 1 April and 10 June 2020.	Robert Koch Institut [22]
All	Proportion of non-COVID-19 patients requiring ventilation	42%		Proportion of patients with 24h+ stay in ICU on mechanical ventilation on the assessment day.	Study in German ICUs [23]
All	ICU bed to nurse ratio	2.5:1		Recommended or official ICU bed to nurse ratio in France, Germany and Italy.	Various sources [24–27]
All	ICU bed to doctor ratio	8:1		Recommended ICU bed to doctor ratio based on review of evidence from various countries.	Faculty of Intensive Care Medicine [28,29]

* Taken as upper bound of this variable. Reductions in the deficit in capacity threshold (30% reduction in these figures to represent cancellation of electives and 0% non-COVID-19 occupancy) were considered in order to account for uncertainty surrounding demand for care from non-COVID-19 patients this winter (see *Methods: Modelled Scenarios)*.

[†] In the absence of country-specific data, a multiplier to convert headcounts to FTE was derived from the 2017 OECD datasets of "Physicians employed in hospital" and "Professional nurses and midwives employed in hospitals" by taking the median multiplier for all Western European countries (0.896 and 0.868, respectively) [30]

3.3 Spare capacity in ICUs

Model results of ICU capacity constraints in France, Germany and Italy under no mitigation and different suppression scenarios sustained for four weeks when triggered are shown in Figures 2 – 4. Across the three countries, beds were consistently the most constrained ICU resource. Without mitigation of the pandemic, all three countries are estimated to experience significant shortages of ICU beds over the winter season (Table 2), with the median maximum deficits corresponding to the same number as the existing bed capacity in Germany and France, and 2.7 times the existing bed capacity in Italy. In France and Italy, bed deficits were projected to last for almost the entire winter season, peaking in January, whereas in Germany they start around December and continue growing throughout the projection period.

Ventilators reached smaller median maximum deficits of approximately 5,000 and 9,500 under the unmitigated scenario in France and Germany, respectively. The projections suggest no staff shortages in Germany, in contrast to a median maximum deficit of 941 doctor FTEs in France and 201 doctor FTEs and 2,401 nurse FTEs in Italy (Table 2). However, in contrast to bed deficits, reduction in baseline occupancy through cancellation of elective surgery was estimated to be sufficient to restore positive spare capacity of staff and ventilators in the three countries (Figures 2 – 4). Similarly, with strong suppression measures in the lockdown scenarios, our estimates suggest that these resources generally did not reach a deficit in France, Germany or Italy during the projection period (Table 2).

The modelled suppression scenarios highlight the large effect reactive lockdown measures can have on mitigating shortfalls in ICU bed capacity. For a four-week lockdown as effective as during the first peak, the magnitude and duration of shortages in ICU bed capacity varied across countries and trigger thresholds, but reductions compared to the unmitigated scenario were large throughout (Table 2, Figures 2 – 4). Depending on the trigger threshold, the lockdown scenario reduced median maximum bed deficits between 56-89% and 65-96% and reduced the median duration of deficits between 33-65% and 30-81% in France and Germany, respectively. Due to the comparatively lower assumed ICU bed occupancy by non-COVID-19 patients in Italy, reactive lockdowns only resulted in deficits in beds for the highest ICU trigger threshold.

Under the 1/2 ICU capacity trigger threshold lockdown scenario, remaining median maximum deficits of 4,741, 10,805 and 889 beds (representing 45%, 38% and 17% of baseline bed capacity respectively) and median durations of deficit of 85, 51 and 29 days were estimated in France, Germany and Italy, respectively. However, on average these deficits were estimated to be prevented by additional reductions in baseline ICU occupancy through cancellation of elective surgery (Figures 2 – 4).

3.4 Effect of varying trigger thresholds, duration and effectiveness on the impact and time in lockdown

The impact of, and total time spent under, a reactive lockdown was compared under different assumptions of trigger thresholds, lockdown duration and lockdown effectiveness.

Spare ICU bed capacity varied substantially between the highest (1/2 ICU capacity) and lowest (1/5 ICU capacity) threshold used to trigger a lockdown. In France and Germany, the highest trigger threshold resulted in increases of 3 and 9 times the maximum deficits under the lowest thresholds, respectively (Table 2), and the lowest trigger threshold consistently resulted in the shortest time with a shortage of beds (Figure 5). In Italy, the lowest trigger threshold similarly resulted in the largest median spare ICU bed capacity over the projection period, and bed deficits were prevented altogether

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under all but the 1/2 ICU capacity threshold. This difference between countries is largely explained by the substantially lower baseline occupancy of ICU beds in Italy by non-COVID patients (48%) compared to France (87%) and Germany (79%) (Figure 1A). The lower baseline occupancy affords reactive strategies more time for the impact of lockdown measures to have an effect before reaching capacity limits.

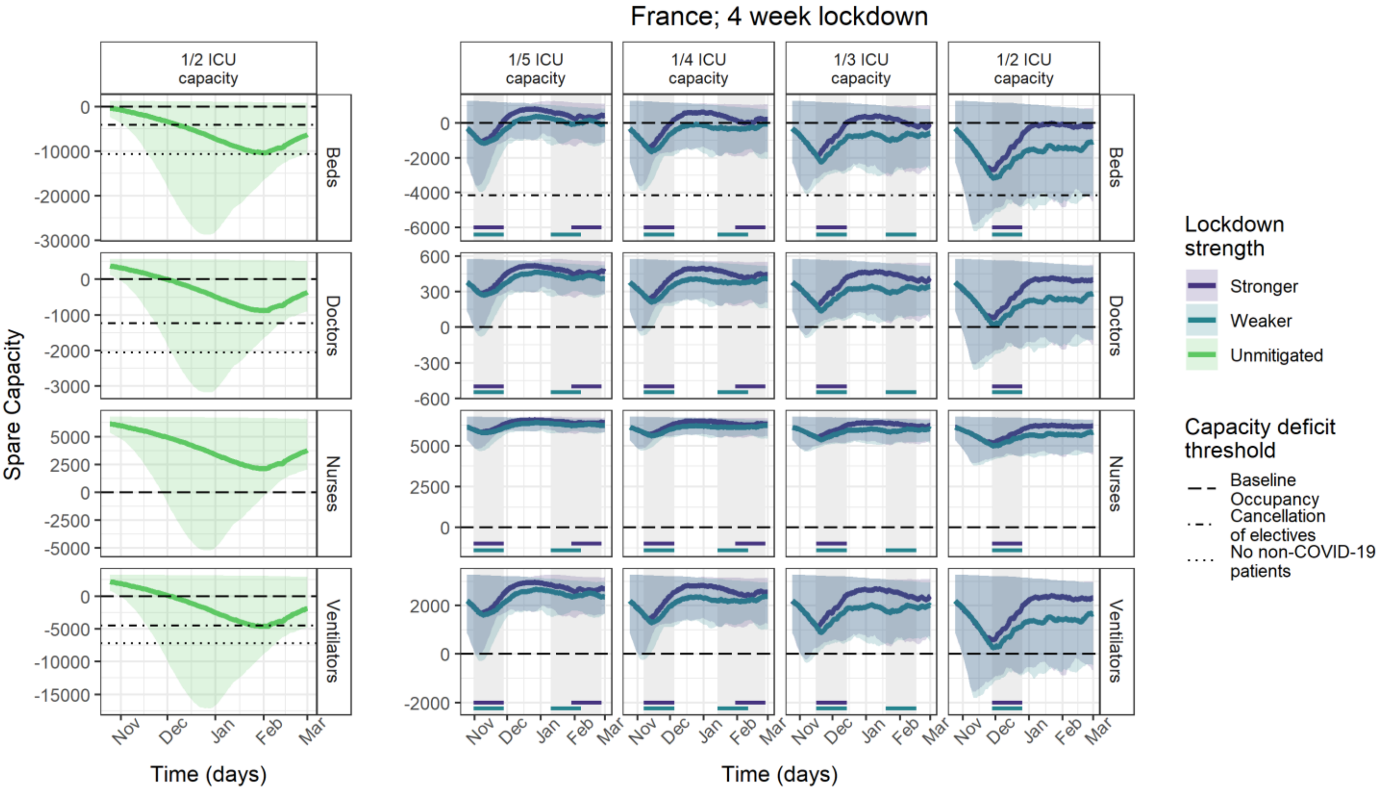

Figure 2: Spare capacity estimates (median; 95% credible intervals) for France under the unmitigated scenario and the four reactive lockdown scenarios under two different suppression levels (stronger: lockdown R_t =0.58; weaker: lockdown R_t =0.8) and specified lockdown length of four weeks. Grey shaded areas indicate periods of lockdown with horizontal coloured lines indicating the corresponding lockdown strength under which this was triggered. The dashed line (spare capacity = 0) indicates the threshold between positive spare capacity and a deficit in capacity. The dot-dashed and dotted lines indicate an effective reduction in this threshold owing to the cancellation of elective surgery and the removal of all non-COVID-19 patients respectively, allowing the reallocation of resources to COVID-19 patients.

In contrast to the different trigger thresholds, altering the length of each lockdown between two and six weeks resulted in minimal reductions in the maximum deficits under equivalent scenarios (Supplementary Figures 4 – 9, Supplementary Tables 2 – 3). This is largely due to lockdowns needing to be implemented immediately in the scenarios with the lowest ICU trigger thresholds, reflecting that ICU demand is already significantly increased at the beginning of the projection period. However, average spare ICU bed capacity tended to increase with lockdown length, notably in France, while the relationship between lockdown length and number of days in deficits varied by country. In Germany, the number of days of bed deficits are not dependent on lockdown length due to the particularly low level of R_t achieved during the first lockdown (Figure 1B, Figure 5).

A weaker lockdown also resulted in only small increases in the maximum bed deficits compared to the stronger lockdown for a given trigger threshold (Table 2), except for Germany where the lockdown during the first peak was particularly effective (Figure 1B). However, expected bed deficits persisted for longer under the weaker lockdown scenarios in all three countries, despite the total time in lockdown generally increasing under each trigger strategy (Supplementary Figure 10).

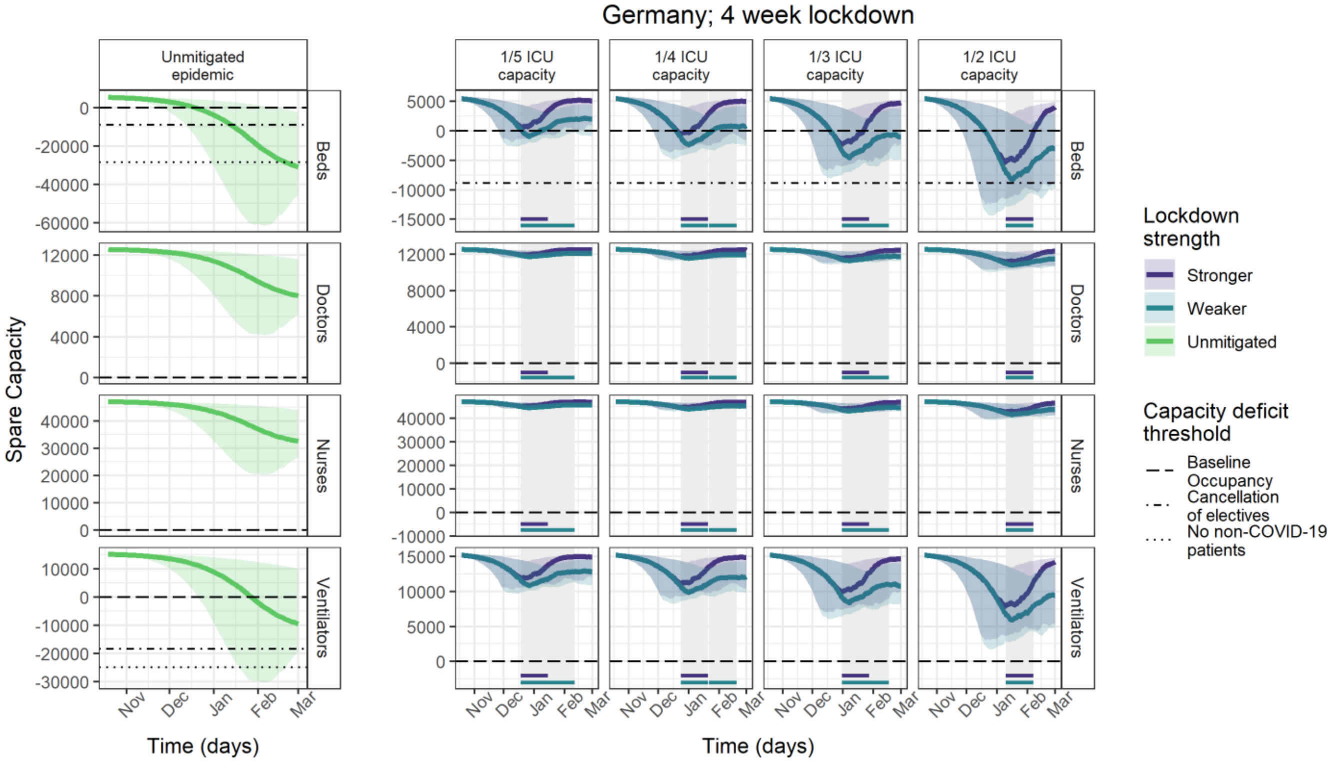

Figure 3: Spare capacity estimates (median; 95% credible intervals) for Germany under the unmitigated scenario and the four reactive lockdown scenarios under two different suppression levels (stronger: lockdown $R_t = 0.35$; weaker: lockdown $R_t = 0.8$) and specified lockdown length of four weeks. Grey shaded areas indicate periods of lockdown with horizontal coloured lines indicating the corresponding lockdown strength under which this was triggered. The dashed line (spare capacity = 0) indicates the threshold between positive spare capacity and a deficit in capacity. The dot-dashed and dotted lines indicate an effective reduction in this threshold owing to the cancellation of elective surgery and the removal of all non-COVID-19 patients respectively, allowing the reallocation of resources to COVID-19 patients.

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Across the three countries, the total time spent in lockdown in France and Italy over the projection period increases slightly under lower trigger thresholds (Figure 5). In Germany, the effectiveness of the first lockdown results in a similar average amount of time in lockdown under different trigger thresholds. In Italy, the similarity in the two- and four-week lockdown length scenarios reflects that successive lockdowns are quickly implemented in the two-week lockdown scenario, with a two-week lockdown unable to reduce transmission enough to reduce ICU demand below the ICU trigger threshold. The comparatively lower assumed total ICU capacity in Italy (5,200 beds) compared to France (10,640 beds) and Germany (28,403 beds) also resulted in more frequent lockdowns being implemented in Italy, with more than 40 days predicted to be spent in lockdown before the 1st March. Lockdowns of pre-determined fixed start and end dates were generally estimated to have a similar effect on reducing deficits, but with slightly increased total amount of time spent in lockdown over the period (Supplementary Figures 11 – 13).

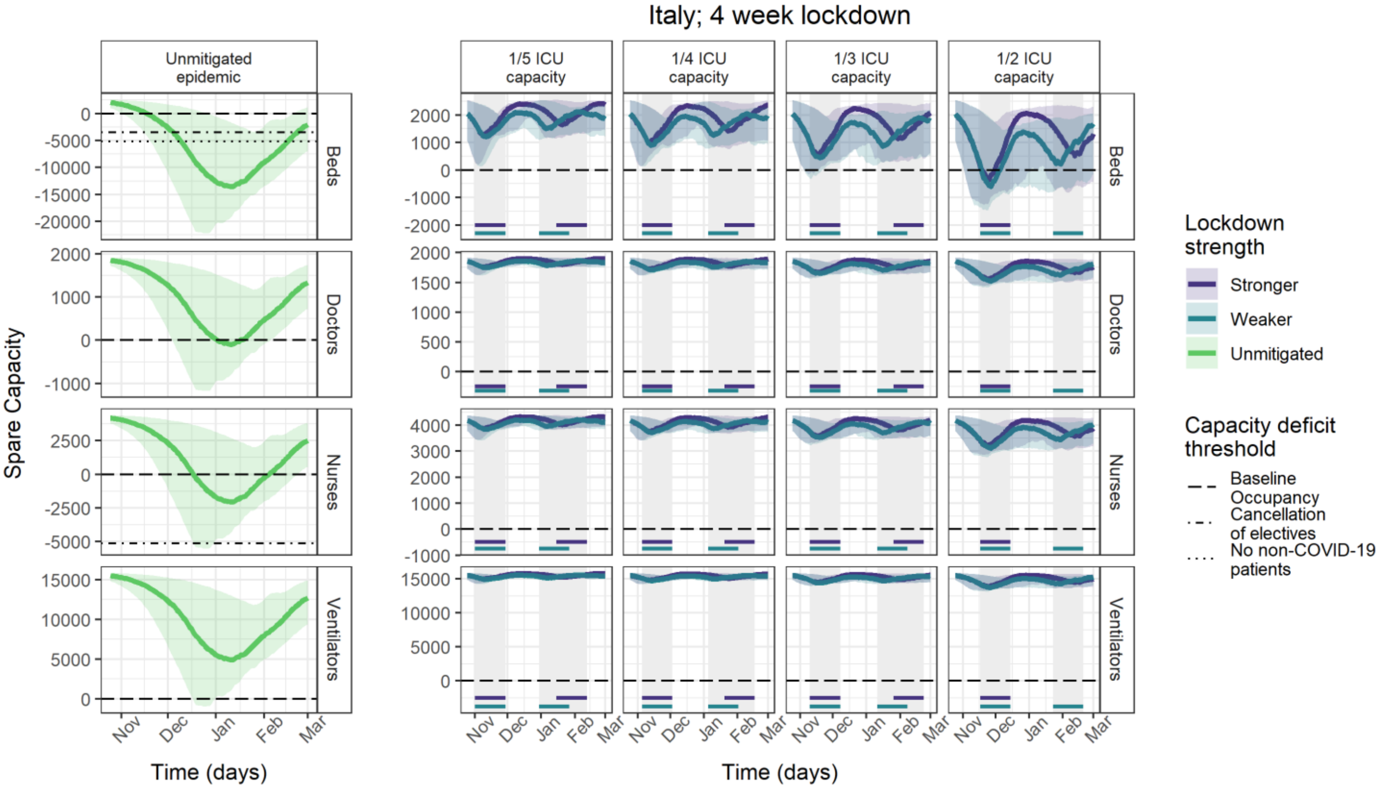

Figure 4: Spare capacity estimates (median; 95% credible intervals) for Italy under the unmitigated scenario and the four reactive lockdown scenarios under two different suppression levels (stronger: lockdown R_t = 0.6; weaker: lockdown R_t = 0.8) and specified lockdown length of four weeks. Grey shaded areas indicate periods of lockdown with horizontal coloured lines indicating the corresponding lockdown strength under which this was triggered. The dashed line (spare capacity = 0) indicates the threshold between positive spare capacity and a deficit in capacity. The dot-dashed and dotted lines indicate an effective reduction in this threshold owing to the cancellation of elective surgery and the removal of all non-COVID-19 patients respectively, allowing the reallocation of resources to COVID-19 patients.

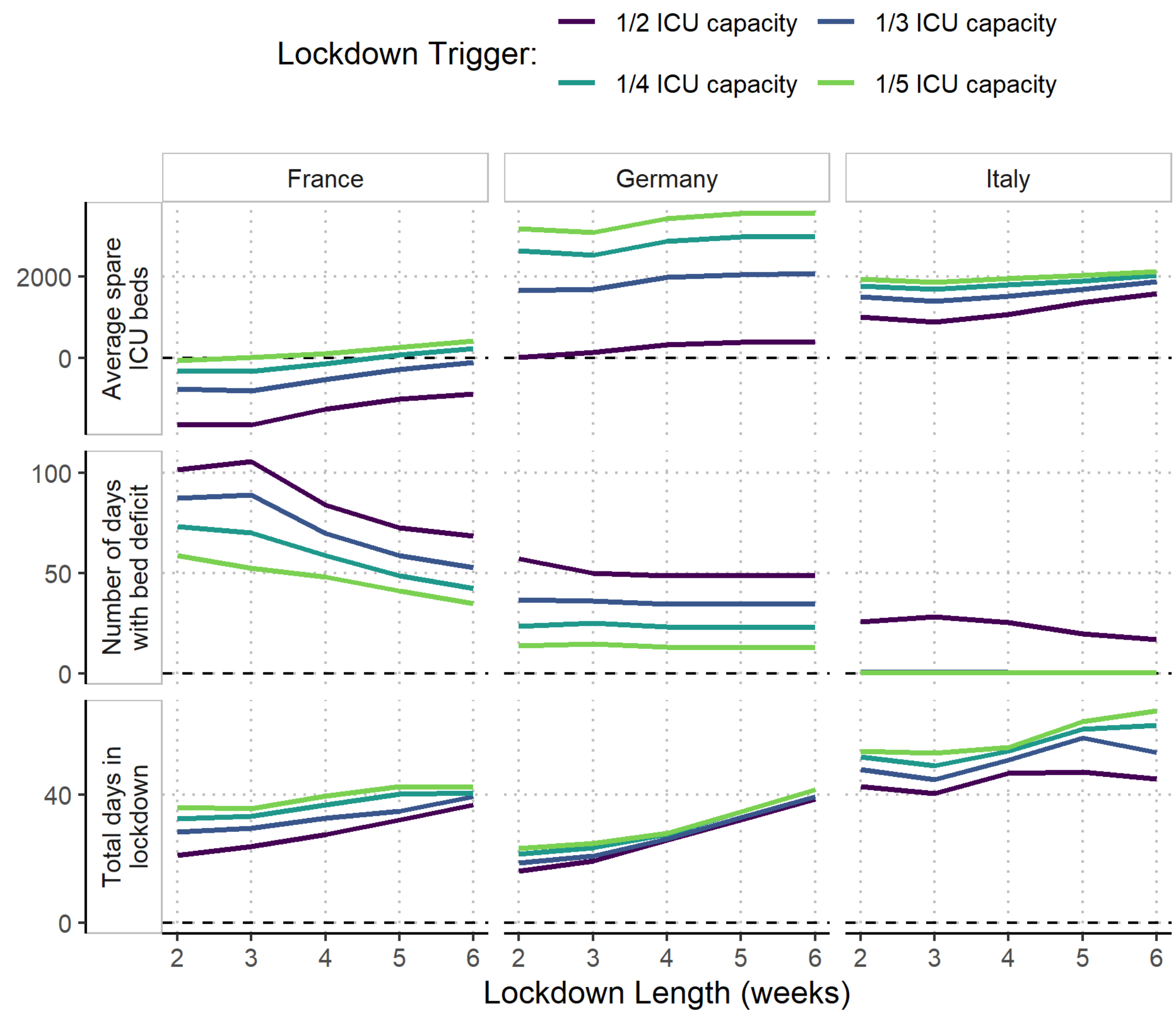

Figure 5: Impact of the duration and timing of lockdowns on spare capacity of ICU beds. The effect of lockdown length on the average spare capacity of ICU beds; the number of days with a deficit in ICU beds and the total number of days spent in lockdown is shown for France, Germany and Italy under the stronger suppression scenarios (France: R_t = 0.58; Germany: R_t = 0.35; Italy: R_t = 0.6). For each plot the mean of 100 simulation repetitions over the projection period (25th October 2020 – 1st March 2021) is shown.

Table 2: The median estimated maximum capacity deficit and number of days in deficit with 95% credible intervals relative to baseline occupancy under the unmitigated and reactive scenarios under two suppression levels (stronger*: lockdown R_t at levels estimated during first peak; weaker: lockdown $R_t = 0.8$) for each country and capacity resource under lockdown periods lasting for four weeks.

Country	Resource	Result	Unmitigated	Stronger lockdown*				Weaker lockdown			
				1/5 ICU capacity	1/4 ICU capacity	1/3 ICU capacity	1/2 ICU capacity	1/5 ICU capacity	1/4 ICU capacity	1/3 ICU capacity	1/2 ICU capacity
France	Beds	Maximum capacity deficit	10869 (0 – 28902)	1217 (0 – 3617)	1771 (0 – 3641)	2808 (0 – 3888)	4741 (0 – 5963)	1278 (0 – 3980)	1888 (0 – 3906)	2915 (0 – 4079)	4859 (0 – 6327)
		Time in deficit (days)	*127 (0 – 127)*	*45 (0 – 73)*	*60 (0 – 83)*	*70 (0 – 98)*	*85 (0 – 125)*	*72 (0 – 93)*	*95 (0 – 118)*	*120 (0 – 127)*	*127 (0 – 127)*
	Doctors	Maximum capacity deficit	941 (0 – 3195)	0 (0 – 35)	0 (0 – 37)	0 (0 – 68)	0 (0 – 174)	0 (0 – 80)	0 (0 – 71)	0 (0 – 92)	190 (0 – 373)
		Time in deficit (days)	*91 (0 – 118)*	*0 (0 – 8)*	*0 (0 – 9)*	*0 (0 – 14)*	*23 (0 – 49)*	*0 (0 – 15)*	*0 (0 – 15)*	*0 (0 – 17)*	*26 (0 – 59)*
	Nurses	Maximum capacity deficit	0 (0 – 5288)	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
		Time in deficit (days)	*0 (0 – 60)*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*
	Ventilators	Maximum capacity deficit	4978 (0 – 17240)	0 (0 – 47)	0 (0 – 63)	0 (0 – 231)	811 (0 – 1642)	0 (0 – 294)	0 (0 – 244)	0 (0 – 361)	892 (0 – 1889)
		Time in deficit (days)	*89 (0 – 117)*	*0 (0 – 4)*	*0 (0 – 4)*	*0 (0 – 9)*	*20 (0 – 45)*	*0 (0 – 13)*	*0 (0 – 12)*	*0 (0 – 16)*	*24 (0 – 54)*
Germany	Beds	Maximum capacity deficit	30850 (2269 – 61583)	1081 (336 – 2000)	2749 (1744 – 3923)	5491 (1991 – 7042)	10805 (1991 – 13132)	1598 (547 – 2835)	3385 (1891 – 4845)	6296 (1991 – 8476)	11554 (1991 – 14759)
		Time in deficit (days)	*72 (16 – 96)*	*14 (7 – 18)*	*24 (17 – 26)*	*36 (16 – 40)*	*51 (16 – 58)*	*28 (14 – 43)*	*41 (16 – 67)*	*56 (16 – 86)*	*71 (16 – 91)*
	Doctors	Maximum capacity deficit	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
		Time in deficit (days)	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*
	Nurses	Maximum capacity deficit	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
		Time in deficit (days)	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*

Country	Resource	Result	Unmitigated	Stronger lockdown*				Weaker lockdown			
				1/5 ICU capacity	1/4 ICU capacity	1/3 ICU capacity	1/2 ICU capacity	1/5 ICU capacity	1/4 ICU capacity	1/3 ICU capacity	1/2 ICU capacity
Germany	Ventilators	Maximum capacity deficit	9458 (0 – 30357)	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
		Time in deficit (days)	*33* *(0 – 71)*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*
Italy	Beds	Maximum capacity deficit	14402 (5777 – 22822)	0[†]	0[†]	*0* *(0 – 183)*	889 (379 – 1348)	0[†]	0[†]	0 (0 – 357)	995 (488 – 1608)
		Time in deficit (days)	*104* *(64 – 114)*	*0[†]*	*0[†]*	*0* *(0 – 8)*	*29* *(12 – 37)*	*0[†]*	*0[†]*	*0* *(0 – 14)*	*36* *(15 – 46)*
	Doctors	Maximum capacity deficit	201 (0 – 1254)	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
		Time in deficit (days)	*23* *(0 – 45)*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*
	Nurses	Maximum capacity deficit	2401 (0 – 5769)	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
		Time in deficit (days)	*50* *(0 – 60)*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*
	Ventilators	Maximum capacity deficit	0 (0 – 1396)	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
		Time in deficit (days)	*0* *(0 – 18)*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*

**France: R_t = 0.58; Germany: R_t = 0.35; Italy: R_t = 0.6.*

[†] *No deficits projected under any of the 100 simulation replicates.*

4. Discussion

In this study we examined potential constraints of four key ICU resources in France, Germany, and Italy under different scenarios of epidemic progression over the winter of 2020/21. The unmitigated scenarios resulted in COVID-19 ICU patient numbers exceeding those seen in the first peak, thus inducing capacity deficits. Triggered lockdown scenarios substantially reduced these deficits. Our study has found that across all epidemic scenarios, beds are consistently the most constrained ICU resource. Preparing for a potential shortfall in beds should be a priority for all national and regional healthcare providers this winter period. Even without suppression strategies, a simultaneous deficit in all four resources (beds, doctors, nurses and ventilators) is not predicted by this model over the projection horizon for any country. Projections of constraints in doctors, nurses and ventilators vary across countries, but were found to be manageable through the implementation of lockdowns, as well through reductions in baseline bed occupancy, for example via the cancellation of elective surgery.

The results suggest that lockdowns triggered based on ICU capacity could lead to large increases in spare bed capacity during the winter season compared to no intervention, reducing deficits in all countries to lower levels which can then be managed with hospital provision interventions. Lower trigger thresholds generally minimise deficits by instigating lockdowns earlier, but their impact is highly dependent on baseline ICU bed numbers and average non-COVID-19 patient occupancy. For example, Italy, with a lower average occupancy, can accommodate greater demand from COVID-19 patients relative to the total ICU bed capacity. For a given trigger threshold, increasing the length of lockdown only provides small decreases in the number of days in deficits. On the other hand, a lockdown less effective than the first peak reduces deficits compared to the unmitigated scenario, but could also lead to an increase in the amount of time spent in lockdown and the requirement of a lower trigger threshold compared to a stronger lockdown. Our results highlight the dependencies between these metrics, suggesting that absolute benefits of different strategies must be weighed against the feasibility and drawbacks of increased amount of time spent in lockdown.

Our study integrates two critical frameworks of significance in the control of the pandemic: hospital capacity estimation and epidemiological simulations. While previous studies have used epidemiological modelling to project ICU demand, data on hospital capacity were limited to bed numbers, and failed to consider the other key ICU resources and the dependencies between them [10]. Further strengths of this study include the use of a dual-demand model considering changes in demand for ICU care of both COVID-19 and non-COVID-19 patients, and the incorporation of COVID-19-related staff sickness which has shown to result in substantial additional constraints [42]. Our results also provide insights into how requirements for ICU capacity management may vary between countries with different healthcare systems and epidemic trajectories. Specifically, this allows us to consider how to combine interventions to alleviate strain on hospital capacity effectively.

First, the number of COVID-19 patients can be reduced by NPIs, such as lockdowns and physical distancing, as demonstrated in this study. This strategy was widely deployed at the beginning of the epidemic and has been recently reintroduced in the countries under consideration here [43–46]. Whilst lockdowns have proved to be effective in controlling COVID-19 epidemics across European settings [43], their wider, indirect impacts (on the economy, children's education and broader population health [1]) risk inducing a public health and economic crisis larger than the one it aims to supress. Although reactive lockdowns can be triggered based on clear, logical criteria, they are likely to be disruptive and difficult to implement as they require accurate timely data and there is uncertainty at the time of implementation in what their duration will be. Additionally, they still introduce 20-60 days of lockdowns depending on the country. Our research suggests that scheduled lockdowns, with pre-specified start and end dates can also successfully overcome potential capacity deficits but with a greater amount of time in lockdown (35-84 days) (Supplementary Figures 11 – 13). Such a strategy may be less socially disruptive by removing some uncertainty and may prove an effective strategy in countries in which fragmented health systems may lead to delays in implementing reactive lockdown strategies and where data on hospital occupancy is poor. However, we note that the success of such lockdowns is much more dependent on ensuring a stronger level of suppression. Furthermore, the efficacy of future lockdowns across different countries is highly variable. On the one hand, the experience with lockdowns during the first wave may help countries to implement them more effectively going forward. On the other hand, there is evidence to suggest that the population may be less likely to adhere strictly to control policies with each successive lockdown [47]. This makes the long-term tenability of this strategy unclear. Nevertheless, in this study even weaker reactive lockdown scenarios led to substantial reductions in ICU bed shortages compared to the unmitigated scenario.

Second, capacity deficits may be partially managed by reducing the number of non-COVID-19 patients admitted to ICU. This is primarily achieved through the cancellation of elective surgery [10], although our results suggest that on its own this would not be sufficient to address the deficits in ICU bed capacity in France, Germany and Italy over the winter season. Moreover, this policy pushes the healthcare burden onto a different group of patients, possibly resulting in excess morbidity and mortality [11]. National-level triaging criteria for the allocation of ICU resources in the event of demand outstripping supply were also introduced in some places, for example in Italy [48]. However, this raises complex ethical issues. Ultimately, under such strategies the burden is redistributed rather than alleviated and it is unclear whether the short-term benefits will outweigh the long-term costs.

Finally, as an alternative to managing patient demand, ICU capacity can be increased through supply-side hospital provision interventions. This was a common approach at the beginning of the outbreak [10] and are often most effective when implemented simultaneously [11]. For example, countries achieved increases in bed numbers by setting up surge capacity (such as field hospitals and requisitioning the use of private healthcare facilities) to treat patients with complex care needs [2–4]. Our results suggest that such measures to increase bed supply may still be needed to address small remaining deficits even with implementation of a lockdown but, critically, could prevent the need to cancel elective surgery. Additionally, the results also suggest that generally there is a sufficient capacity of staff and ventilators to fully operationalise any additional required surge beds [11,49]. Although often expensive and with logistical challenges ahead of implementation, it is likely that hospital provision interventions will continue to be a vitally important tool in terms of expanding ICU capacity to ensure the provision of care to all patients during the pandemic this winter.

There are some limitations of this study. First, data were sometimes missing or of low quality. Due to poor documentation at national level, it was not possible to quantify the expansion in hospital capacity beyond pre-pandemic levels during the first surge of COVID-19 patients. As such, modelled capacity deficits may be overestimated, although many of the implemented hospital provision interventions were temporary. Data from the first peaks in Spring 2020 in the respective countries are used to parameterise the model, e.g. ventilation requirements, but these may be different in the future due to changes in clinical practice. For example, the use of dexamethasone for treating individuals receiving oxygen has been shown to decrease COVID-19 mortality [50]. Data on the use of dexamethasone over time in each country are lacking, however, the resultant reduction on IFR could explain the small underestimation of ICU demand at the beginning of the second wave (Supplementary Figure 2). Second, modelled estimates of the spare capacity of nurses and doctors are likely to be uncertain as ward-based bed-to-patient ratios have previously been shown to be inconsistent in approximating national staffing requirements [51,52], and there is no single recommended methodological standard for staff ratios across the countries [53]. However, our unmitigated scenario results broadly align with a recent study analysing healthcare pressure in Europe due to the COVID-19 pandemic [54]. Third, the model does not account for cohorting of COVID-19 and non-COVID-19 patients within hospitals. Although essential to prevent nosocomial transmission, this likely translates to a reduction of available resources. However, the extent to which this occurs depends on a hospital-by-hospital basis and hence is beyond the scope of this analysis. Lastly, the comparison between different lockdown triggers and lengths is limited by having a fixed end date for comparison (1st March 2021). Consequently, the timing of lockdowns within this evaluation period leads to non-monotonic relationship between lockdown length and the spare capacity of ICU beds.

While the trajectory of the COVID-19 pandemic over winter cannot be known yet, our findings suggest that a combination of strategies will be required to overcome potential ICU capacity deficits and ensure the treatment of all patients, regardless of COVID-19 status, in France, Germany and Italy. Although this analysis focussed on these three countries, similar questions surrounding the required winter interventions must now be answered across Europe, with substantial second waves being observed across the continent, which have eclipsed the first wave in several countries. The large trade-offs inherent in each strategy should not be underestimated, and careful, continuous decision-making by national policymakers will be required across the winter period 2020/21.

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6. Supplementary Material

6.1 Calculation of spare capacity

The calculations underpinning spare capacity estimates as set out in *Methods* are described mathematically below. An overview of the notation used is provided in Supplementary Table 1, while Supplementary Figure 1 provides an illustration of the relationship between ICU bed demand and capacity.

Supplementary Table 1: Notation used in spare capacity equations.

Subscripts	
$\boldsymbol{c}$	Refers to capacity variable (beds, nurses, doctors, ventilators)
$\boldsymbol{t}$	Refers to the day in the projection period
$\boldsymbol{r}$	Refers to the simulation replicate (ranging from 1 to 100)
Variables	
$\boldsymbol{B}$	Total number of beds
$\boldsymbol{P_{t.r}^{COVID}}$	Expected bed occupancy of COVID-19 patients at time t under replicate r
$\boldsymbol{P^{non-COVID}}$	Average bed occupancy for non-COVID-19 patients
$\boldsymbol{V}$	The number of ventilators
$\boldsymbol{N}$	Total nurse FTE
$\boldsymbol{D}$	Total doctor FTE
Model Parameters	
$\boldsymbol{pV^{COVID}}$	Percentage of COVID-19 patients requiring a ventilator
$\boldsymbol{pV^{non-COVID}}$	Percentage of non-COVID-19 patients requiring a ventilator
$\boldsymbol{rN}$	Maximum number of ICU beds that a nurse could safely look after
$\boldsymbol{rD}$	Maximum number of ICU beds that a doctor could safely look after
$\boldsymbol{s_N}$	Rate of COVID-19 related nurse sickness or absence
$\boldsymbol{s_D}$	Rate of COVID-19 related doctor sickness or absence

The primary outcome was the spare capacity resource (beds, doctors, nurses and ventilators) at each point of the projection period, which was calculated as:

$$Spare\ capacity_{c,t,r} = Resource\ available_{c,t,r} - Resource\ needed_{c,t,r}$$

$$for\ c \in \{beds, doctors, nurses, ventilators\}$$

$$for\ t \in \{projection\ period\}$$

$$for\ r \in \{1, \dots, 100\}$$

For the four resources, this equation translates to the following:

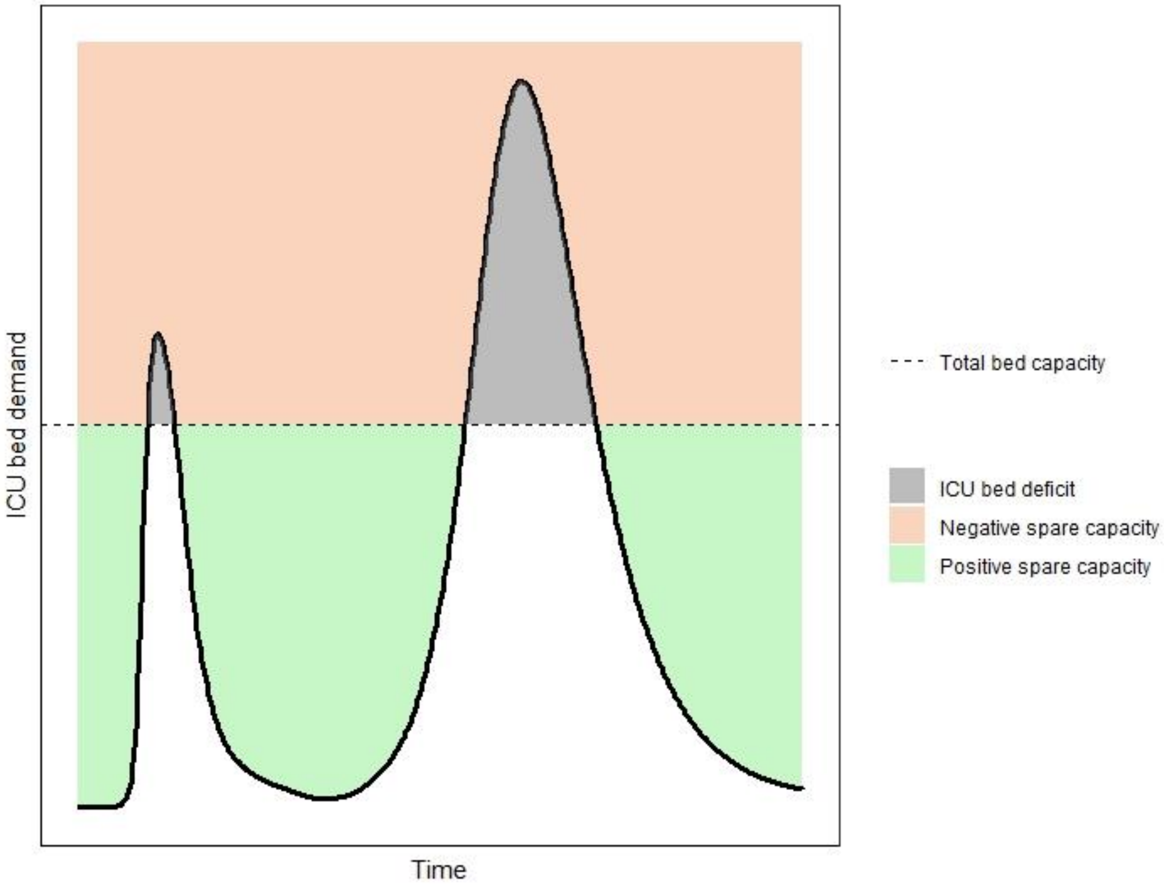
$$Spare\ capacity\ of\ beds_{t,r} = B - Beds\ needed_{t,r}$$

where: $Beds\ needed_{t,r} = P_{t,r}^{COVID} + P^{non-COVID}$

$$Spare\ capacity\ of\ doctors_t = ((1 - s_D) \times D) - \frac{Beds\ needed_{t,r}}{rD}$$

$$Spare\ capacity\ of\ nurses_{t,r} = ((1 - s_N) \times N) - \frac{Beds\ needed_{t,r}}{rN}$$

$$Spare\ capacity\ of\ ventilators_{t,r} = V - (pV^{COVID} \times P_{t,r}^{COVID} + pV^{non-COVID} \times P^{non-COVID})$$

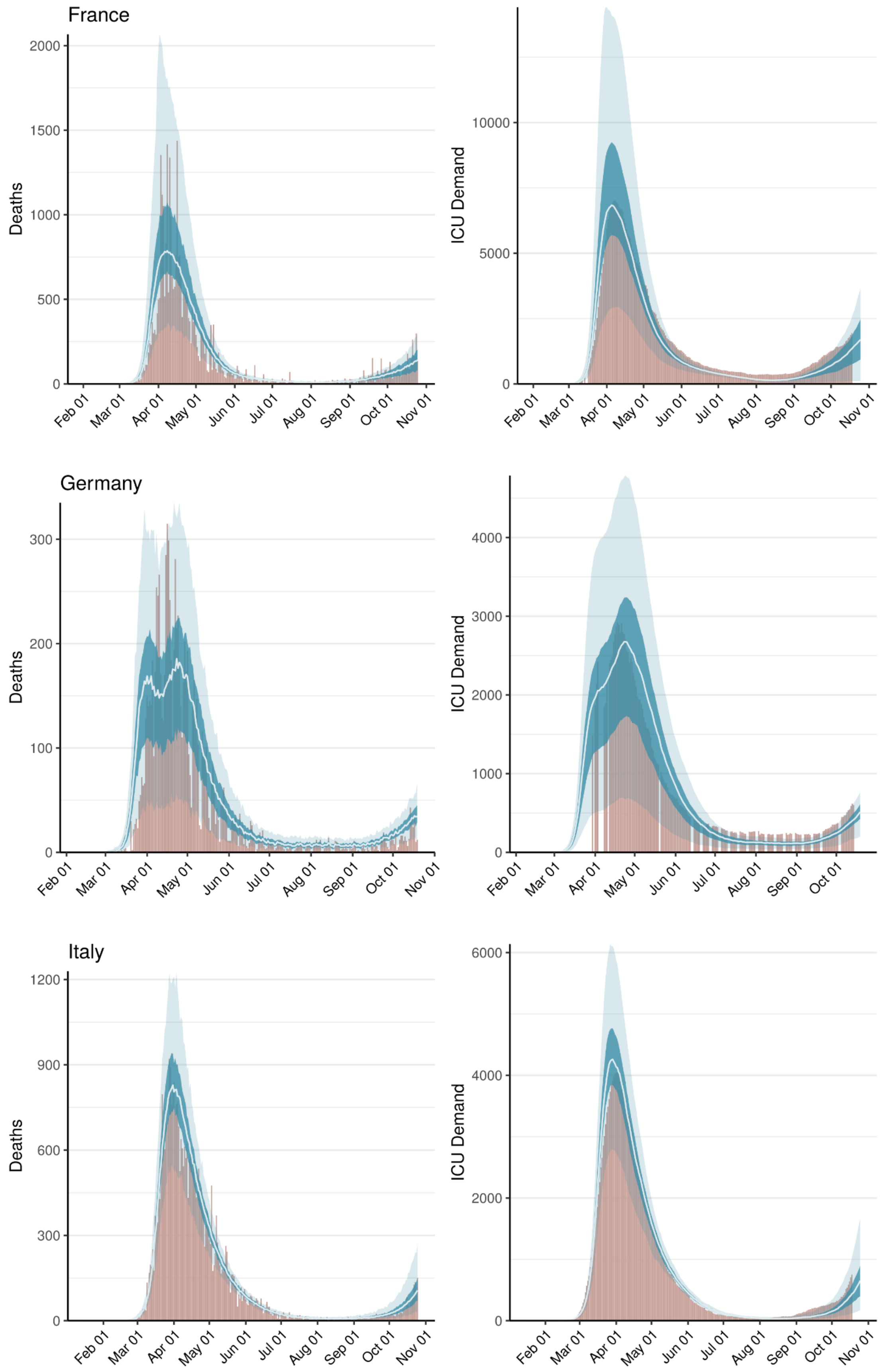


Supplementary Figure 1: Graphical illustration of the relationship between bed demand and capacity. The solid black line indicates demand for ICU care from COVID-19 and non-COVID-19 patients while the dashed black line indicates the total supply of beds available. Demand falling below this line (green) results in positive spare capacity of beds to treat further patients, whereas demand falling above this line (red) indicates a negative spare capacity (capacity deficit) with demand outstripping supply. The magnitudes and duration of ICU deficits are captured by the grey shaded area.

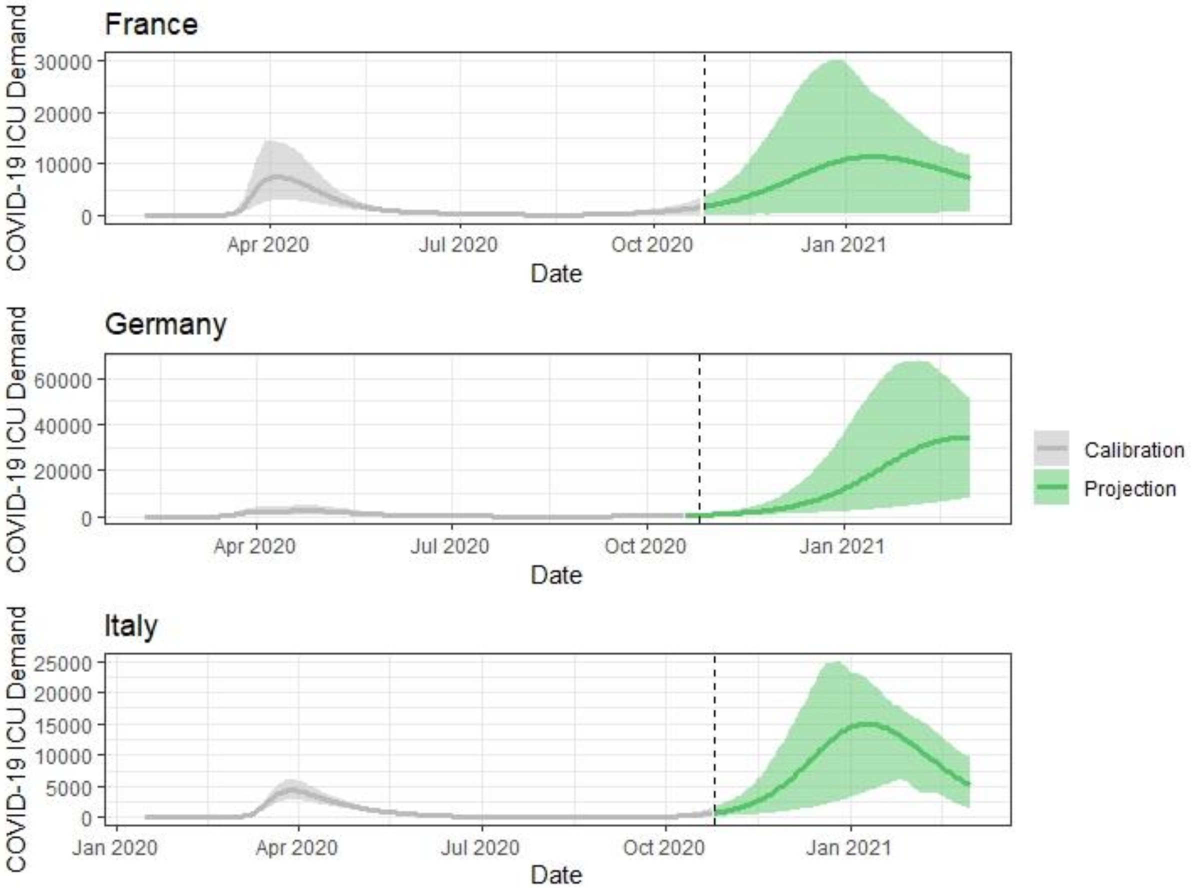
6.2 Epidemiological models

Supplementary Figure 2 shows the epidemic fit of COVID-19 deaths and ICU fits compared to the observed data for France, Germany and Italy.

Supplementary Figure *3*: Unmitigated scenario (median; 95% credible intervals) for France, Germany and Italy under current estimated Rt values. The projection period indicated in green with grey showing the epidemic fit.Supplementary Figure 3 shows the unmitigated scenarios for France, Germany and Italy.



Supplementary Figure 2: Calibrated epidemiological model to daily deaths and ICU demand. Model estimated deaths (left) and daily number of COVID-19 patients in ICU (right) is shown in blue (dark blue 50% interquartile range, light blue 95% quantile), with reported deaths and ICU demand shown in red for France [37], Germany [22] and Italy [37].

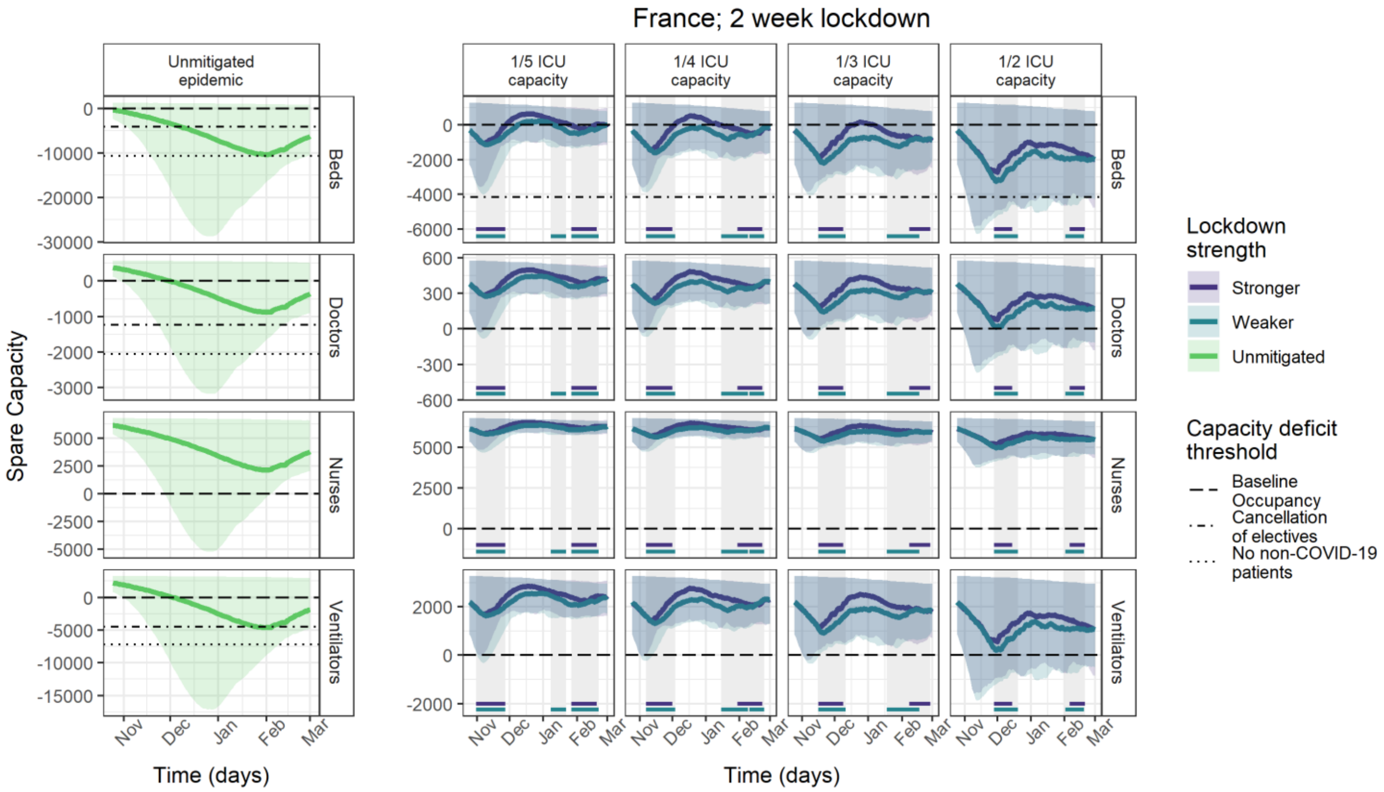


Supplementary Figure 3: Unmitigated scenario (median; 95% credible intervals) for France, Germany and Italy under current estimated R_t values. The projection period indicated in green with grey showing the epidemic fit.

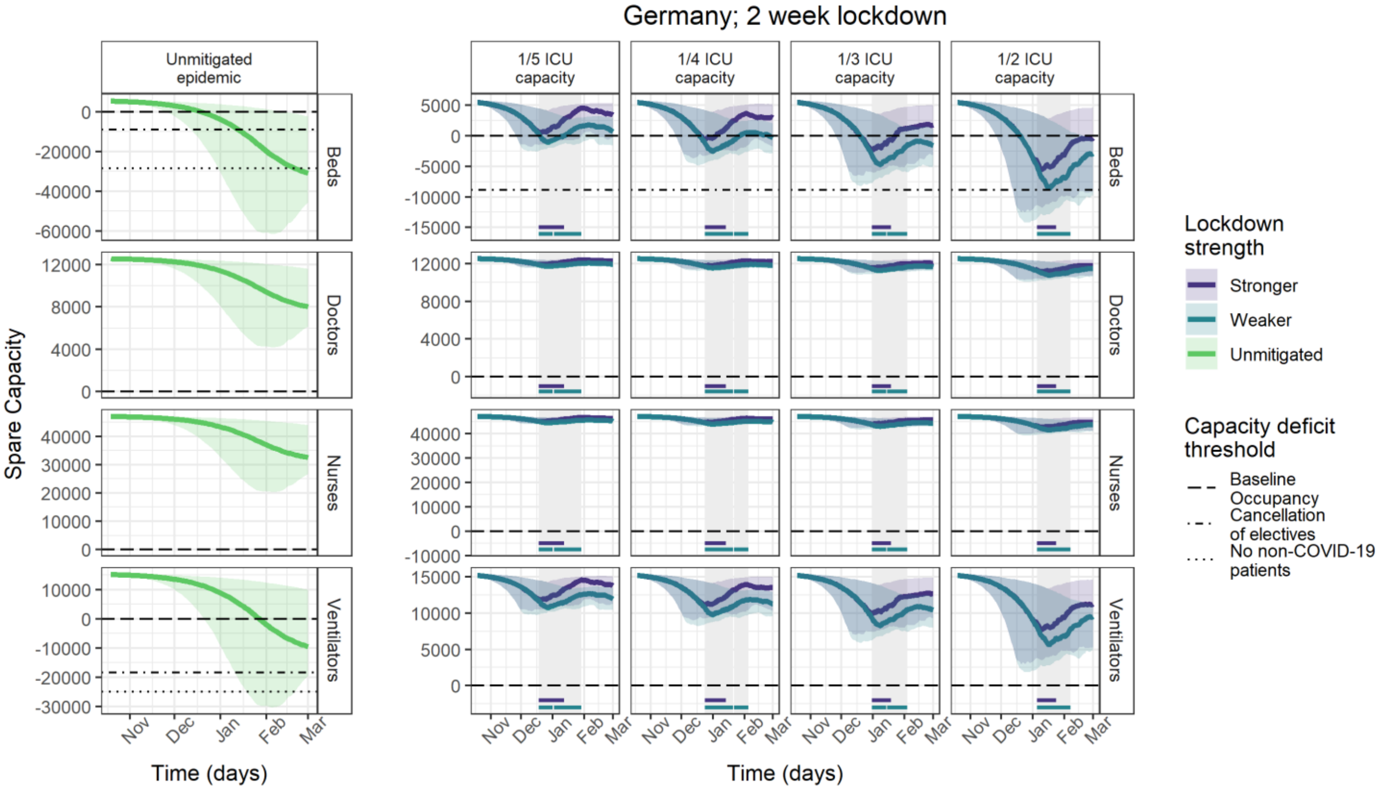
6.3 Spare capacity estimates per country and lockdown scenario

6.3.1 Two-week lockdown scenarios

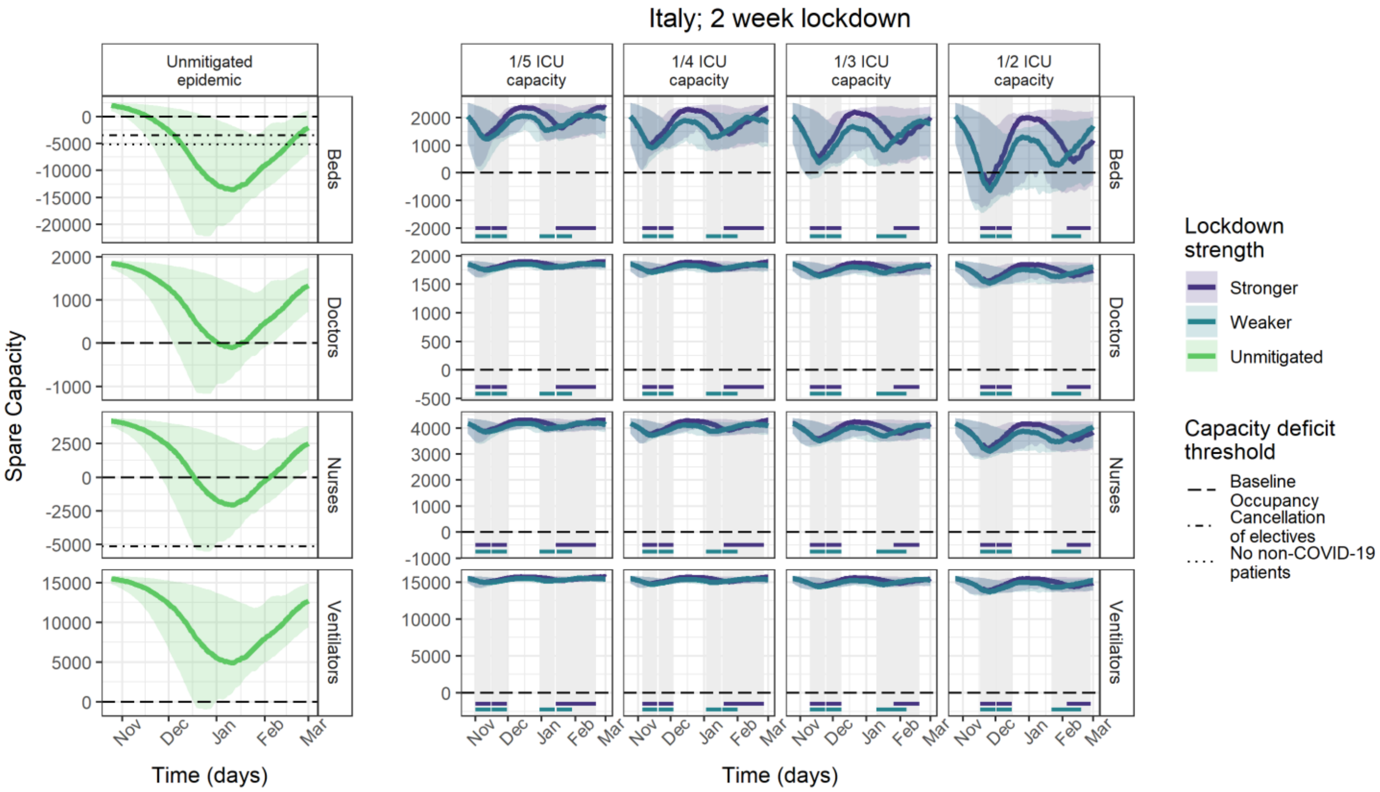
Supplementary Figures 4 – 6 show median spare capacity estimates and 95% credible intervals under the two levels of suppression for different lockdown triggers, assuming a lockdown length of two weeks for France, Germany and Italy, respectively. Supplementary Table 2 shows the maximum observed deficits under each trigger threshold for each suppression level and country. These are analogous to Figures 2 – 4 and Table 2.



Supplementary Figure 4: Spare capacity estimates (median; 95% credible intervals) for France under the unmitigated scenario and the four reactive lockdown scenarios under two different suppression levels (stronger: lockdown R_t = 0.58; weaker: lockdown R_t = 0.8) and specified lockdown length of two weeks. Grey shaded areas indicate periods of lockdown with horizontal-coloured lines indicating the corresponding lockdown strength under which this was triggered. The dashed line (spare capacity = 0) indicates the threshold between positive spare capacity and a deficit in capacity. The dot-dashed and dotted lines indicate an effective reduction in this threshold owing to the cancellation of elective surgery and the removal of all non-COVID-19 patients respectively, allowing the reallocation of resources to COVID-19 patients.



Supplementary Figure 5: Spare capacity estimates (median; 95% credible intervals) for Germany under the unmitigated scenario and the four reactive lockdown scenarios under two different suppression levels (stronger: lockdown R_t = 0.35; weaker: lockdown R_t = 0.8) and specified lockdown length of two weeks. Grey shaded areas indicate periods of lockdown with horizontal-coloured lines indicating the corresponding lockdown strength under which this was triggered. The dashed line (spare capacity = 0) indicates the threshold between positive spare capacity and a deficit in capacity. The dot-dashed and dotted lines indicate an effective reduction in this threshold owing to the cancellation of elective surgery and the removal of all non-COVID-19 patients respectively, allowing the reallocation of resources to COVID-19 patients.



Supplementary Figure 6: Spare capacity estimates (median; 95% credible intervals) for Italy under the unmitigated scenario and the four reactive lockdown scenarios under two different suppression levels (stronger: lockdown R_t = 0.6; weaker: lockdown R_t = 0.8) and specified lockdown length of two weeks. Grey shaded areas indicate periods of lockdown with horizontal-coloured lines indicating the corresponding lockdown strength under which this was triggered. The dashed line (spare capacity = 0) indicates the threshold between positive spare capacity and a deficit in capacity. The dot-dashed and dotted lines indicate an effective reduction in this threshold owing to the cancellation of elective surgery and the removal of all non-COVID-19 patients respectively, allowing the reallocation of resources to COVID-19 patients.

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Supplementary Table 2: The median estimated maximum capacity deficit and number of days in deficit with 95% credible intervals relative to baseline occupancy under the unmitigated and reactive scenarios under two suppression levels (stronger*: lockdown R_t at levels estimated during first peak; weaker: lockdown R_t = 0.8) for each country and capacity resource under lockdown periods lasting for two weeks.

Country	**Resource**	**Result**	**Stronger lockdown***				**Weaker lockdown**			
			1/5 ICU capacity	**1/4 ICU capacity**	**1/3 ICU capacity**	**1/2 ICU capacity**	**1/5 ICU capacity**	**1/4 ICU capacity**	**1/3 ICU capacity**	**1/2 ICU capacity**
France	Beds	Maximum capacity deficit	1209 (0 – 3591)	1800 (0 – 3628)	2767 (0 – 3898)	4753 (0 – 6022)	1287 (0 – 4018)	1866 (0 – 3884)	2909 (0 – 4078)	4799 (0 – 6411)
		Time in deficit (days)	*64 (0 – 85)*	*76 (0 – 121)*	*0 (0 – 13)*	*109 (0 – 127)*	*87 (0 – 108)*	*103 (0 – 126)*	*126 (0 – 127)*	*127 (0 – 127)*
	Doctors	Maximum capacity deficit	0 (0 – 31)	0 (0 – 35)	0 (0 – 70)	176 (0 – 335)	0 (0 – 85)	0 (0 – 68)	0 (0 – 92)	182 (0 – 384)
		Time in deficit (days)	*0 (0 – 8)*	*0 (0 – 9)*	*0 (0 – 13)*	*23 (0 – 47)*	*0 (0 – 16)*	*0 (0 – 15)*	*0 (0 – 19)*	*27 (0 – 62)*
	Nurses	Maximum capacity deficit	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
		Time in deficit (days)	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*
	Ventilators	Maximum capacity deficit	0 (0 – 29)	0 (0 – 55)	0 (0 – 238)	819 (0 – 1682)	0 (0 – 320)	0 (0 – 229)	0 (0 – 360)	850 (0 – 1947)
		Time in deficit (days)	*0 (0 – 3)*	*0 (0 – 5)*	*0 (0 – 9)*	*20 (0 – 43)*	*0 (0 – 13)*	*0 (0 – 12)*	*0 (0 – 16)*	*24 (0 – 58)*
Germany	Beds	Maximum capacity deficit	1098 (280 – 1948)	2731 (1805 – 3922)	5484 (1991 – 7052)	10787 (1991 – 13280)	1657 (509 – 2819)	3383 (1926 – 4946)	6276 (1991 – 8526)	11674 (1991 – 14625)
		Time in deficit (days)	*14 (7 – 23)*	*24 (18 – 29)*	*37 (16 – 51)*	*59 (16 – 82)*	*29 (12 – 56)*	*42 (15 – 71)*	*62 (16 – 86)*	*72 (16 – 92)*
	Doctors	Maximum capacity deficit	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
		Time in deficit (days)	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*	*0[†]*

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Country	**Resource**	**Result**	**Stronger lockdown***				**Weaker lockdown**			
			1/5 ICU capacity	**1/4 ICU capacity**	**1/3 ICU capacity**	**1/2 ICU capacity**	**1/5 ICU capacity**	**1/4 ICU capacity**	**1/3 ICU capacity**	**1/2 ICU capacity**
Germany	Nurses	Maximum capacity deficit	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
		Time in deficit (days)	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]
	Ventilators	Maximum capacity deficit	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
		Time in deficit (days)	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
Italy	Beds	Maximum capacity deficit	0[†]	0[†]	*0 (0 – 222)*	892 (370 – 1413)	0[†]	0[†]	0 (0 – 301)	1023 (506 – 1585)
		Time in deficit (days)	*0*[†]	*0*[†]	*0 (0 – 8)*	*29 (11 – 38)*	*0*[†]	*0*[†]	*0 (0 – 13)*	*36 (15 – 46)*
	Doctors	Maximum capacity deficit	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
		Time in deficit (days)	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]
	Nurses	Maximum capacity deficit	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
		Time in deficit (days)	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]
	Ventilators	Maximum capacity deficit	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
		Time in deficit (days)	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]

*France: R_t =0.58; Germany: R_t =0.35; Italy: R_t =0.6.

[†] No deficits projected under any of the 100 simulation replicates.

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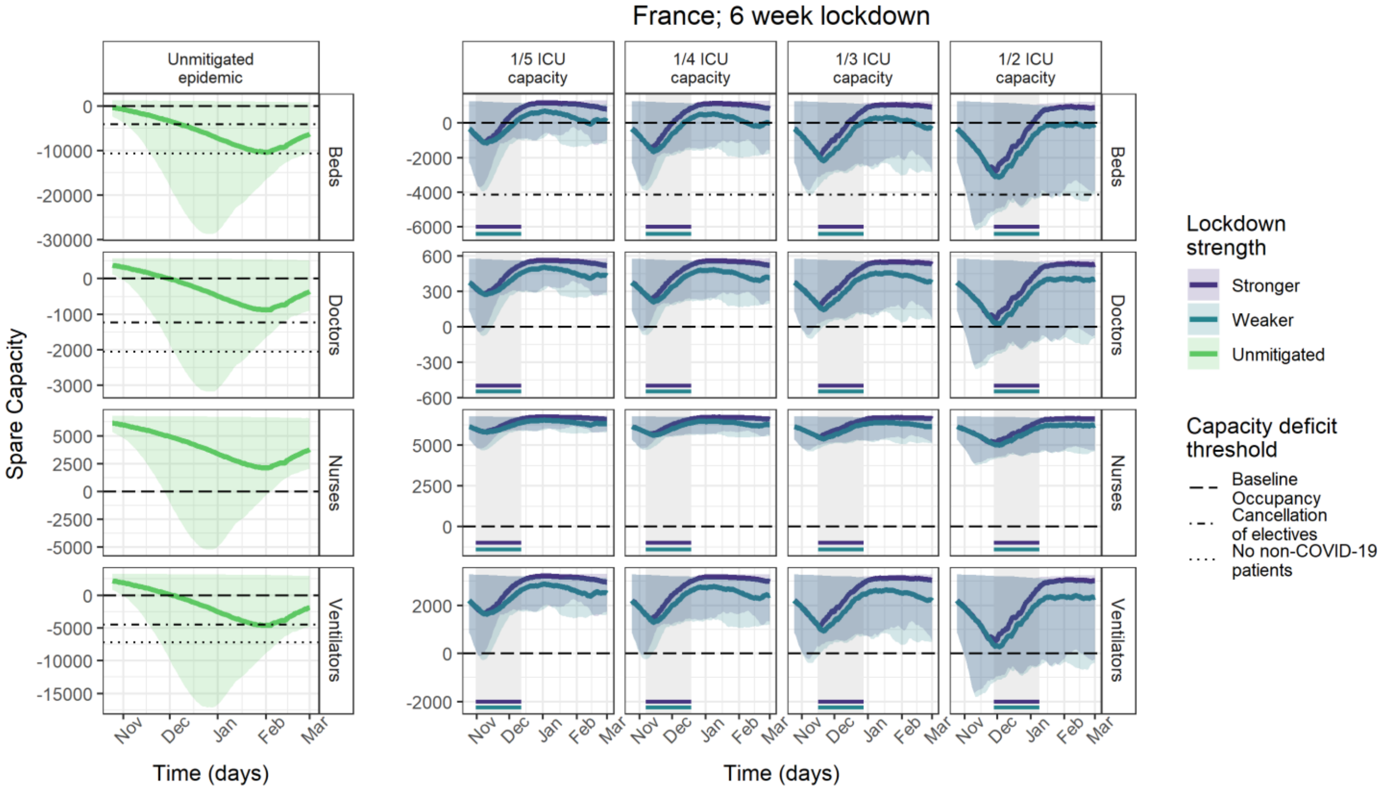
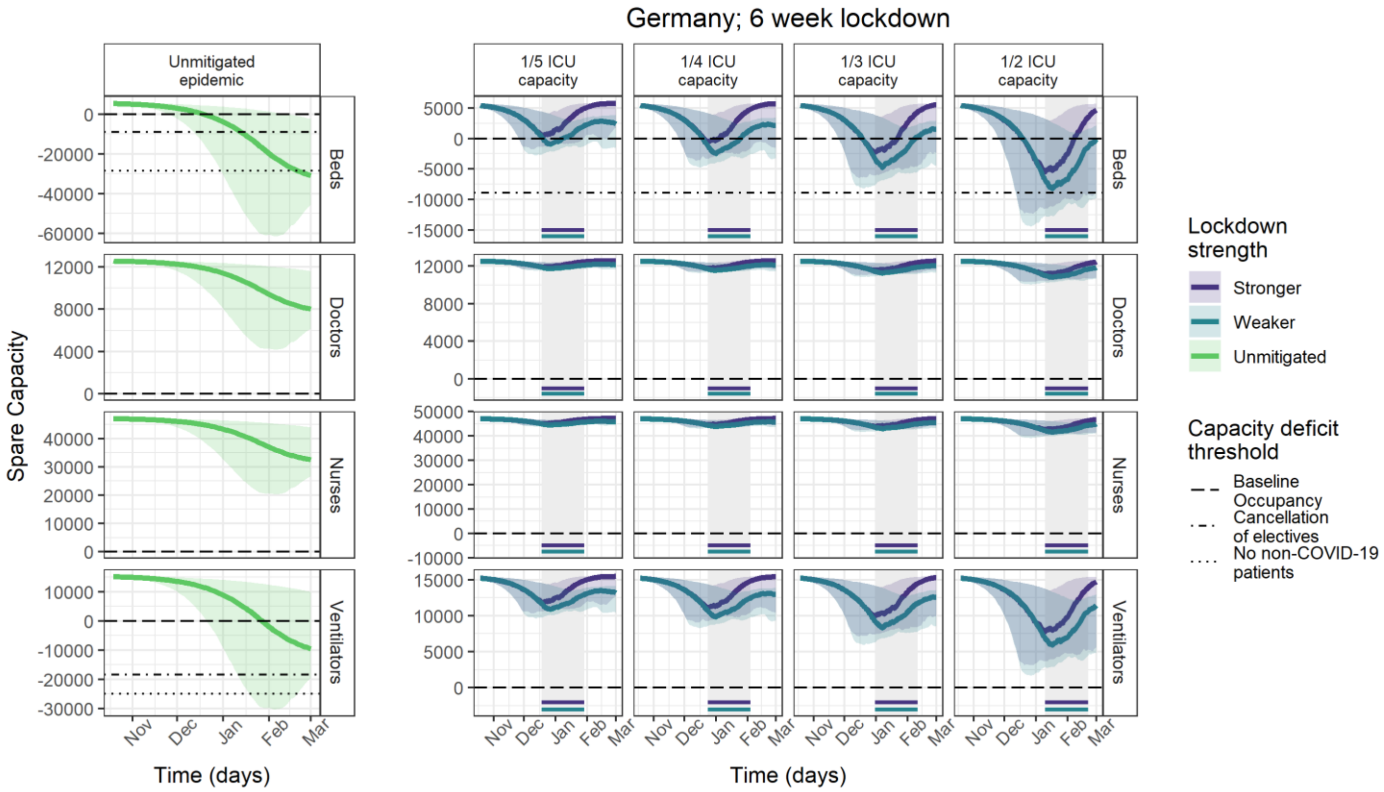
6.3.2 Six-week lockdown scenarios

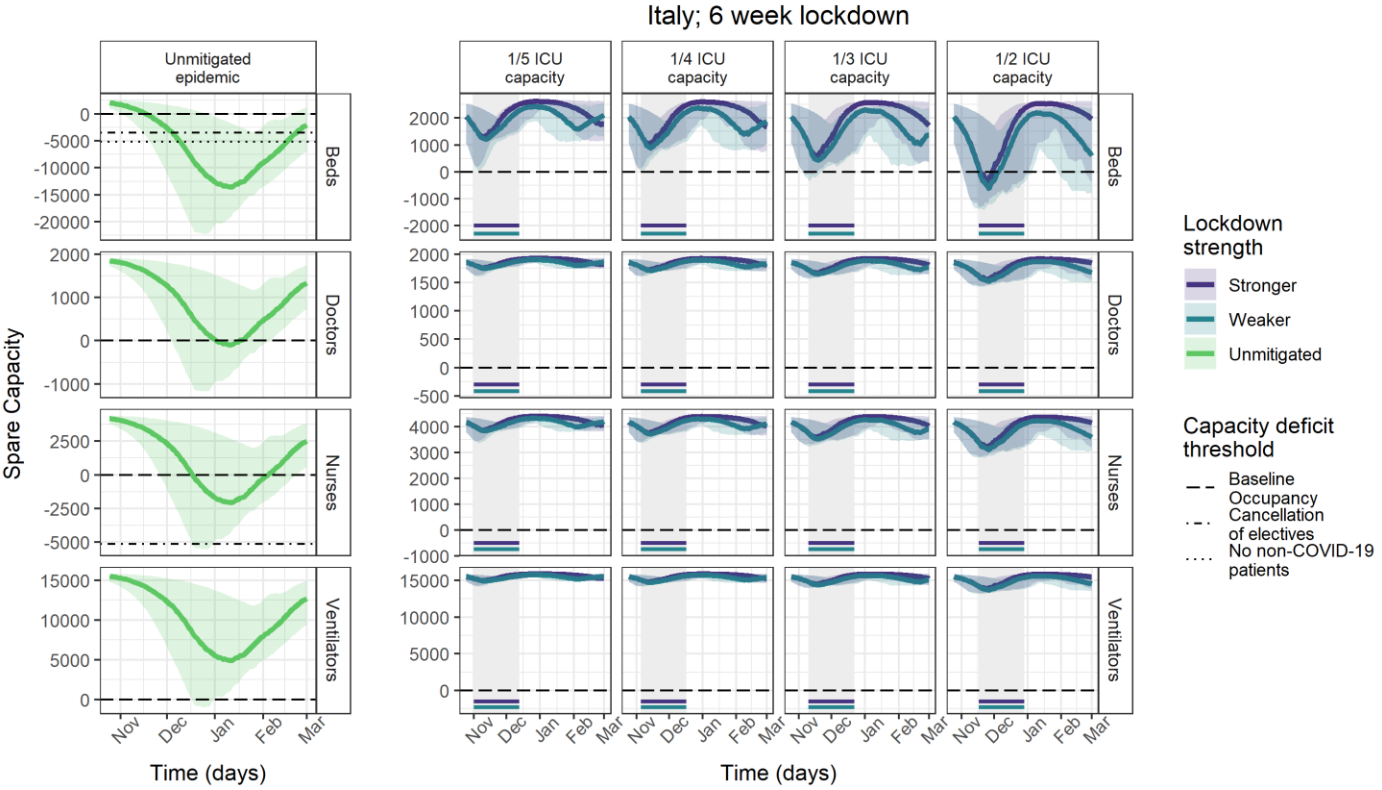
Supplementary Figures 7 – 9 show median spare capacity estimates and 95% credible intervals under the two levels of suppression for different lockdown triggers, assuming a lockdown length of six weeks for France, Germany and Italy, respectively. Supplementary Table 3 shows the maximum observed deficits under each trigger threshold for each suppression level and country. These are analogous to Figures 2 – 4 and Table 2.



Supplementary Figure 7: Spare capacity estimates (median; 95% credible intervals) for France under the unmitigated scenario and the four reactive lockdown scenarios under two different suppression levels (stronger: lockdown $R_t = 0.58$; weaker: lockdown $R_t = 0.8$) and specified lockdown length of six weeks. Grey shaded areas indicate periods of lockdown with horizontal-coloured lines indicating the corresponding lockdown strength under which this was triggered. The dashed line (spare capacity = 0) indicates the threshold between positive spare capacity and a deficit in capacity. The dot-dashed and dotted lines indicate an effective reduction in this threshold owing to the cancellation of elective surgery and the removal of all non-COVID-19 patients respectively, allowing the reallocation of resources to COVID-19 patients.



Supplementary Figure 8: Spare capacity estimates (median; 95% credible intervals) for Germany under the unmitigated scenario and the four reactive lockdown scenarios under two different suppression levels (stronger: lockdown R_t = 0.35; weaker: lockdown R_t = 0.8) and specified lockdown length of six weeks. Grey shaded areas indicate periods of lockdown with horizontal-coloured lines indicating the corresponding lockdown strength under which this was triggered. The dashed line (spare capacity = 0) indicates the threshold between positive spare capacity and a deficit in capacity. The dot-dashed and dotted lines indicate an effective reduction in this threshold owing to the cancellation of elective surgery and the removal of all non-COVID-19 patients respectively, allowing the reallocation of resources to COVID-19 patients.



Supplementary Figure 9: Spare capacity estimates (median; 95% credible intervals) for Italy under the unmitigated scenario and the four reactive lockdown scenarios under two different suppression levels (stronger: lockdown R_t = 0.6; weaker: lockdown R_t = 0.8) and specified lockdown length of six weeks. Grey shaded areas indicate periods of lockdown with horizontal-coloured lines indicating the corresponding lockdown strength under which this was triggered. The dashed line (spare capacity = 0) indicates the threshold between positive spare capacity and a deficit in capacity. The dot-dashed and dotted lines indicate an effective reduction in this threshold owing to the cancellation of elective surgery and the removal of all non-COVID-19 patients respectively, allowing the reallocation of resources to COVID-19 patients.

Supplementary Table 3: The median estimated maximum capacity deficit and number of days in deficit with 95% credible intervals relative to baseline occupancy under the unmitigated and reactive scenarios under two suppression levels (stronger*: lockdown R_t at levels estimated during first peak; weaker: lockdown R_t = 0.8) for each country and capacity resource under lockdown periods lasting for six weeks.

Country	**Resource**	**Result**	**Stronger lockdown***				**Weaker lockdown**			
			1/5 ICU capacity	**1/4 ICU capacity**	**1/3 ICU capacity**	**1/2 ICU capacity**	**1/5 ICU capacity**	**1/4 ICU capacity**	**1/3 ICU capacity**	**1/2 ICU capacity**
France	Beds	Maximum capacity deficit	1205 (0 – 3711)	1812 (0 – 3636)	2799 (0 – 3899)	4699 (0 – 6065)	1300 (0 – 3966)	1895 (0 – 3901)	2905 (0 – 4160)	4838 (0 – 6257)
		Time in deficit (days)	*36 (0 – 64)*	*43 (0 – 69)*	*55 (0 – 81)*	*70 (0 – 111)*	*54 (0 – 93)*	*66 (0 – 108)*	*76 (0 – 112)*	*91 (0 – 127)*
	Doctors	Maximum capacity deficit	0 (0 – 46)	0 (0 – 37)	0 (0 – 70)	170 (0 – 340)	0 (0 – 78)	0 (0 – 70)	0 (0 – 102)	187 (0 – 365)
		Time in deficit (days)	0 (0 – 10)	0 (0 – 9)	0 (0 – 13)	*22 (0 – 28)*	*0 (0 – 15)*	*0 (0 – 15)*	*0 (0 – 18)*	*27 (0 – 55)*
	Nurses	Maximum capacity deficit	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$
		Time in deficit (days)	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$
	Ventilators	Maximum capacity deficit	0 (0 – 111)	0 (0 – 60)	0 (0 – 239)	783 (0 – 1711)	0 (0 – 284)	0 (0 – 240)	0 (0 – 416)	877 (0 – 1842)
		Time in deficit (days)	0 (0 – 6)	0 (0 – 4)	0 (0 – 8)	*20 (0 – 24)*	*0 (0 – 11)*	*0 (0 – 12)*	*0 (0 – 14)*	*24 (0 – 55)*
Germany	Beds	Maximum capacity deficit	1089 (201 – 1938)	2769 (1749 – 3812)	5490 (1991 – 6975)	10714 (1991 – 13088)	1615 (554 – 2868)	3459 (1983 – 4858)	6311 (1991 – 8471)	11589 (1991 – 14839)
		Time in deficit (days)	14 (6 – 17)	24 (16 – 26)	36 (16 – 40)	*51 (16 – 57)*	*26 (12 – 53)*	38 (15 – 61)	52 (16 – 70)	68 (16 – 79)
	Doctors	Maximum capacity deficit	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$
		Time in deficit (days)	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$	$0^{\dagger}$

Country	Resource	Result	Stronger lockdown*				Weaker lockdown			
			1/5 ICU capacity	1/4 ICU capacity	1/3 ICU capacity	1/2 ICU capacity	1/5 ICU capacity	1/4 ICU capacity	1/3 ICU capacity	1/2 ICU capacity
Germany	Nurses	Maximum capacity deficit	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
		Time in deficit (days)	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
	Ventilators	Maximum capacity deficit	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]
		Time in deficit (days)	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
Italy	Beds	Maximum capacity deficit	0[†]	0[†]	*0 (0 – 182)*	889 (394 – 1374)	0[†]	0[†]	0 (0 – 381)	1039 (390 – 1568)
		Time in deficit (days)	*0*[†]	*0*[†]	0 (0 – 8)	*17 (12 – 26)*	*0*[†]	*0*[†]	0 (0 – 12)	20 (13 – 43)
	Doctors	Maximum capacity deficit	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
		Time in deficit (days)	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]
	Nurses	Maximum capacity deficit	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
		Time in deficit (days)	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]
	Ventilators	Maximum capacity deficit	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]	0[†]
		Time in deficit (days)	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]	*0*[†]

*France: R_t =0.58; Germany: R_t =0.35; Italy: R_t =0.6.

[†] No deficits projected under any of the 100 simulation replicates.

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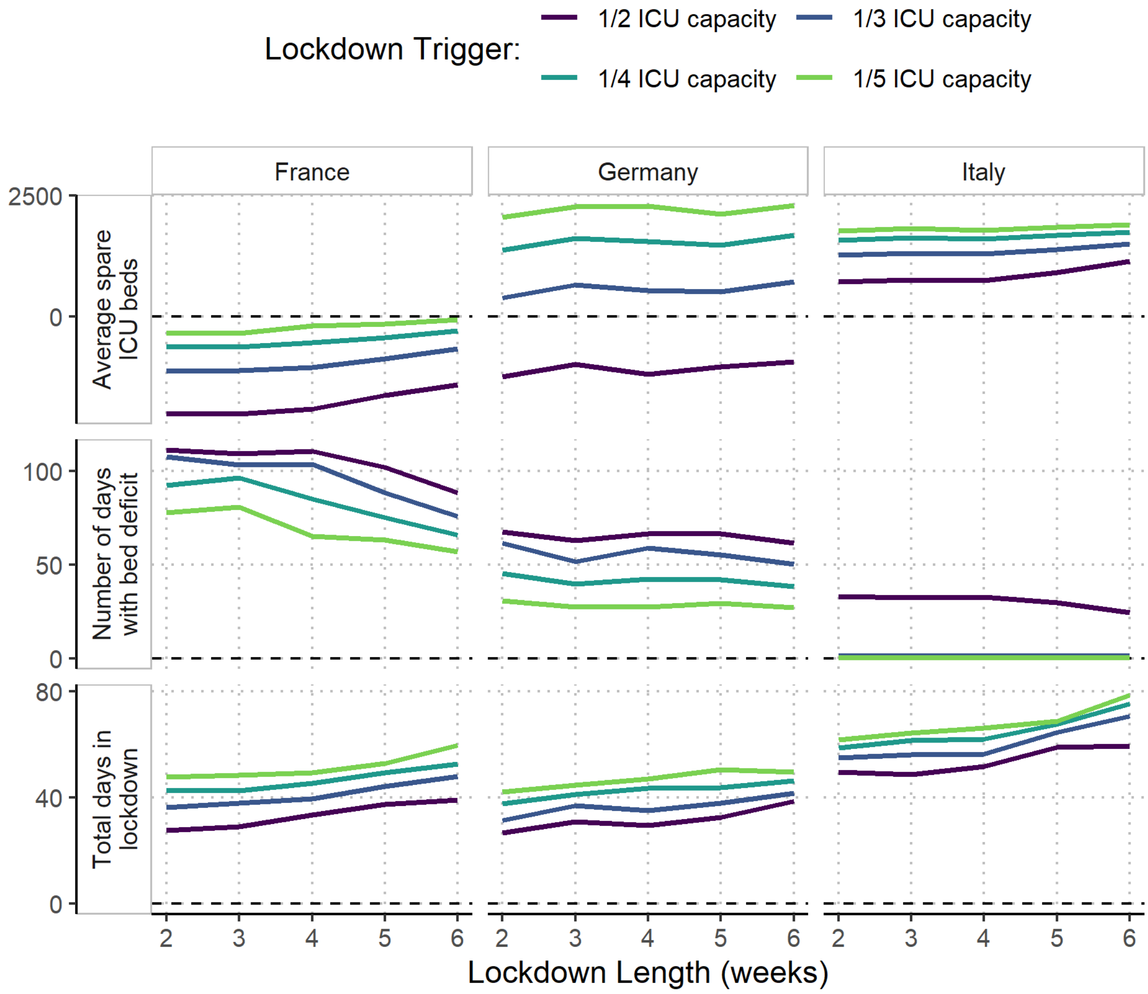
6.4 Effect of varying trigger thresholds and duration on the impact and time in lockdown under weaker level of suppression

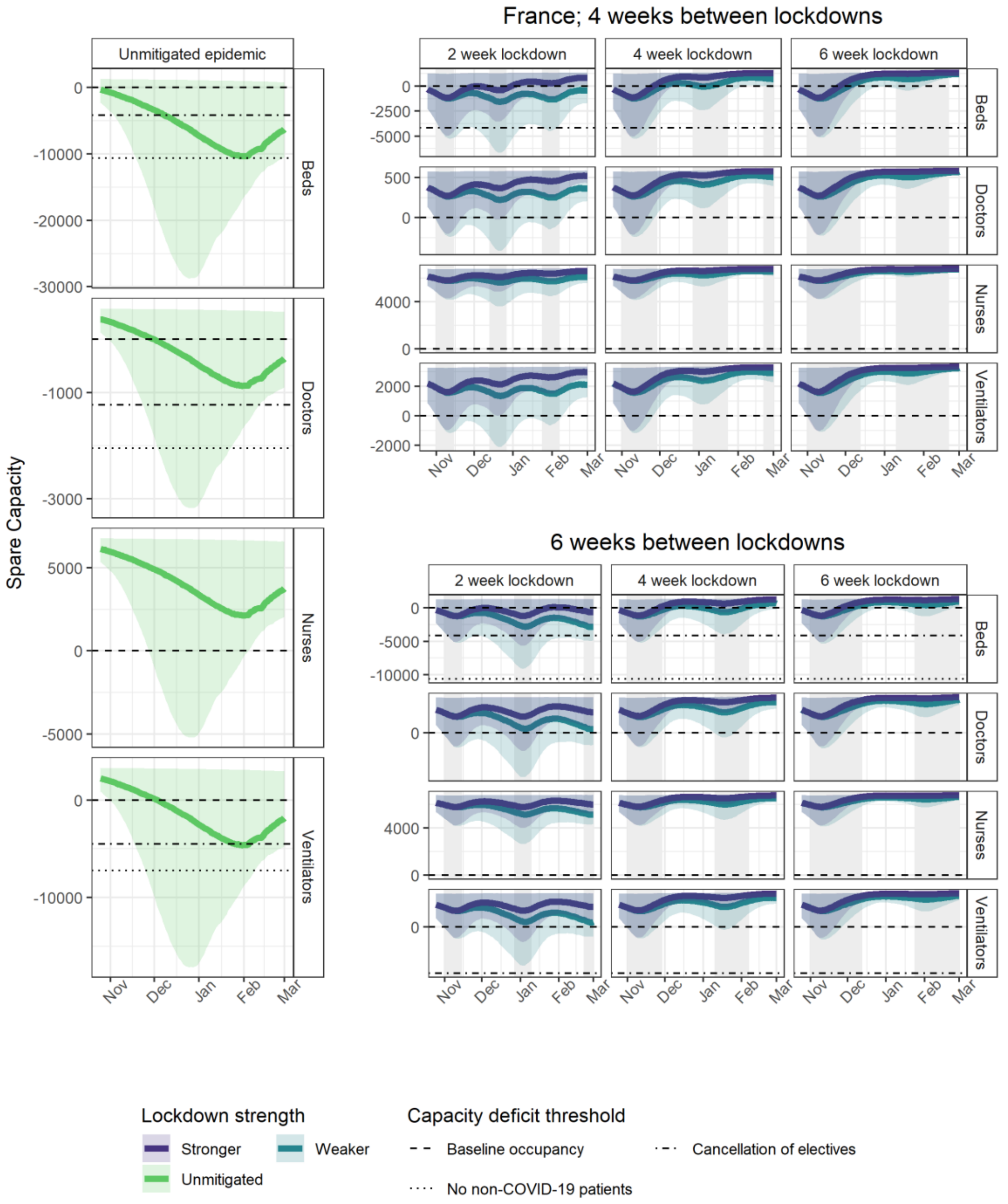
Supplementary Figure 10 shows the effect of varying trigger thresholds and lockdown duration on the impact and time in lockdown under the weaker level of suppression (R_t = 0.8). This is analogous to Figure 5.



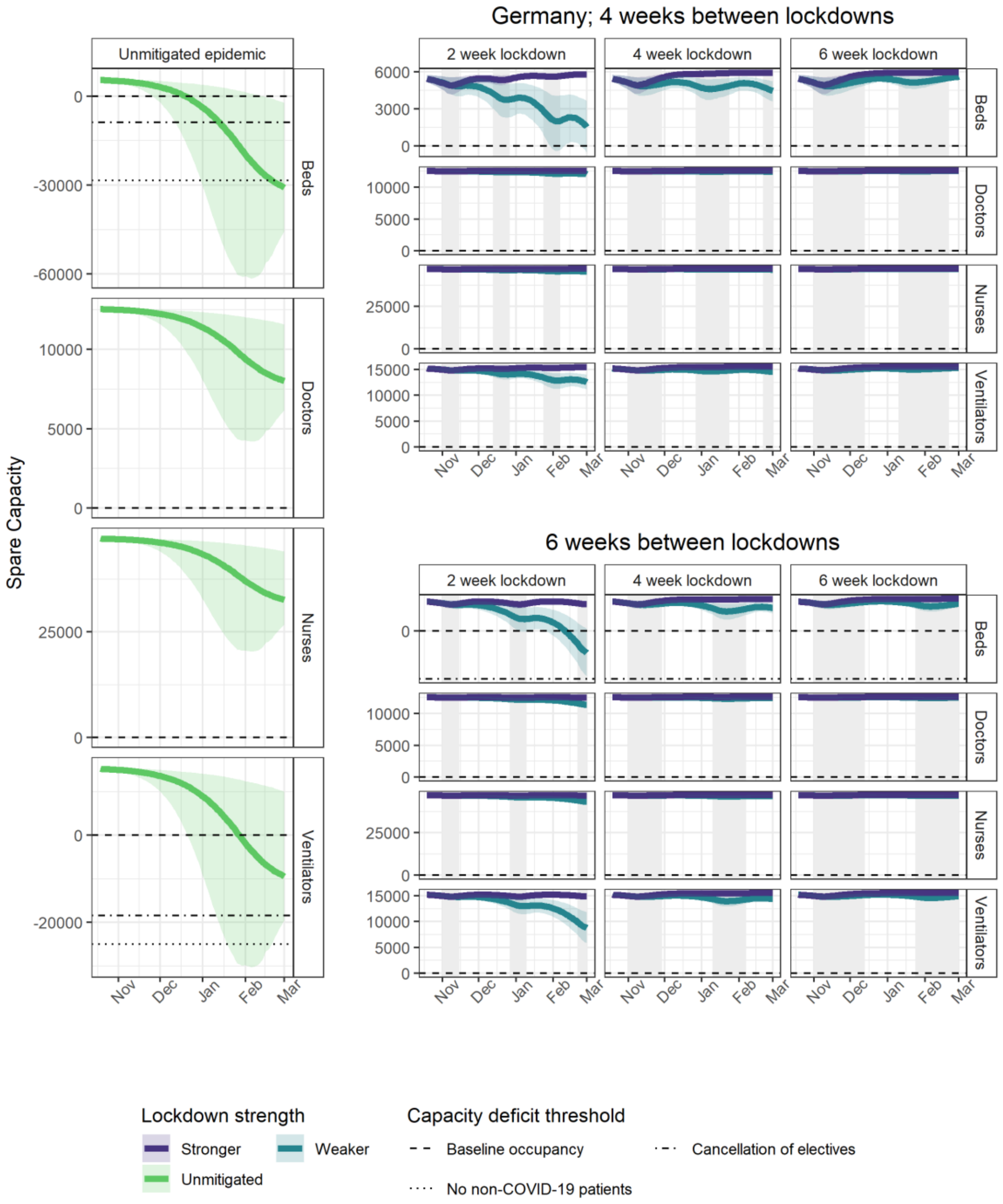
Supplementary Figure 10: Impact of the duration and timing of lockdowns on spare capacity of ICU beds. The effect of lockdown length on the average spare capacity of ICU beds; the number of days with a deficit in ICU beds and the total number of days spent in lockdown is shown for France, Germany and Italy under the weaker suppression scenarios (R_t = 0.8). For each plot the median of 100 simulation repetitions over the projection period (25th October 2020 – March 2021) is shown.

6.5 Scheduled lockdown scenarios

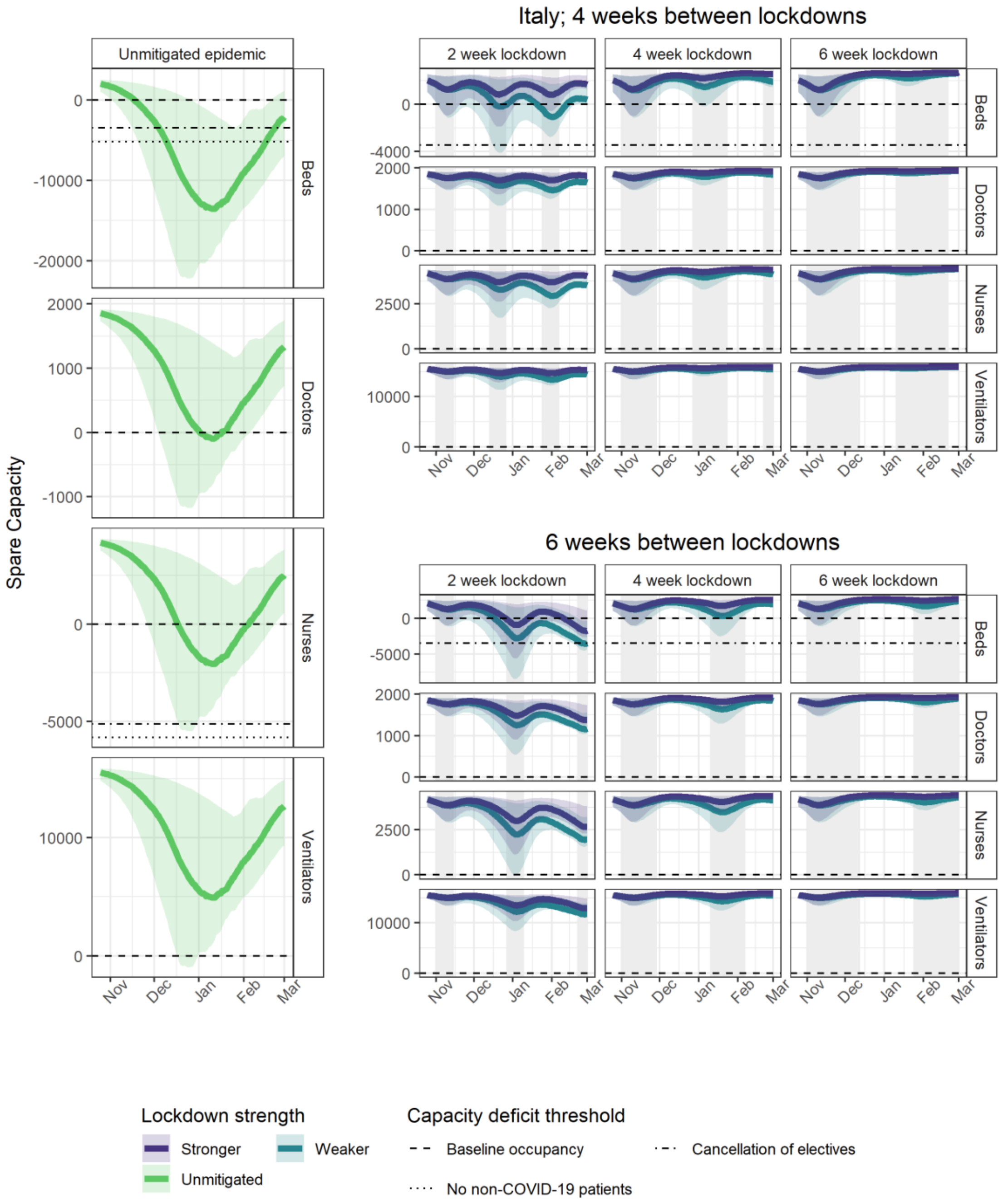
Supplementary Figures 11 – 13 show scenarios in which lockdowns are fixed at pre-determined time points under the two levels of suppression for France, Germany and Italy, respectively.



Supplementary Figure 11: Spare capacity estimates and 95% credible intervals for France under fixed lockdown scenarios under two levels of suppression (stronger: lockdown $R_t = 0.58$; weaker: lockdown $R_t = 0.8$) for different durations of lockdown and time between lockdowns. Grey shaded periods indicate periods of lockdown. The dashed line (spare capacity = 0) indicates the threshold between positive spare capacity and a deficit in capacity. The dot-dashed and dotted lines indicate an effective reduction in this threshold owing to the cancellation of elective surgery and the removal of all non-COVID-19 patients respectively, allowing the reallocation of resources to COVID-19 patients.



Supplementary Figure 12: Spare capacity estimates and 95% credible intervals for Germany under fixed lockdown scenarios under two levels of suppression (stronger: lockdown $R_t = 0.35$; weaker: lockdown $R_t = 0.8$) for different durations of lockdown and time between lockdowns. Grey shaded periods indicate periods of lockdown. The dashed line (spare capacity = 0) indicates the threshold between positive spare capacity and a deficit in capacity. The dot-dashed and dotted lines indicate an effective reduction in this threshold owing to the cancellation of elective surgery and the removal of all non-COVID-19 patients respectively, allowing the reallocation of resources to COVID-19 patients.



Supplementary Figure 13: Spare capacity estimates and 95% credible intervals for Italy under fixed lockdown scenarios under two levels of suppression (stronger: lockdown R_t = 0.6; weaker: lockdown R_t = 0.8) for different durations of lockdown and time between lockdowns. Grey shaded periods indicate periods of lockdown. The dashed line (spare capacity = 0) indicates the threshold between positive spare capacity and a deficit in capacity. The dot-dashed and dotted lines indicate an effective reduction in this threshold owing to the cancellation of elective surgery and the removal of all non-COVID-19 patients respectively, allowing the reallocation of resources to COVID-19 patients.

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