REPORT 35: How can we keep schools and universities open? Differentiating closures by economic sector to optimize social and economic activity while containing SARS-CoV-2 transmission

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Summary

There is a trade-off between the education sector and other economic sectors in the control of SARS-CoV-2 transmission. Here we integrate a dynamic model of SARS-CoV-2 transmission with a 63-sector economic model reflecting sectoral heterogeneity in transmission and economic interdependence between sectors. We identify control strategies which optimize economic production while keeping schools and universities operational and constraining infections such that emergency hospital capacity is not exceeded. The model estimates an economic gain of between £163bn and £205bn for the United Kingdom compared to a blanket lockdown of non-essential activity over six months, depending on hospital capacity. Sectors identified as potential priorities for closure are contact-intensive and/or less economically productive.

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1. Introduction

School and university closures are a key non-pharmaceutical intervention (NPI) in the control of the COVID-19 pandemic [1, 2], and were implemented by many countries in the first half of 2020 when infections were rising rapidly. By mid-2020, UNESCO estimated that around 60% of the world's students had their education disrupted by national closures of educational institutions during the pandemic [3]. Even short periods of missed education can have grave consequences for educational development [4-6], reduce lifetime earning potential [7], and damage social and psychological development of children and young adults [8]. School closures are also associated with lost income and productivity of carers who cannot work because of childcare responsibilities [9]. Households from disadvantaged backgrounds are worst affected [6].

The high economic and social costs of school and university closures have led most countries to re-start education activities in the second half of 2020 [10-12], although this was projected to increase SARS-CoV-2 transmissions and put heavy pressure on health services [13]. To maintain control, many European countries have recently tightened NPIs in other areas of society, most notably through closure of businesses deemed non-essential for day-to-day life. However, lockdowns are also associated with high economic and social costs [14-17], and they are a crude lever if implemented as a blanket policy across the whole economy. Economic sectors differ greatly in the infection risk that they pose to both workers and consumers, in their potential to implement effective social distancing measures, and in the contributions they make to Gross Domestic Product (GDP).

The world has no experience of how lockdowns can be finetuned to keep the pandemic in check, thereby preventing health services from being overwhelmed, whilst allowing educational institutions to stay open and minimizing economic costs associated with business closures. We present a closure strategy, differentiated by economic sector, which identifies an optimal six-month trajectory of selective opening and closing of 63 sectors while keeping educational institutions operational and infections and hospital admissions under control.

2. Methods

2.1 DAEDALUS: An integrated model of Gross Domestic Product and SARS-CoV-2 transmission

We developed DAEDALUS, an integrated economic-epidemiological model. DAEDALUS acknowledges that relatively contact-light sectors that employ fewer workers carry fewer infections back into the community when they are open than more contact-intensive counterparts with more workers. However, this does not necessarily imply prioritizing the sectors of the economy that contribute most to economic value relative to the spread of infection. There are important interdependencies between sectors, all of which rely to some extent on inputs from other sectors to produce their final outputs; a sector that is nominally opened may not be able to function properly if its supply chain is interrupted [18, 19]. DAEDALUS accommodates such interactions by relying on standard Input-Output (IO) tables prepared as part of the national accounts [20].

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We integrate the economic model into a deterministic Susceptible-Exposed-Infectious-Removed (SEIR) model of SARS-CoV-2 transmission that projects the spread of infection at the workplace, in households and in the community as sectors are opened and closed to varying degrees. The SEIR model accommodates sectoral heterogeneity in risks of infection between co-workers, non-workers in the community, and at the interface between these groups. DAEDALUS then finds the trajectory of opening and closing sectors that maximises national GDP subject to epidemiological constraints on SARS-CoV-2 transmission, which include a requirement to keep hospital admissions within acceptable bounds. The chosen closure of sectors under optimal solutions is influenced by at least four sector characteristics and their interplay, notably size of workforce, contact rates, GDP contribution and interdependence with other sectors. The technical description of DAEDALUS and software are published on GitHub.

2.2 Economic model

The economic configuration in DAEDALUS – the extent to which each sector is open – can be changed at specific time points over a planning horizon, set to six months in this application. Each sector contributes to GDP in proportion to the level it is open and according to its production possibilities, defined as Gross Value Added (GVA). All necessary intermediate domestic inputs required by an active sector must be available, even if they are produced by another sector. We allow no 'excess' production of final products, i.e. sectors cannot produce more than their pre-pandemic output. However, in this application, we do allow sectors to build up inventories if domestic demand and exports are lower compared to pre-pandemic times. We constrain all scenarios by the economic configuration that allows essential services to operate, i.e. closing all sectors completely is not possible. The essential economic configuration assumes all sectors must be operational to at least 80% (healthcare at 100%) of the values observed during the first lockdown period in the United Kingdom (UK) from March–May 2020 [21]. Relaxing the lower bound below the observed lockdown value allows for uncertainty regarding the precise observed lockdown values, and genuine changes in production processes [22, 23].

The decision variables in DAEDALUS are the extent to which each sector is open in each time period. Partial or full opening and closing of sectors are assumed to give rise to proportional changes in the active workforce, and the associated impact on disease transmission. The model then seeks to identify the set of decision variables that maximizes GVA across all sectors over the six months, whilst keeping the education sector open at or above 80% of pre-pandemic levels and containing maximum daily hospital occupancy of COVID-19 patients (H_{max}) within available capacity. We also constrain the effective reproductive number R_t at or below 1 at the end of six months, ensuring that the legacy of infections does not escalate rapidly just beyond the intervention period.

We apply DAEDALUS to the economy of the UK divided into 63 economic sectors (see Tab. S1 for the education sector definitions). To characterize interdependence between sectors, we use the most recent IO table prepared for the calendar year 2016 [24]. We use data from the Office of National Statistics on the workforce [25], and on the proportion of those working from home [21].

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2.3 SARS-CoV-2 transmission

In the epidemiological model the actively working adult population is disaggregated by economic sectors. Partial or full opening of a sector increases the number of actively working adults. The remainder of the population is assigned to the community sector, which is disaggregated into 4 age groups: pre-school, school-age, working-age adult not in active employment, and retired. Transmission is modelled with a SEIR model. Only working-age adults move between the community and economic sectors, as sectors are opened and closed.

We calibrate four model parameters to English hospitalization data from 20th February to 30th June 2020: the basic reproductive number R_0; effectiveness of lockdown δ; epidemic start time and lockdown onset. Transmissibility is calibrated to the fitted basic reproductive number R_0 and pre-lockdown contact patterns using the next-generation eigenvalue method [26]. Additional parameter estimates are aligned with Imperial College's Real-time Model [27]. A scalar multiplier δ is used to capture the dampening impact of NPIs and individuals' behaviour on transmissions as represented by R_t, capturing the combined effect of NPIs other than closures that are difficult to estimate empirically, including social distancing in social and work environments, facemasks, testing-and-tracing, shielding of the vulnerable, travel restrictions, and limits to social gatherings. The fitted value of δ over the initial lockdown period represents the lower bound (optimistic) estimate of the impact of NPIs. For the forward projections, we adjust δ to reflect less stringent NPIs and weaker adherence in the post-lockdown period.

2.4 Contact matrices

Transmission dynamics are influenced by the number of contacts made by individuals at different locations. Contact rates are derived from a survey conducted in 2012 in France [28]. While more recent contact surveys have been conducted, to our knowledge this is the only survey that includes sector-specific and work-related information of respondents. We mapped the industry sectors of the survey to the industry sectors of the UK IO table, and use the mean number of daily contacts recorded by individuals over a two-day period (trimmed of outliers).

We define three contact matrices. The **community matrix** defines contacts between individuals within the community (comprising individuals not in the labour force, workers when not at work or when working from home), specifically contacts made in one's own household, in outside spaces, in retail, hospitality and leisure outlets. Contacts while using public transport, between students in schools and universities, and between consumers of the same or different sectors are considered community contacts. The **worker-to-worker matrix** defines contacts made between workers within a sector, applicable to individuals while at the workplace. Contacts between workers of different sectors are captured in the community matrix, even if they occur at the workplace. The **worker-to-consumer matrix** is diagonal and defines contacts experienced by workers from consumers within each sector.

In the education sector, we account for the number of contacts between students (=consumers). School contacts are estimated separately in two age groups (pre-school age: 0 – 4; school age: 5 – 18). Similarly, hospitality consumer contacts are estimated considering age-heterogeneity in hospitality contacts. We assume that transport and school and university contacts add to the infection risk only in proportion to which the sector is open and workers do not work from home. The columns of each

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matrix are weighted by the population actively working in each sector. For example, opening the hospitality sector will increase community transmission as people meet in pubs and restaurants, independently of the sector in which they work.

2.5 Modelling Scenarios

In our main results, we use DAEDALUS to maximize total GDP while tracking the spread of SARS-CoV-2 over six months, with decisions on economic configurations starting in September 2020. We assume that decision makers can increase or decrease the extent to which each sector is open three times: at the beginning, and after months 2 and 4. DAEDALUS provides a continuous function of disease progress within each interval, allowing for discontinuities at the transition points. It incorporates five types of constraint for the optimization:

- interdependencies of supply and demand between sectors are respected;
- in each sector, economic activity is sustained throughout to at least 80% of lockdown values (healthcare 100%);
- the demand for goods and services does not exceed pre-pandemic levels;
- hospital occupancy remains within capacity H_{max} throughout the intervention period;
- $R_t \leq 1$ at the end of the intervention period.

In contrast to the economic constraints, the epidemiological constraints are highly non-linear. We assume that H_{max}, maximum spare emergency hospital capacity for the treatment of COVID-19 patients, does not vary over six months but make three alternative assumptions on H_{max} at 12,000, 18,000 and 24,000 beds (a peak number of around 18,000 COVID-19 patients occupied beds in April 2020).

We project GDP, total disease incidence, and hospital occupancy for five scenarios:

- **Scenario A (GDP max):** maximizes GDP subject to five epidemiological and economic constraints; like any other sector, education may be closed fully or partly;
- **Scenario B (education open):** optimizes GDP subject to the five constraints; the education sector remains operational at or above 80% of pre-pandemic production (less than 100% to account for NPIs such as online teaching at universities);
- **Scenario LDA (lockdown):** imposes lockdowns of all non-essential activity across all sectors, including those of the education sector, at production levels observed during the initial lockdown period. Scenario LDA results in the lowest attainable infections but at high economic costs, and projects lower bounds on infections and GDP;
- **Scenario LDB (lockdown except education):** as LDA, except that the education sector remains operational at or above 80%;
- **Scenario FO (fully open):** the economic specification that leaves all sectors fully open for six months. It relaxes all epidemiological constraints but assumes NPIs and voluntary behaviour changes as captured by δ. Scenario FO results in the greatest GDP but at the cost of high infections and deaths; it projects upper bounds on infections and GDP.

Outcomes from scenarios A and B constitute optimal solutions with respect to both GDP and infections (given the respective constraints). Scenarios LDA, LDB and FO are descriptive scenarios that do not

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seek to optimize GDP for the infections caused. Optimizations use 'Global search' with derivative-based base algorithm fmincon in MATLAB's global optimization toolbox.

3. Results

3.1 Maximizing GDP via a closure strategy differentiated by economic sector

The strategy that maximizes GDP while keeping infections within constraints (Scenario A) allows the potential closure of all economic sectors, including the education sector. If emergency hospital capacity for COVID-19 patients is constrained at H_{max}=18,000, the optimal solution is to let infections increase over September and October, then from November impose more stringent economic configurations to honour the epidemiological constraints (Figs. 1A, see S1A for H_{max}=12,000, S2A for H_{max}=24,000). We find that GDP maximization focuses solely on closure of the education sector (Figs. 1B, S1B, S2B). The strategy requires the education sector to close down to 93% of pre-pandemic activity in September-October, 54% in November-December and 76% in January-February (Tab. S2), assuming H_{max}=18,000. If H_{max}=12,000, then the education sector needs to close more (83%, 51%, 65%). If H_{max}=24,000 then closure is only required in November-December (56%) and January-February (86%). Other sectors including accommodation & food service activities (which includes hotels, restaurants, cafes, and pubs) can stay open under any H_{max}. Educational activities are likely chosen for closure by DAEDALUS because they contribute significantly to transmission, but relatively little to short-term GDP as measured in national accounts. Our analysis considers economic production over only six months, and not any longer-term economic benefits of keeping schools and universities open which are likely substantial. The difficulty of measuring the GVA contribution of educational activities is widely acknowledged [29].

The GDP achieved by Scenario A is £877bn over six months (H_{max}=18,000, Fig. 3A), higher than the £660bn of a blanket lockdown (Scenario LDA), but lower than the £889bn achieved with a fully open economy (Scenario FO). However, Scenario FO results in high incidence and deaths. FO also means that around 68,000 COVID-19 patients would require hospital treatment at the projected peak in January 2021, compared to 18,000 patients under Scenarios A.

3.2 Optimizing GDP while keeping education activities operational

Scenario LDB requires all sectors to close at levels observed during the first lockdown period except the education sector, which would operate at 80% of pre-pandemic activity. LDB would keep maximum hospital occupancy at around 10,000 at the peak (Fig. 3B), lower than during the first peak in April 2020 albeit not as low as LDA that allows the education sector to close as other sectors (Fig. 3A). This is because expanding the activity of the education sector increases transmission.

DAEDALUS seeks out an economic configuration that is associated with less economic loss than LDB, while education is allowed to stay open. Scenario B follows a differentiated sectoral closure strategy that maximizes GDP, allowing infections (hospital occupancy and deaths) to increase up to the hospital constraint (Figs. 2A H_{max}=18,000, S3A H_{max}=12,000, S4A H_{max}=24,000). The optimal strategy is to let infections increase gradually from September to December, and then impose more stringent economic configurations in January and February to honour the constraint on R_t at the end of the

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intervention period. If H_{max}=18,000, targeted for closure are creative, arts & entertainment (47% November-December, 39% January-February, Tab. S3), sports, amusement & recreation (39% November-February), membership organisations (44% September-October, 40% November-February) and other personal services, which includes hairdressing and beauty treatments (40% November-February). In January-February, retail and accommodation & food services need to close 89% and 78%, respectively. If H_{max}=12,000, additional closures are required in November and December, including accommodation & food services (78%), and retail (91%). From January onwards, accommodation & food services and retail need to close substantially (35% and 52%). If H_{max}=24,000, fewer closures are required and retail, accommodation & food services, and the arts can stay (nearly) fully open, but not some of the other sectors including sports & recreation which are still required to partially close.

The economic output achieved following a strategy that optimises GDP while the education sector is operational is £863bn over six months (H_{max}=18,000, Fig. 3B, Tab. S4 exact GVA losses), a gain of £193bn over the £670bn associated with a blanket lockdown of all sectors except education (Scenario LDB). The gain would be £163bn at H_{max}=12,000, and £205bn at H_{max}=24,000. There is a GDP loss associated with the 'education open' scenarios B compared to the 'GDP-maximizing' scenarios A (Figs. 3A and 3B), even when GDP is optimized via sectoral closures. When comparing B against A, the GDP maximizing scenario that may require the partial or full closure of any sector including education, the loss in GDP is £14bn (£877bn – £863bn, H_{max}=18,000). The loss between Scenarios A and B is significantly higher at £40bn if H_{max}=12,000, and lower at £5bn if H_{max}=24,000. This loss occurs because forcing the education sector open requires the closure of other sectors that make greater nominal GVA contributions, to compensate for the increase in transmissions caused by the education sector.

3.3 The role of hospital capacity

Hospital capacity has an important role to play in the trade-off between the closure of the education and other sectors. The optimal solution under Scenario A keeps occupancy at the maximum over 3 months (December-February), while it reaches the maximum for only one month (February) under Scenario B. This has very different implications for hospitals that we do not quantify here, but which are important to consider. Sector closures can be less stringent if decision makers are prepared to let the level of infections (and hospitalizations and deaths) increase, and if they invest in an expansion of emergency hospital capacity. The gain in GDP for Scenario B when hospital capacity is increased from 12,000 to 18,000 is £30bn over six months, and £12bn for an increase from 18,000 to 24,000 (Fig. 3B, Tab. S4). This gain occurs because the increase in hospital capacity by 6,000 beds allows for a more open economy (Figs. S3B, 2B, S4B). Over the first lockdown period, the UK managed to increase capacity to 18,000 beds by cancelling many elective surgeries, using private hospital capacity, deploying retired medical and nursing staff, constructing field hospitals and re-organizing care. Such interventions are not costless. Increasing capacity to 24,000 beds would require creation of additional hospital capacity and/or rationing of beds among all patients requiring life-saving intensive hospital care.

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3.4 Quantifying the loss of Gross Value Added by sector

We can quantify the GVA loss across the economic sectors that require partial closure under scenario B when comparing with Scenario FO (fully open economy). Given its relatively high contribution to transmission compared to GVA, the education sector would operate at 80% under any H_{max}. But for the other sectors, there are gains associated with increasing hospital capacity for Scenarios B (Fig. 4, Tab. S4). If H_{max}=12,000, the GVA loss for accommodation and food services amount to about £9.2bn, for retail about £8.3bn, personal services about £5.4bn, and for arts about £4.9bn. However, if we increased hospital capacity to H_{max}=24,000, there would be no GVA loss for accommodation and food and retail, and losses of less than £2bn for the other sectors. If we allow hospitalizations and infections to increase there will be more deaths, which of course are of central importance to decision makers but which we do not calculate as part of this study. Instead, they are implicit in the level of hospital capacity chosen by decision-makers.

3.5 Stringency of non-pharmaceutical interventions

The projections from all scenarios rest on the assumption that other NPIs are relatively stringent, i.e. that interventions such as wearing facemasks, social distancing, reduced mixing of households, self-isolation, and others are implemented and well adhered to. The fitted value of δ is 0.54, which reflects the reduction in R_t achieved by NPIs over the lockdown period. For all scenarios, we allow for about 11% less stringency in NPIs in the period after May 2020 by setting δ=0.6. We find that small increases in δ ranging from 0.61 to 0.64 for Scenario B (H_{max}=18,000) result in much stricter closures required to keep within the epidemiological constraints (Tab. S5 versus S3), and a substantial associated GVA loss (Fig. 5, Tab. S4). Weak NPIs translate into economic losses because stricter closures are required to keep within hospital capacity. For δ=0.64, sectors with high GVA losses are retail (£21bn), 'accommodation and food services' (£26bn), and 'human health activities' (£20bn), compared to Scenario FO. There is no feasible solution for δ=0.65 if hospital occupancy is constrained at 18,000 or below. This implies that it is impossible to keep the economy even minimally operational AND maximum hospital occupancy at 18,000 if there is weak adherence to NPIs. Effectively, a society that accepts more stringent NPIs is rewarded with a higher GDP and/or fewer infections. This implies that there is effectively a four-way trade-off between GDP, infections (and deaths), hospital capacity and social liberties.

3.6 Sensitivity analyses

Projected incidence is sensitive to contact rates in the community and the education sector (Fig. S5), and to assumptions on the proportion of workers working-from-home (Fig. S6). Children are probably less susceptible to infection than adults [30-32], though evidence is still conflicting [33, 34]. We evaluated the outcomes for scenario B (H_{max}=18,000) if children under the age of 16 have a 50% lower susceptibility to infection. We refitted the model to the same data and found that school closures have less impact on transmission dynamics (Fig S7). This implies that economic sectors need to close more strictly at a greater loss to GVA compared to the assumption of equal susceptibility, although the sectors recommended for closure are the same. Finally, we evaluated outcomes when changes to the economic configuration are allowed every month instead of two months (Fig. S7). The reduction in

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GVA loss is modest (£487 million, Tab. S4), which may not justify the upheaval associated with more frequent changes in policy.

4. Discussion

DAEDALUS examines the extent to which economic activity can be sustained whilst educational institutions are kept open and has been applied to the UK. If a differentiated sectoral closure strategy is followed, whereby certain economic sectors are partially closed over a six-month period, a GDP gain of between £163bn and £205bn over six months can be secured (depending on spare hospital capacity) compared to a blanket lockdown of all non-essential services. Differentiated sectoral closures that keep hospital occupancy at a set maximum (between 12,000 and 24,000) throughout the period are compared with a fully open economy that is projected to cause about 68,000 COVID-19 patients under active care at its peak. Activities that require partial closure in various months over autumn and winter 2020/21 are accommodation and food services including restaurants and bars, retail, creative and arts, entertainment, sports, amusement, recreation, and activities of membership organisations. To achieve the same outcomes, sectoral lockdowns need to be much stricter if other non-pharmaceutical interventions such as social distancing are weak. Decision makers can reoptimize for a new intervention period before the end of six months if objectives change or new data become available.

There are several studies that seek to model the economic impact of SARS-CoV-19 and control strategies [35]. Pichler et al [18] use a sophisticated economic model that considers interdependencies between sectors arising from both essential and non-essential inputs, and pandemic-related shocks to demand, supply and employment. The economic model is combined with a simple transmission model to project the impact of the March 2020 lockdown on GDP and transmission. Some studies investigate combined epidemiological and economic effects of lockdown policies, but fall short of calculating impact on GVA by sector considering their complex interdependencies [36-40]. Lastly, some studies assess the economic and financial impacts of the SARS-CoV-19 pandemic and control strategies at national and international level, but they do not integrate the analysis with an epidemiological model and do not offer projections of the combined economic and epidemiological impact of alternative policy interventions [35]. DAEDALUS poses the decision makers' problem as a constrained optimization of economic output and offers clear guidance on which sectors to open when, and to what extent. The parameters of the epidemiological model are aligned with Imperial College's Real-time Model [27].

Our analysis has important limitations. DAEDALUS relies on contact data classified by economic sector of employment. Although the French survey on which our data are based is likely to be representative of many high-income countries, such data would ideally be tailored directly to the country and the detailed sectors under scrutiny. Additionally, the sector in which the survey respondent is employed is reported only at high level and does not give further information on what type of work the individual performs. There are large variations in physical proximity by occupation type [41]. Similarly, we have made only rudimentary efforts to adjust for NPIs put in place to reduce transmission risk and voluntary behaviour change. It will be important to refine DAEDALUS as new data become available.

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The most recent available IO table is from 2016 and does not reflect recent changes in the economy. In line with usual IO methodology, we assume Leontief production functions with constant returns to scale [42]. With heterogeneous sectors it will always be the case that partial opening of a sector may be able to focus on subsectors that are highly productive or have low reliance on inputs from other sectors that remain closed. However, policymakers may find it difficult to formulate granular opening/closure policies focusing on economic activities within sectors and instead be forced towards blanket sectoral policies. A further concern is that – with constraints on supplies – some producers may change to alternative suppliers. However, relatively fixed production processes mean that there is likely to be limited scope for changing the sector in which the supplies are produced. Producers may instead seek to solve supply chain problems by importing inputs for which there are domestic shortages. We have built in some flexibility in production processes by allowing some tolerance in maximum and minimum levels of economic activity.

Finally, we make no allowance for changes in prices or demand for final products. To some extent, if demand changes for a sector's produce are expected and can be quantified, this can be incorporated into DAEDALUS by imposing an exogenous change to the relevant economic constraint. The major challenge is identifying the likely nature and magnitude of such changes in the absence of available data, although estimates may be forthcoming as evidence from countries' experiences becomes available.

DAEDALUS tries to minimize the deleterious effects to the broader economy of protecting education and health services, a policy trade-off that is being confronted worldwide. While the world is waiting for an effective vaccine, the policy challenge will be how to keep educational institutions open, the economy partially open, and keep the pandemic controlled so that health services are not overwhelmed. We need novel types of economic model that incorporate transmission dynamics as constraints [43]. DAEDALUS makes a first attempt. Faced with the prospect of a generation of children with poor educational outcomes and a recession of historic magnitude, we have little choice but to quantify difficult trade-offs. While the precise monthly economic configurations identified by our study are sensitive to the stringency of other NPIs, the recommended priority list of sectors to keep open and close proved robust to extensive sensitivity analyses.

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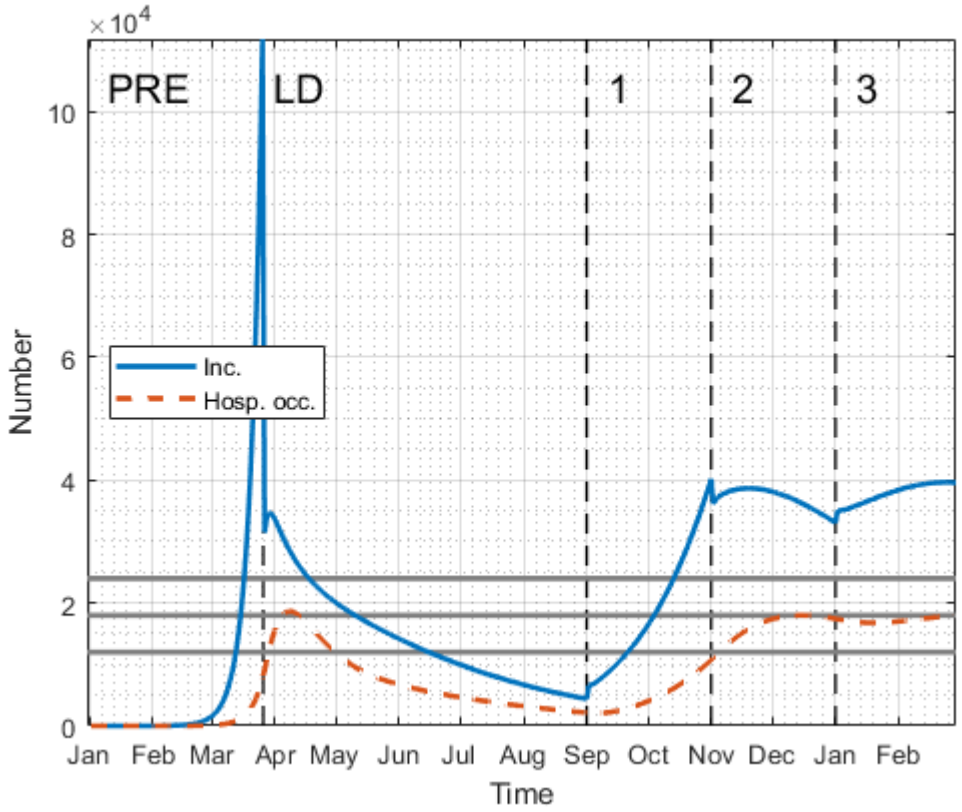
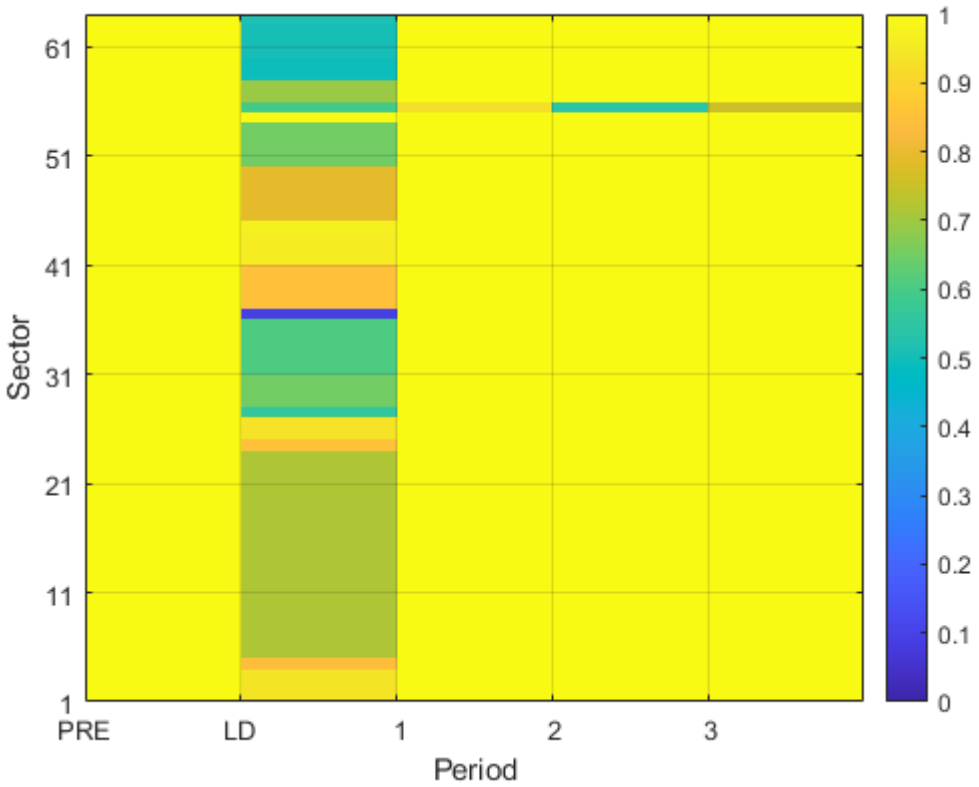
6. Figures



Panel 1A: Projected incidence and hospital occupancy



Panel 1B: Economic configuration across 63 economic sectors

Figure 1: Projected incidence, hospital occupancy and optimal economic configuration under scenario A (GDP maximization), hospital capacity 18,000 beds, January 2020 to February 2021

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Figure 1 Note: Scenario A maximizes GDP via successive bi-monthly opening and closing of 63 sectors over a six-months intervention period, subject to epidemiological and economic constraints; any economic sector including the education sector may be closed down to 80% of observed closure during the lockdown period (March – May 2020), but not lower, in order to sustain essential services; model fitted to English hospitalization data from 20th March to 30th June 2020;

Panel 1A shows projected daily infection incidence and daily hospital occupancy between January 2020 and February 2021. Three grey horizontal lines display alternative assumptions on maximum emergency hospital capacity for the treatment of COVID-19 patients. Here, hospital capacity is constrained at 18,000 beds (2nd line from below);

Panel 1B illustrates the economic configuration (bi-monthly sector openings) associated with Scenario A GDP maximization. PRE is the pre-pandemic period, LD is the lockdown period March – May 2020 in the UK, plotted for comparison based on data for closures of higher-level sector categories; Period 1-2 is September-October 2020, period 3-4 is November-December 2020, period 5-6 is January-February 2021; sectors are listed on the vertical axis, and months on the horizontal axis. Openings vary between fully open as pre-pandemic (yellow, 1) to closed (blue, 0), with optimal openings for each month over the intervention period September 2020 to February 2021 indicated.

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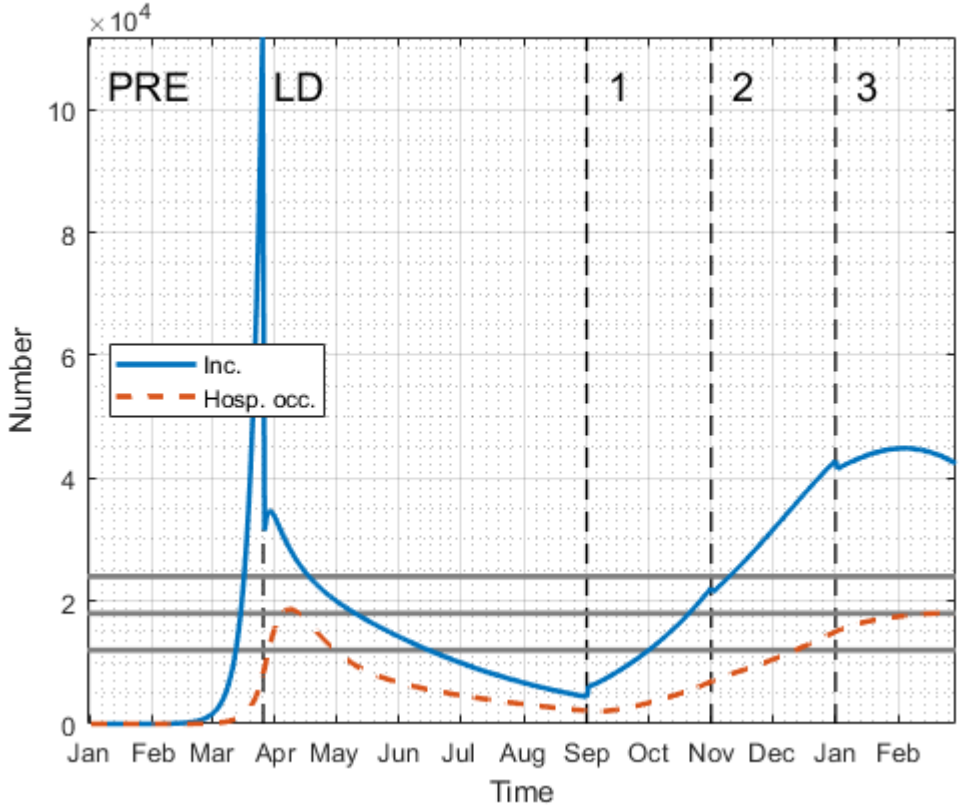
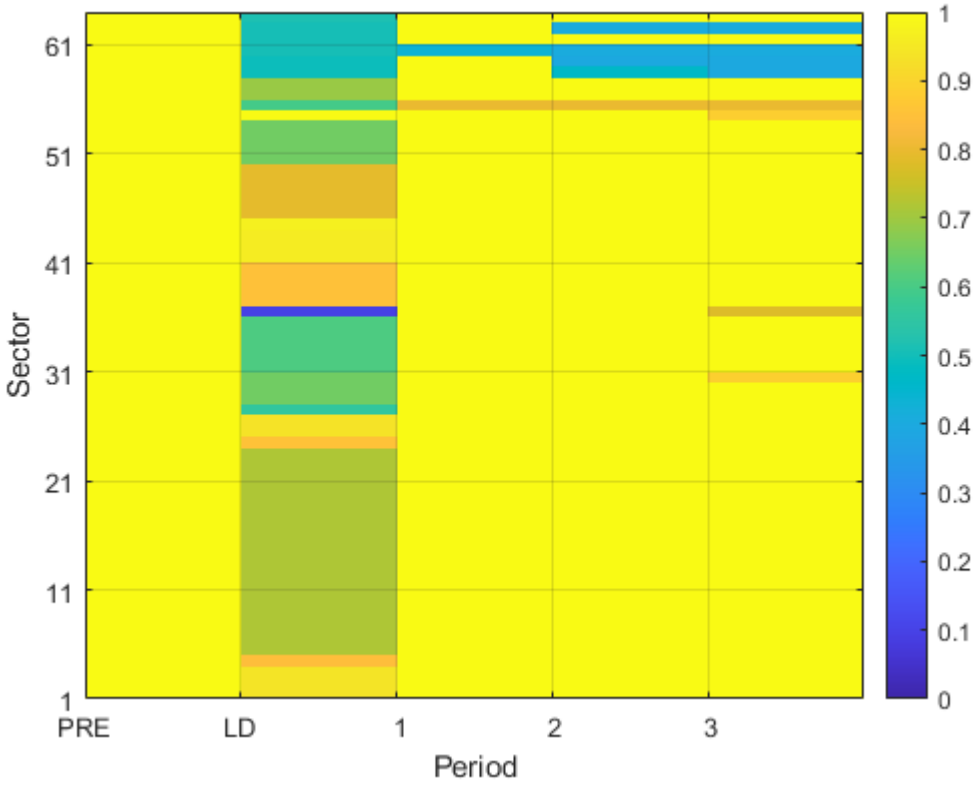


Panel 2A: Projected incidence and hospital occupancy



Panel Panel 2B: Economic configuration across 63 economic sectors

Figure 2: Projected incidence, hospital occupancy and optimal economic configuration under scenario B (education open), hospital capacity 18,000 beds, January 2020 to February 2021

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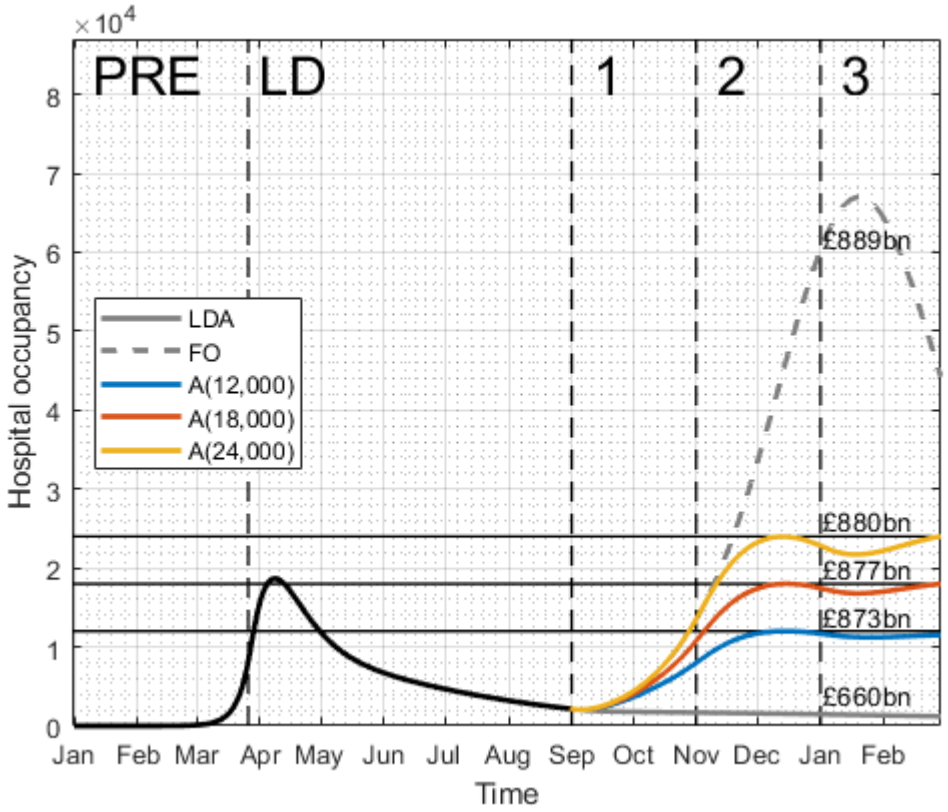
Figure 2 Note: Scenario B optimizes GDP via successive bi-monthly opening and closing of 63 sectors over a six-months intervention period, subject to epidemiological and economic constraints; any economic sector except for the education sector may be closed down to 80% of observed closure during the lockdown period (March – May 2020), but not lower, in order to sustain essential services; the education sector is constrained to stay open at or above 80% of pre-pandemic production levels; model fitted to hospitalization data for England from 20th March to 30th June 2020;

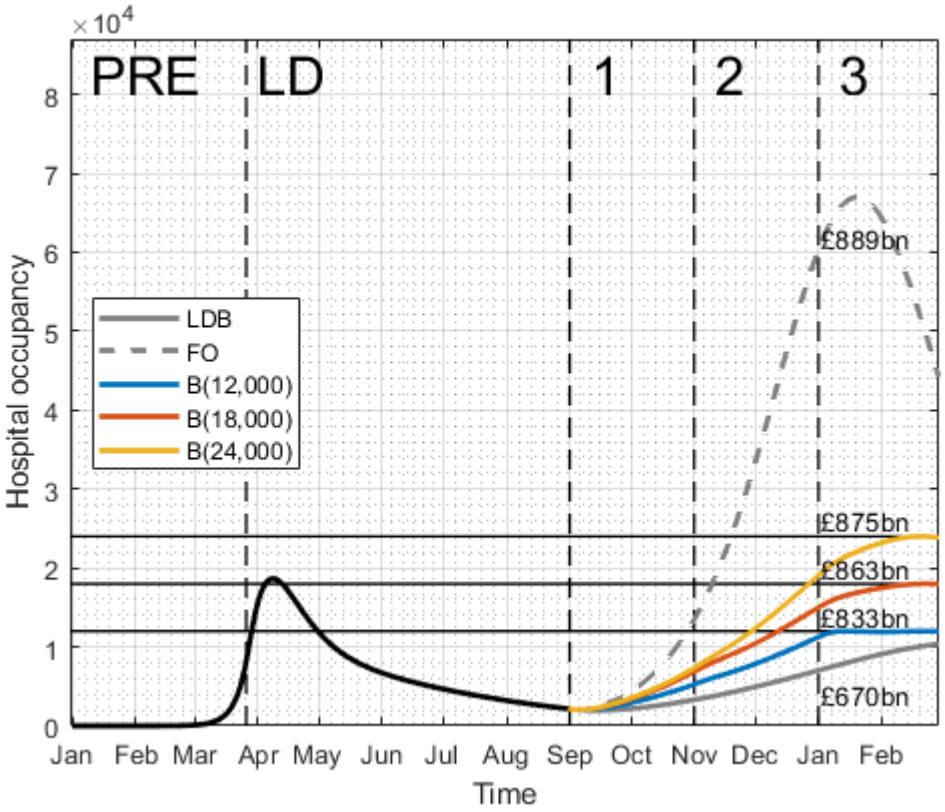
Panel 2A shows projected daily infection incidence and daily hospital occupancy between January 2020 and February 2021. The three grey horizontal lines display alternative assumptions on hospital capacity. Here, hospital capacity is constrained at 18,000 beds (2nd line from below);

Panel 2B illustrates the economic configuration (bi-monthly sector openings) associated with Scenario B 'education open'. PRE is the pre-pandemic period, LD is the lockdown period March – May 2020 in the UK, plotted for comparison based on data for closures of higher-level sector categories; Period 1-2 is September-October 2020, period 3-4 is November-December 2020, period 5-6 is January-February 2021; sectors are listed on the vertical axis, and months on the horizontal axis. Openings vary between fully open as pre-pandemic (yellow, 1) to closed (blue, 0), with optimal openings for each month over the intervention period September 2020 to February 2021 indicated.

DOI: https://doi.org/10.25561/83928



Panel 3A: Scenarios A (GDP maximization), LDA (lockdown), FO (fully open)



Panel 3B: Scenario B (education open), LDB (lockdown except education), FO (fully open)

Figure 3: Fitted and projected hospital occupancy and GDP for all scenarios, 3 hospital capacity constraints, January 2020 to February 2021

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Figure 3 Note: In scenario A any economic sector -including the education sector- may be closed down to 80% of observed closure during the lockdown period but not lower to sustain essential services;
in scenario B the education sector is open at 80% throughout and all other sectors may be closed down to 80% of observed closure during the lockdown period; in scenario LDA in panel 3A all economic sectors are closed to levels observed closure during the lockdown period;
in scenario LDB in panel 3B all economic sectors are closed to levels of observed closure during the lockdown period except for the education sector which is operational at 80%;
in scenario FO all sectors are open;
in all scenarios including FO, stringent NPIs and self-productive behaviour reduce transmission;
H_{max} represents three alternative assumptions on spare emergency hospital capacity for COVID-19 patients in scenarios A and B, indicated by the three grey horizontal lines;
displayed is aggregate GDP over six months;
PRE is the pre-pandemic period, LD is the lockdown period March – May 2020 in the UK.

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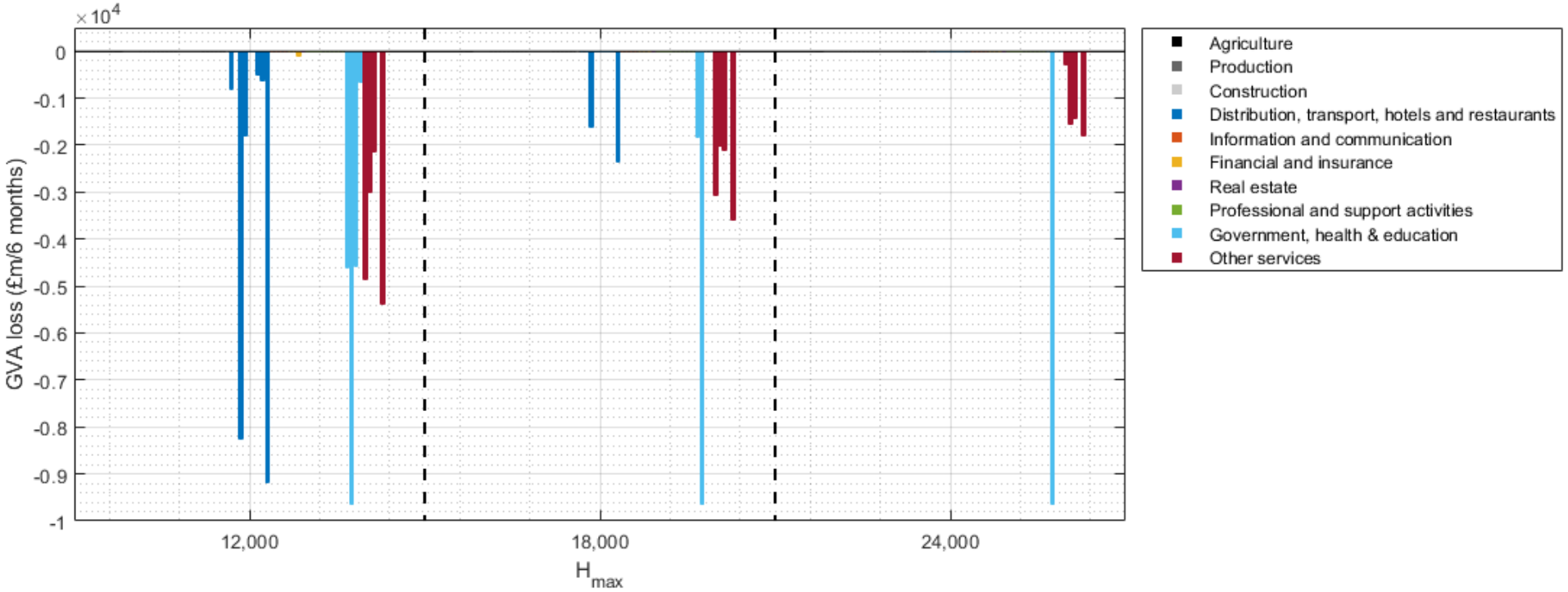

Figure 4: Loss in Gross Value Added due to sector closures under scenario B (education open) compared to FO (fully open), September 2020 to February 2021

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Figure 4 Note: The figure shows the extent of loss in Gross Value Added (GVA) over six months of the sectors selected for closure by Scenario B; GVA loss on the vertical axis denotes the aggregate loss in GVA £ million over six months that occurs because the sectors are partially closed, compared to a fully open economy (Scenario FO); H_{max} represents three alternative assumptions on spare emergency hospital capacity for COVID-19 patients. See Tab. S3 for exact values of closures for all 63 economic sectors;

H_{max}=12,000: **Dark blue sectors** from 'Distribution, transport, hotels and restaurants' from left to right are 28 'Wholesale and retail trade and repair of motor vehicles and motorcycles', 30 'Retail trade, except of motor vehicles and motorcycles' (loss of £8.3bn), 31 'Land transport and transport via pipelines', 34 'Warehousing and support activities for transportation', 35 'Postal and courier activities', 36 'Accommodation and food service activities' (loss of £9.2bn); **light blue sectors** from 'Government, health & education' from left to right are 55 'Public administration and defence; compulsory social security', 56 'Education' (loss of £9.7bn), 57 'Human health activities', 58 'Social work activities'; **dark red sectors** from 'Other services' from left to right are 59 'Creative, arts and entertainment activities; libraries, archives, museums and other cultural activities, gambling and betting activities', 60 'Sports activities and amusement and recreation activities', 61 'Activities of membership organisations', 63 'Other personal service activities'.

H_{max}=18,000: **dark blue sectors** from 'Distribution, transport, hotels and restaurants' from left to right are 30 'Retail trade, except of motor vehicles and motorcycles', 36 'Accommodation and food service activities'; **light blue sectors** from 'Government, health & education' from left to right are 55 'Public administration and defence; compulsory social security', 56 'Education' (loss of £9.7bn); **dark red sectors** from 'Other services' from left to right are 59 'Creative, arts and entertainment activities; libraries, archives, museums and other cultural activities; gambling and betting activities', 60 'Sports activities and amusement and recreation activities', 61 'Activities of membership organisations' 63 'Other personal service activities'.

H_{max}=24,000: **light blue sector** from 'Government, health & education' from left to right is 56 'Education' (loss of £9.7bn); **dark red sectors** from 'Other services' from left to right are 59 'Creative, arts and entertainment activities; libraries, archives, museums and other cultural activities; gambling and betting activities', 60 'Sports activities and amusement and recreation activities', 61 'Activities of membership organisations' 63 'Other personal service activities'.

DOI: https://doi.org/10.25561/83928

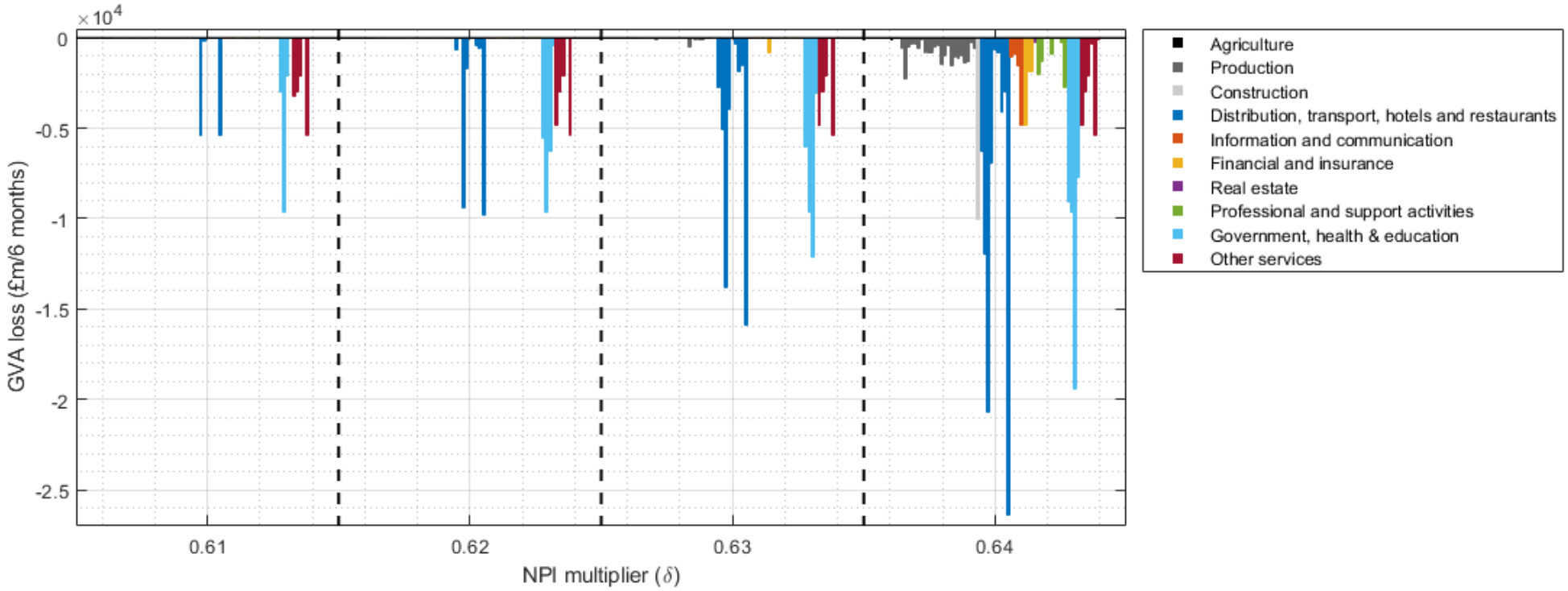

Figure 5: Loss in Gross Value Added under Scenario B (education open) and alternative assumptions on stringency of non-pharmaceutical interventions, September 2020 to February 2021

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Figure 5 note: Extent of loss in Gross Value Added (GVA) over six months of the sectors selected for closure by Scenario B under alternative assumptions on the stringency of NPIs and voluntary behaviour change from stronger (δ=0.61) to weaker (δ=0.64) stringency. The multiplier δ captures the dampening impact of NPIs and individuals' behaviour on transmissions as represented by R_t, including social distancing in social and work environments, facemasks, testing-and-tracing, self-isolation, shielding of the vulnerable, travel restrictions, and limits to social gatherings. Calibrated value of δ for the lockdown period March - May 2020 is 0.54.
GVA loss on the vertical axis denotes the aggregate loss in GVA £ million over six months that occurs because the sectors are partially closed, compared to a fully open economy (Scenario FO); H_{max}=18,000.

Sectors with aggregate GVA loss close to and above £5bn over 6 months are:

δ=0.61 (relatively stringent NPIs): Dark blue sectors from 'Distribution, transport, hotels and restaurants' from left to right are 30 'Retail trade, except of motor vehicles and motorcycles', and 36 'Accommodation and food service activities'; light blue sector from 'Government, health & education' is 56 'Education'; dark red sector from 'Other services' is 63 'Other personal service activities'.

δ=0.62: Dark blue sectors from 'Distribution, transport, hotels and restaurants' are 30 'Retail trade, except of motor vehicles and motorcycles', and 36 'Accommodation and food service activities'; light blue sectors from 'Government, health & education' are 55 'Public administration and defence; compulsory social security', 56 'Education', and 57 'Human health activities'; dark red sectors from 'Other services' are 59 'Creative, arts and entertainment activities; libraries, archives, museums and other cultural activities; gambling and betting activities', and 63 'Other personal service activities'.

δ=0.63: Dark blue sectors from 'Distribution, transport, hotels and restaurants' are 29 'Wholesale trade, except of motor vehicles and motorcycles', 30 'Retail trade, except of motor vehicles and motorcycles' (high loss of nearly £14bn), and 36 'Accommodation and food service activities' (high loss of nearly £16bn); light blue sectors from 'Government, health & education' are 55 'Public administration and defence; compulsory social security', 56 'Education', and 57 'Human health activities' (high loss of over £12bn); dark red sectors from 'Other services' are '59 Creative, arts and entertainment activities; libraries, archives, museums and other cultural activities; gambling and betting activities', and 63 'Other personal service activities'.

δ=0.64 (relatively weak NPIs): Light grey sector is 'Construction'; dark blue sectors from 'Distribution, transport, hotels and restaurants' are 28 'Wholesale and retail trade and repair of motor vehicles and motorcycles', 29 'Wholesale trade, except of motor vehicles and motorcycles' (high loss of £12bn), 30 'Retail trade, except of motor vehicles and motorcycles' (high GVA loss of nearly £21bn), 31 'Land transport and transport via pipelines', and 36 'Accommodation and food services' (high GVA loss of over £26bn); orange sector from 'Information and communication' is 40 'Computer programming, consultancy and related activities; information service activities; yellow sector from 'Financial and insurance' is 41 'Financial service activities, except insurance and pension funding'; light blue sectors from 'Government, health & education' are 55 'Public administration and defence; compulsory social security', 56 'Education', and 57 'Human health activities' (high GVA loss of over £19bn); dark red sectors from 'Other services' are 59 'Creative, arts and entertainment activities; libraries, archives, museums and other cultural activities; gambling and betting activities', and 63 'Other personal service activities'.

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7. Supplement

Table S1: Economic activities classified under Sector Industry Classification P (56 Education)

Code 85100: Pre-primary education	Church schools at nursery and primary level
List of activities classified inside the UK SIC Code 85100	Hospital schools at nursery and primary level
	Kindergartens
	Nursery schools
	Preprimary education
Code 85200: Primary education	Infant schools
List of activities classified inside the UK SIC Code 85200	Junior schools
	Middle schools deemed primary
	Preparatory schools
	Primary and preprimary education
	Primary education
	Primary schools
	Special schools at primary and preprimary level
Code 85310: General secondary education	Church schools at secondary level
List of activities classified inside the UK SIC Code 85310	Sixth form colleges
	Secondary schools
	Secondary modern schools
	Secondary level education
	School examination board
	Public schools
	Hospital schools at secondary level
	Grammar schools
	Convent schools at secondary level

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	Comprehensive schools
	Special schools at secondary level
Code 85320: Technical and vocational secondary education	Agricultural college
List of activities classified inside the UK SIC Code 85320	Management training establishment
	Military school
	Music teacher (own account)
	Nautical school
	Royal Academy of Dramatic Art
	School of arts and crafts
	School of speech and drama
	Secretarial college
	Seminary
	Technical and vocational adult education (excl. cultural, sports, recreation education and the like)
	Technical and vocational education
	Technical and vocational secondary education
	Technical college
	Tertiary college
	Tourist guide instruction
	Tuition for ships licences for commercial certificates and permits
	Instruction for chefs, hoteliers and restaurateurs
	Government training centre
	Apprentice school
	Arts and crafts school
	Ballet school
	City and Guilds of London Institute
	Civil service college
	Tuition for ships licences for commercial certificates and permits
	Instruction for chefs, hoteliers and restaurateurs
	Government training centre

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	Apprentice school
	Arts and crafts school
	Ballet school
	City and Guilds of London Institute
	Civil service college
Code 85410: Post-secondary non-tertiary education	College of nursing
List of activities classified inside the UK SIC Code 85410	Higher education (sub degree level)
	Postsecondary nontertiary vocational education
	School of languages
	Vocational education at postsecondary nontertial level
Code 85421: First-degree level higher education	College of higher education (degree level)
List of activities classified inside the UK SIC Code 85421	University college
	University
	Universities Central Council on Admissions
	Theological college specialising in higher education course
	Study leading to a one year post graduate certificate of education (PGCE)
	Polytechnics
	Performing arts schools providing tertiary education
	Open University
	Military college
	Medical school
	Law college
	Higher education at the first degree level
	Graduate school for business studies
	Firstdegree level higher education
	Dental college or school
	Council for National Academic Awards
	Correspondence college specialising in higher education courses (degree level)
	University medical or dental school

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Code 85422: Post-graduate level higher education	Higher education at postgraduate level
List of activities classified inside the UK SIC Code 85422	Postgraduate college
Code 85510: Sports and recreation education	Bridge instructor
List of activities classified inside the UK SIC Code 85510	Teachers of sport
	Swimming instruction
	Sports and recreation education
	Sport and game schools
	Ski instructor (own account)
	Riding school
	Martial arts instruction
	Instructors of sport
	Gymnastics instruction
	Coaches of sport
	Chess instructor
	Card game instruction
	Yoga instruction
Code 85520: Cultural education	Art instruction
List of activities classified inside the UK SIC Code 85520	Photography schools (except commercial)
	Performing arts schools (except academic)
	Fine arts schools (except academic)
	Dancing schools and dance instructor activities
	Dancing school
	Dancing master
	Dancing academy (ballroom)
	Cultural education
	Piano teachers and other music instruction
Code 85530: Driving school activities	Driving instruction
List of activities classified inside the UK SIC Code 85530	Driving school activities
	Flying school activities (not type rating)

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	Flying schools not issuing commercial certificates and permits
	Sailing schools not issuing commercial certificates and permits
	School of motoring
	Ship licence tuition (not commercial certificates)
	Shipping schools not issuing commercial certificates and permits
Code 85590: Other education n.e.c.	Academic tutoring
List of activities classified inside the UK SIC Code 85590	National institute for adult continuing education
	Other adult and other education n.e.c.
	Private training providers
	Professional examination review courses
	Public speaking training
	Religious instruction
	Speed reading instruction
	Survival training
	Teacher n.e.c.
	Mentally handicapped adult training
	Lifeguard training
	Adult education centre
	Adult education residential college
	Computer training
	Continuation school
	Correspondence college (not leading to degree level qualifications)
	Council for Accreditation of Correspondence Colleges
	Day continuation school
	Language instruction and conversational skills instruction
	Learning centres offering remedial courses
	Workers Educational Association
Code 85600: Educational support activities	Educational consulting
List of activities classified inside the UK SIC Code 85600	Educational guidance counselling activities

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	Educational support activities
	Educational testing activities
	Educational testing evaluation activities
	Organisation of student exchange programmes
	Scholastic agent
	School agent

Source: https://www.siccode.co.uk/section/p

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Table S2: Closures of the education sector under Scenarios A (GDP maximization) and LDA (lockdown)

LDA*	A: max occupancy 12,000 beds			A: max occupancy 18,000 beds			A: max occupancy 24,000 beds			sector	
	Sept/Oct	Nov/Dec	Jan/Feb	Sept/Oct	Nov/Dec	Jan/Feb	Sept/Oct	Nov/Dec	Jan/Feb	division	description
0.59	0.83	0.51	0.65	0.93	0.54	0.76	1	0.56	0.86	56	Education

Note: shown are closures (1: open, 0: fully closed) of the education sector in percentage compared to pre-pandemic level of production; we find that under scenario A, all sectors except for the education sector are open at pre-pandemic levels; each column shows bi-monthly periods of fixed closures of the education sector; *Under scenario LDA, the closure values for all sectors except for the education sector are the same as in LDB, see Tab. S3.

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Table S3: Closures of economic sectors under Scenarios B (education open) and LDB (lockdown except education)

LDB	B (12,000)			B (18,000)			B (24,000)			Sectors		
Sept-Feb	Sept/ Oct	Nov/ Dec	Jan/ Feb	Sept/ Oct	Nov/ Dec	Jan /Feb	Sept/ Oct	Nov/ Dec	Jan/Feb	Sections and divisions		Description
0.94	1	1	1	1	1	1	1	1	1	[A]	1	Crop and animal production, hunting and related service activities
0.94	1	1	1	1	1	1	1	1	1	[A]	2	Forestry and logging
0.94	1	1	1	1	1	1	1	1	1	[A]	3	Fishing and aquaculture
0.84	1	1	1	1	1	1	1	1	1	[B-E]	4	Mining and quarrying
0.72	1	1	1	1	1	1	1	1	1	[B-E]	5	Manufacture of food products, beverages and tobacco products
0.72	1	1	1	1	1	1	1	1	1	[B-E]	6	Manufacture of textiles, wearing apparel and leather products
0.72	1	1	1	1	1	1	1	1	1	[B-E]	7	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
0.72	1	1	1	1	1	1	1	1	1	[B-E]	8	Manufacture of paper and paper products
0.72	1	1	1	1	1	1	1	1	1	[B-E]	9	Printing and reproduction of recorded media
0.72	1	1	1	1	1	1	1	1	1	[B-E]	10	Manufacture of coke and refined petroleum products
0.72	1	1	1	1	1	1	1	1	1	[B-E]	11	Manufacture of chemicals and chemical products
0.72	1	1	1	1	1	1	1	1	1	[B-E]	12	Manufacture of basic pharmaceutical products and pharmaceutical preparations
0.72	1	1	1	1	1	1	1	1	1	[B-E]	13	Manufacture of rubber and plastic products
0.72	1	1	1	1	1	1	1	1	1	[B-E]	14	Manufacture of other non-metallic mineral products
0.72	1	1	1	1	1	1	1	1	1	[B-E]	15	Manufacture of basic metals
0.72	1	1	1	1	1	1	1	1	1	[B-E]	16	Manufacture of fabricated metal products, except machinery and equipment
0.72	1	1	1	1	1	1	1	1	1	[B-E]	17	Manufacture of computer, electronic and optical products
0.72	1	1	1	1	1	1	1	1	1	[B-E]	18	Manufacture of electrical equipment
0.72	1	1	1	1	1	1	1	1	1	[B-E]	19	Manufacture of machinery and equipment not. elsewhere. classified.
0.72	1	1	1	1	1	1	1	1	1	[B-E]	20	Manufacture of motor vehicles, trailers and semi-trailers
0.72	1	1	1	1	1	1	1	1	1	[B-E]	21	Manufacture of other transport equipment

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0.72	1	1	1	1	1	1	1	1	1	[B-E]	22	Manufacture of furniture; other manufacturing
0.72	1	1	1	1	1	1	1	1	1	[B-E]	23	Repair and installation of machinery and equipment
0.85	1	1	1	1	1	1	1	1	1	[B-E]	24	Electricity, gas, steam and air conditioning supply
0.94	1	1	1	1	1	1	1	1	1	[B-E]	25	Water collection, treatment and supply
0.94	1	1	1	1	1	1	1	1	1	[B-E]	26	Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services
0.56	1	1	1	1	1	1	1	1	1	[F]	27	Construction
0.65	1	1	0.84	1	1	1	1	1	1	[G-I]	28	Wholesale and retail trade and repair of motor vehicles and motorcycles
0.65	1	1	1	1	1	1	1	1	1	[G-I]	29	Wholesale trade, except of motor vehicles and motorcycles
0.65	1	0.91	0.52	1	1	0.89	1	1	1	[G-I]	30	Retail trade, except of motor vehicles and motorcycles
0.61	1	1	0.63	1	1	1	1	1	1	[G-I]	31	Land transport and transport via pipelines
0.61	1	1	1	1	1	1	1	1	1	[G-I]	32	Water transport
0.61	1	1	1	1	1	1	1	1	1	[G-I]	33	Air transport
0.61	1	1	0.85	1	1	1	1	1	1	[G-I]	34	Warehousing and support activities for transportation
0.61	1	1	0.7	1	1	1	1	1	1	[G-I]	35	Postal and courier activities
0.09	1	0.78	0.35	1	1	0.78	1	1	1	[G-I]	36	Accommodation and food service activities
0.85	1	1	1	1	1	1	1	1	1	[J]	37	Publishing activities
0.85	1	1	1	1	1	1	1	1	1	[J]	38	Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities
0.85	1	1	1	1	1	1	1	1	1	[J]	39	Telecommunications
0.85	1	1	1	1	1	1	1	1	1	[J]	40	Computer programming, consultancy and related activities; information service activities
0.96	1	1	1	1	1	1	1	1	1	[K]	41	Financial service activities, except insurance and pension funding
0.96	1	1	1	1	1	1	1	1	1	[K]	42	Insurance, reinsurance and pension funding, except compulsory social security
0.96	1	1	0.97	1	1	1	1	1	1	[K]	43	Activities auxiliary to financial services and insurance activities
0.97	1	1	1	1	1	1	1	1	1	[L]	44& 45	Real estate activities & imputed rents of owner-occupied dwellings4

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0.79	1	1	1	1	1	1	1	1	1	[M-N]	46	Legal and accounting activities; activities of head offices; management consultancy activities
0.79	1	1	1	1	1	1	1	1	1	[M-N]	47	Architectural and engineering activities; technical testing and analysis
0.79	1	1	1	1	1	1	1	1	1	[M-N]	48	Scientific research and development
0.79	1	1	1	1	1	1	1	1	1	[M-N]	49	Advertising and market research
0.79	1	1	1	1	1	1	1	1	1	[M-N]	50	Other professional, scientific and technical activities; veterinary activities
0.65	1	1	1	1	1	1	1	1	1	[M-N]	51	Rental and leasing activities
0.65	1	1	1	1	1	1	1	1	1	[M-N]	52	Employment activities
0.65	1	1	1	1	1	1	1	1	1	[M-N]	53	Travel agency, tour operator reservation service and related activities
0.65	1	1	1	1	1	1	1	1	1	[M-N]	54	Security and investigation activities; services to buildings and landscape activities; office administrative, office support and other business support activities
1.01	1	0.9	0.8	1	1	0.88	1	1	1	[O-Q]	55	Public administration and defence; compulsory social security
0.80	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	[O-Q]	56	Education
0.69	1	1	0.69	1	1	1	1	1	1	[O-Q]	57	Human health activities
0.69	1	1	0.91	1	1	1	1	1	1	[O-Q]	58	Social work activities
0.49	0.39	0.39	0.39	1	0.47	0.39	1	1	0.9	[R-T]	59	Creative, arts and entertainment activities; libraries, archives, museums and other cultural activities; gambling and betting activities
0.49	0.39	0.39	0.39	1	0.39	0.39	1	0.67	0.39	[R-T]	60	Sports activities and amusement and recreation activities
0.51	0.4	0.4	0.4	0.44	0.4	0.4	1	0.4	0.4	[R-T]	61	Activities of membership organisations
0.51	1	1	1	1	1	1	1	1	1	[R-T]	62	Repair of computers and personal and household goods
0.51	0.4	0.4	0.4	1	0.4	0.4	1	1	0.4	[R-T]	63	Other personal service activities
0.51	1	1	1	1	1	1	1	1	1	[R-T]	64	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use

Note: shown are closures (1: open, 0: fully closed) of all economic sector in percentage compared to pre-pandemic level of production under scenarios B and LDB; The two months denote periods of fixed economic configurations required under scenario B; the education is open at 80% pre-pandemic production under scenario B; *Under scenario LDA, the closure values for all sectors except for the education sector are the same as in LDB, see Tab. S3.

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Table S4: Loss in Gross Value Added under all scenarios

LDA	LDB	A (12,000)	A (18,000)	A (24,000)	B (12,000)	B (18,000)	B (24,000)	B (6x1, 18,000)	B (δ=0.64 18,000)	Sector sections and divisions		Description
313	313	0	0	0	0	0	0	0	124	[A]	1	Crop and animal production, hunting and related service activities
15	15	0	0	0	0	0	0	0	20	[A]	2	Forestry and logging
16	16	0	0	0	0	0	0	0	0	[A]	3	Fishing and aquaculture
797	797	0	0	0	0	0	0	0	548	[B-E]	4	Mining and quarrying
3815	3815	0	0	0	0	0	0	0	2295	[B-E]	5	Manufacture of food products, beverages and tobacco products
742	742	0	0	0	0	0	0	0	488	[B-E]	6	Manufacture of textiles, wearing apparel and leather products
476	476	0	0	0	0	0	0	0	378	[B-E]	7	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
663	663	0	0	0	0	0	0	0	332	[B-E]	8	Manufacture of paper and paper products
586	586	0	0	0	0	0	0	0	561	[B-E]	9	Printing and reproduction of recorded media
280	280	0	0	0	0	0	0	0	141	[B-E]	10	Manufacture of coke and refined petroleum products
1620	1620	0	0	0	0	0	0	0	813	[B-E]	11	Manufacture of chemicals and chemical products
1629	1629	0	0	0	0	0	0	0	817	[B-E]	12	Manufacture of basic pharmaceutical products and pharmaceutical preparations
1069	1069	0	0	0	0	0	0	0	835	[B-E]	13	Manufacture of rubber and plastic products
797	797	0	0	0	0	0	0	0	523	[B-E]	14	Manufacture of other non-metallic mineral products
592	592	0	0	0	0	0	0	0	436	[B-E]	15	Manufacture of basic metals
2037	2037	0	0	0	0	0	0	0	1495	[B-E]	16	Manufacture of fabricated metal products, except machinery and equipment
1789	1789	0	0	0	0	0	0	0	947	[B-E]	17	Manufacture of computer, electronic and optical products
661	661	0	0	0	0	0	0	0	425	[B-E]	18	Manufacture of electrical equipment
1528	1528	0	0	0	0	0	0	0	1534	[B-E]	19	Manufacture of machinery and equipment not. elsewhere. classified.
2165	2165	0	0	0	0	0	0	0	1086	[B-E]	20	Manufacture of motor vehicles, trailers and semi-trailers
1274	1274	0	0	0	0	0	0	0	1146	[B-E]	21	Manufacture of other transport equipment
1103	1103	0	0	0	0	0	0	0	1004	[B-E]	22	Manufacture of furniture; other manufacturing

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1569	1569	0	0	0	0	0	0	0	1373	[B-E]	23	Repair and installation of machinery and equipment
1906	1906	0	0	0	0	0	0	0	1331	[B-E]	24	Electricity, gas, steam and air conditioning supply
221	221	0	0	0	0	0	0	0	287	[B-E]	25	Water collection, treatment and supply
469	469	0	0	0	0	0	0	0	609	[B-E]	26	Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services
24100	24100	0	0	0	0	0	0	0	10057	[F]	27	Construction
5218	5218	0	0	0	812	0	0	0	6243	[G-I]	28	Wholesale and retail trade and repair of motor vehicles and motorcycles
13101	13101	0	0	0	0	0	0	0	11988	[G-I]	29	Wholesale trade, except of motor vehicles and motorcycles
15095	15095	0	0	0	8269	1603	0	1924	20718	[G-I]	30	Retail trade, except of motor vehicles and motorcycles
5762	5762	0	0	0	1800	0	0	0	6947	[G-I]	31	Land transport and transport via pipelines
1156	1156	0	0	0	0	0	0	0	664	[G-I]	32	Water transport
941	941	0	0	0	0	0	0	0	822	[G-I]	33	Air transport
3875	3875	0	0	0	502	0	0	0	4104	[G-I]	34	Warehousing and support activities for transportation
2507	2507	0	0	0	632	0	0	0	3024	[G-I]	35	Postal and courier activities
28806	28806	0	0	0	9194	2346	0	2535	26376	[G-I]	36	Accommodation and food service activities
885	885	0	0	0	0	0	0	0	1063	[J]	37	Publishing activities
1264	1264	0	0	0	0	0	0	0	893	[J]	38	Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities
2175	2175	0	0	0	0	0	0	0	1537	[J]	39	Telecommunications
4088	4088	0	0	0	0	0	0	0	4854	[J]	40	Computer programming, consultancy and related activities; information service activities
1396	1396	0	0	0	0	0	0	0	4870	[K]	41	Financial service activities, except insurance and pension funding
533	533	0	0	0	0	0	0	0	1860	[K]	42	Insurance, reinsurance and pension funding, except compulsory social security
444	444	0	0	0	106	0	0	0	1856	[K]	43	Activities auxiliary to financial services and insurance activities
3779	3779	0	0	0	0	0	0	0	246	[L]	44&45	Real estate activities & imputed rents of owner-occupied dwellings4

6897	6897	0	0	0	0	0	0	0	2022	[M-N]	46	Legal and accounting activities; activities of head offices; management consultancy activities
2185	2185	0	0	0	0	0	0	0	1275	[M-N]	47	Architectural and engineering activities; technical testing and analysis
2160	2160	0	0	0	0	0	0	0	0	[M-N]	48	Scientific research and development
2520	2520	0	0	0	0	0	0	0	0	[M-N]	49	Advertising and market research
1549	1549	0	0	0	0	0	0	0	904	[M-N]	50	Other professional, scientific and technical activities; veterinary activities
3989	3989	0	0	0	0	0	0	0	0	[M-N]	51	Rental and leasing activities
4642	4642	0	0	0	0	0	0	0	0	[M-N]	52	Employment activities
1666	1666	0	0	0	0	0	0	0	263	[M-N]	53	Travel agency, tour operator reservation service and related activities
6049	6049	0	0	0	0	0	0	0	2773	[M-N]	54	Security and investigation activities; services to buildings and landscape activities; office administrative, office support and other business support activities
0	0	0	0	0	4611	1829	0	2167	9060	[O-Q]	55	Public administration and defence; compulsory social security
19589	9655	16237	12478	9335	9655	9655	9655	9655	9654	[O-Q]	56	Education*
13718	13718	0	0	0	4573	0	0	0	19399	[O-Q]	57	Human health activities*
6285	6285	0	0	0	646	0	0	0	7738	[O-Q]	58	Social work activities
4070	4070	0	0	0	4864	3053	280	2432	4863	[R-T]	59	Creative, arts and entertainment activities; libraries, archives, museums and other cultural activities; gambling and betting activities
2523	2523	0	1	1	3014	2010	1551	2512	3015	[R-T]	60	Sports activities and amusement and recreation activities
1777	1777	0	1	1	2141	2104	1427	1784	2142	[R-T]	61	Activities of membership organisations
613	613	0	0	0	0	0	0	0	314	[R-T]	62	Repair of computers and personal and household goods
4476	4476	0	0	0	5391	3594	1797	2696	5391	[R-T]	63	Other personal service activities
1206	1206	0	0	0	0	0	0	0	69	[R-T]	64	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use
229174	**219240**	**16256**	**12484**	**9354**	**56211**	**26192**	**14711**	**25705**	**196552**			**total GVA loss (compared to FO)**

Note: For all scenarios GVA loss is reported in £ millions against a fully open economy (FO);

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In scenario A any economic sector -including the education sector- may be closed down to 80% of observed closure during the lockdown period but not lower to sustain essential services;
in scenario B the education sector is open at 80% throughout and all other sectors may be closed down to 80% of observed closure during the lockdown period;
in scenario LDA all economic sectors are closed to levels observed closure during the lockdown period March - May 2020;
in scenario LDB all economic sectors except for the education sector are closed to levels of observed closure during the lockdown period and the education sector is operational at 80%;
three alternative assumptions on spare emergency hospital capacity for COVID-19 patients in scenarios A and B (12,000, 18,000, 24,000);
all scenarios assume changes in economic configuration every 2 months except for B (6x1, 18,000) which allows changes every month;
all scenarios including FO assume that stringency of NPIs and self-productive behaviour reduce transmission substantially (δ=0.61) except for scenario B (δ=0.64, 18,000) which assumes weak stringency of non-pharmaceutical interventions and/or little self-protective behaviour in the population;
*Measuring the GVA contribution of education and human health activities is problematic [29]

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Table S5: Closures of economic sectors under weak stringency of non-pharmaceutical interventions (δ=0.64), Scenario B (education open), H_{max}=18,000

Sept/Oct	Nov/Dec	Jan/Feb	Sector sections and divisions		Descriptions
1	1	0.93	[A]	1	Crop and animal production, hunting and related service activities
1	1	0.75	[A]	2	Forestry and logging
1	1	1	[A]	3	Fishing and aquaculture
1	1	0.67	[B-E]	4	Mining and quarrying
1	0.91	0.57	[B-E]	5	Manufacture of food products, beverages and tobacco products
1	0.87	0.57	[B-E]	6	Manufacture of textiles, wearing apparel and leather products
1	0.75	0.57	[B-E]	7	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
1	1	0.57	[B-E]	8	Manufacture of paper and paper products
1	0.61	0.57	[B-E]	9	Printing and reproduction of recorded media
1	1	0.57	[B-E]	10	Manufacture of coke and refined petroleum products
1	1	0.57	[B-E]	11	Manufacture of chemicals and chemical products
1	1	0.57	[B-E]	12	Manufacture of basic pharmaceutical products and pharmaceutical preparations
1	0.76	0.57	[B-E]	13	Manufacture of rubber and plastic products
1	0.87	0.57	[B-E]	14	Manufacture of other non-metallic mineral products
1	0.80	0.57	[B-E]	15	Manufacture of basic metals
1	0.80	0.57	[B-E]	16	Manufacture of fabricated metal products, except machinery and equipment
1	0.98	0.57	[B-E]	17	Manufacture of computer, electronic and optical products
1	0.88	0.57	[B-E]	18	Manufacture of electrical equipment
1	0.57	0.57	[B-E]	19	Manufacture of machinery and equipment not. elsewhere. classified.
1	1	0.57	[B-E]	20	Manufacture of motor vehicles, trailers and semi-trailers
1	0.66	0.57	[B-E]	21	Manufacture of other transport equipment
1	0.65	0.57	[B-E]	22	Manufacture of furniture; other manufacturing
1	0.68	0.57	[B-E]	23	Repair and installation of machinery and equipment
1	1	0.69	[B-E]	24	Electricity, gas, steam and air conditioning supply

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1	1	0.75	[B-E]	25	Water collection, treatment and supply
1	1	0.75	[B-E]	26	Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services
1	1	0.45	[F]	27	Construction
0.71	0.52	0.52	[G-I]	28	Wholesale and retail trade and repair of motor vehicles and motorcycles
1	0.52	0.52	[G-I]	29	Wholesale trade, except of motor vehicles and motorcycles
0.52	0.52	0.52	[G-I]	30	Retail trade, except of motor vehicles and motorcycles
0.61	0.49	0.49	[G-I]	31	Land transport and transport via pipelines
1	0.84	0.49	[G-I]	32	Water transport
1	0.49	0.49	[G-I]	33	Air transport
0.78	0.49	0.49	[G-I]	34	Warehousing and support activities for transportation
0.61	0.49	0.49	[G-I]	35	Postal and courier activities
0.35	0.08	0.08	[G-I]	36	Accommodation and food service activities
1	0.78	0.68	[J]	37	Publishing activities
1	1	0.68	[J]	38	Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities
1	1	0.68	[J]	39	Telecommunications
1	0.78	0.68	[J]	40	Computer programming, consultancy and related activities; information service activities
1	0.81	0.77	[K]	41	Financial service activities, except insurance and pension funding
1	0.81	0.77	[K]	42	Insurance, reinsurance and pension funding, except compulsory social security
0.96	0.77	0.77	[K]	43	Activities auxiliary to financial services and insurance activities
1	1	0.99	[L]	44&45	Real estate activities & imputed rents of owner-occupied dwellings4
1	1	0.81	[M-N]	46	Legal and accounting activities; activities of head offices; management consultancy activities
1	1	0.63	[M-N]	47	Architectural and engineering activities; technical testing and analysis
1	1	1	[M-N]	48	Scientific research and development
1	1	1	[M-N]	49	Advertising and market research
1	1	0.63	[M-N]	50	Other professional, scientific and technical activities; veterinary activities
1	1	1	[M-N]	51	Rental and leasing activities

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1	1	1	[M-N]	52	Employment activities
1	1	0.84	[M-N]	53	Travel agency, tour operator reservation service and related activities
1	1	0.52	[M-N]	54	Security and investigation activities; services to buildings and landscape activities; office administrative, office support and other business support activities
0.80	0.80	0.80	[O-Q]	55	Public administration and defence; compulsory social security
0.80	0.80	0.80	[O-Q]	56	Education*
0.59	0.56	0.56	[O-Q]	57	Human health activities*
0.76	0.56	0.56	[O-Q]	58	Social work activities
0.39	0.39	0.39	[R-T]	59	Creative, arts and entertainment activities; libraries, archives, museums and other cultural activities; gambling and betting activities
0.39	0.39	0.39	[R-T]	60	Sports activities and amusement and recreation activities
0.40	0.40	0.40	[R-T]	61	Activities of membership organisations
1	0.84	0.40	[R-T]	62	Repair of computers and personal and household goods
0.40	0.40	0.40	[R-T]	63	Other personal service activities
1	1	0.92	[R-T]	64	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use

Note: shown are closures (1: open, 0: fully closed) of all economic sectors in percentage compared to pre-pandemic level of production under scenario B assuming weak stringency of non-pharmaceutical interventions and/or little self-protective behaviour in the population (δ=0.64); maximum spare emergency hospital capacity for the treatment of COVID-19 patients is 18,000 beds; the two months denote periods of fixed economic configurations required under scenario B; the education sector is open at 80% pre-pandemic production.

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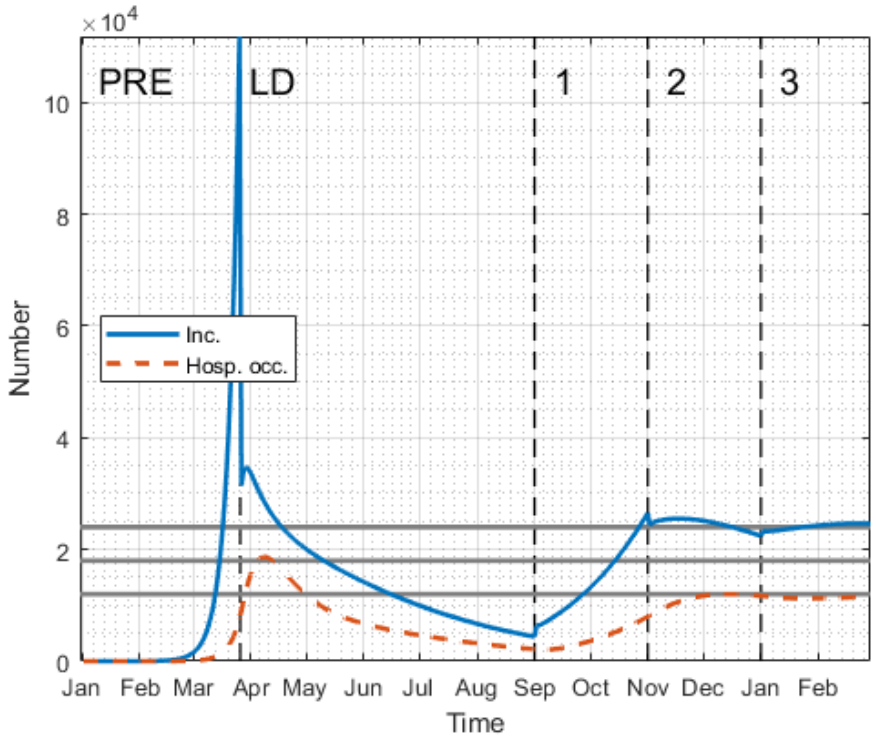
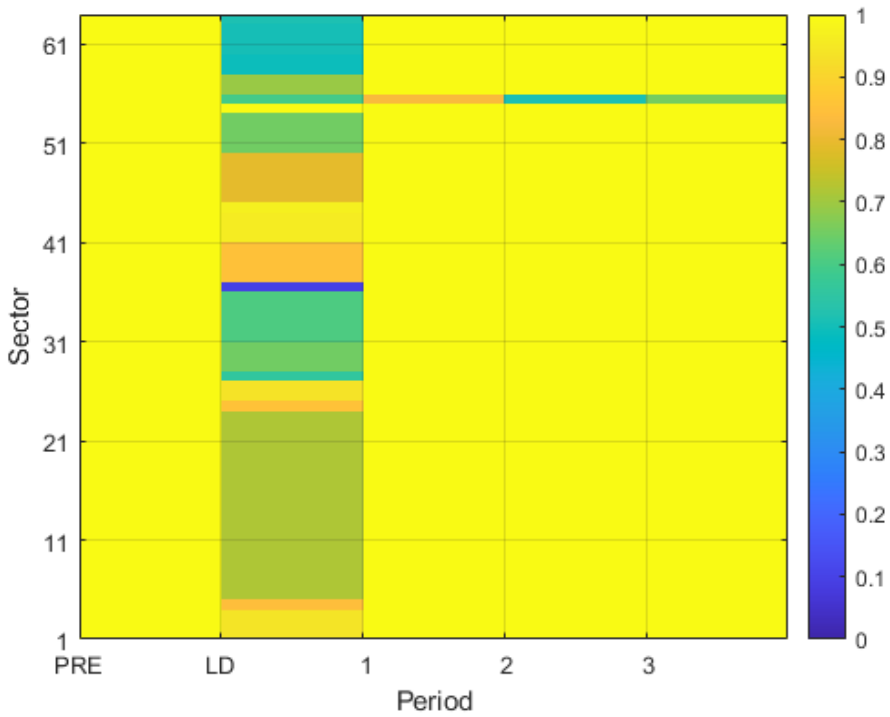


Panel S1A: Projected incidence and hospital occupancy



Panel S1B: Economic configuration across 63 economic sectors

Figure S1: Projected incidence, hospital occupancy and optimal economic configuration under scenario A (GDP maximization), hospital capacity 12,000 beds, January 2020 to February 2021

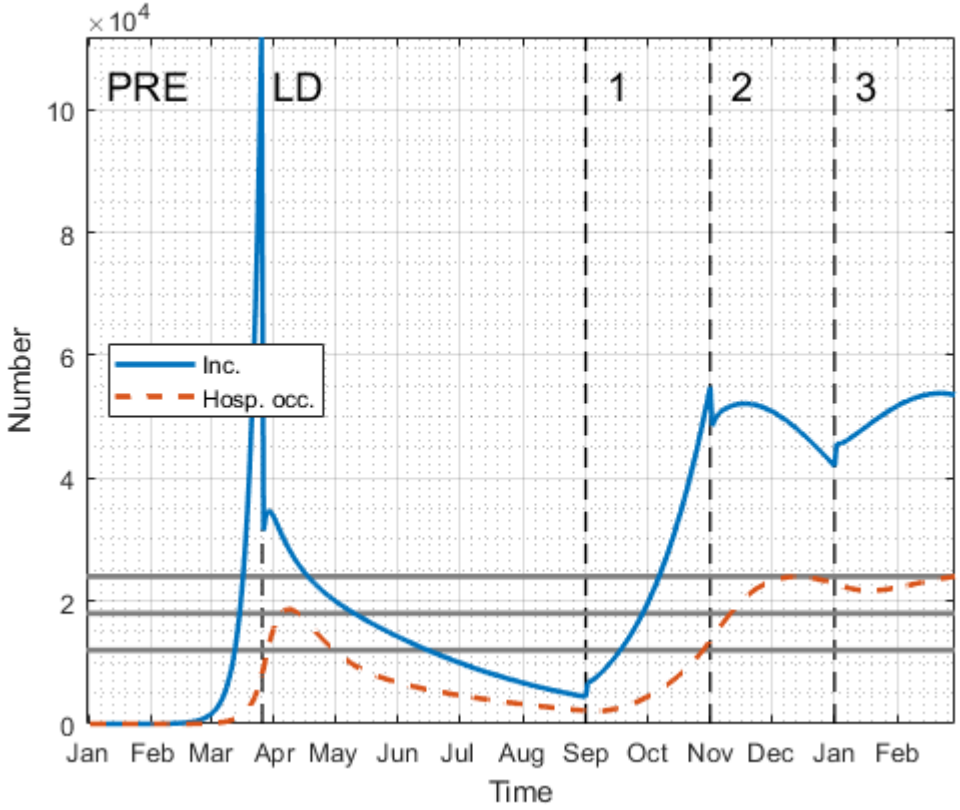
DOI: https://doi.org/10.25561/83928

Figure S1 Note: Scenario A maximizes GDP via successive bi-monthly opening and closing of 63 sectors over a six-months intervention period, subject to epidemiological and economic constraints; any economic sector including the education sector may be closed down to 80% of observed closure during the lockdown period March – May 2020 but not lower to sustain essential services; model fitted to English hospitalization data from 20th March to 30th June 2020;

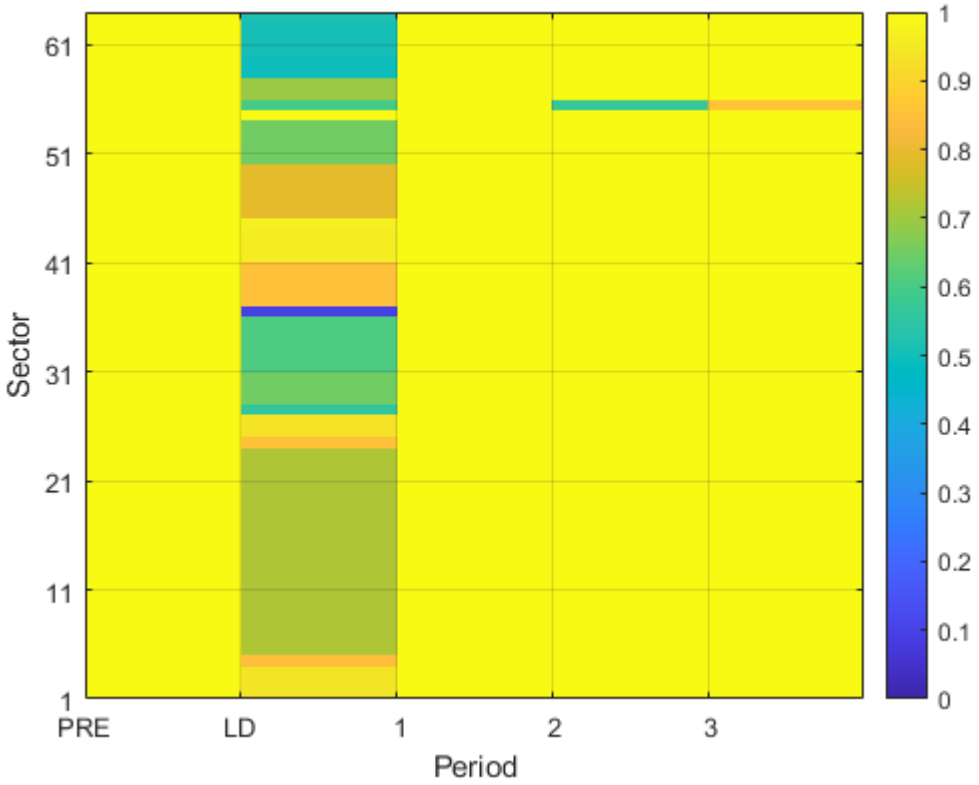
Panel S1A shows projected daily infection incidence and daily hospital occupancy between January 2020 and February 2021. The three grey horizontal lines display alternative assumptions on maximum emergency hospital capacity for the treatment of COVID-19 patients. Here, hospital capacity is constrained at 12,000 beds (1st line from below);

Panel S1B illustrates the economic configuration (bi-monthly sector openings) associated with Scenario A GDP maximization. PRE is pre-pandemic period, LD is the lockdown period March – May 2020 in the UK, plotted for comparison based on data for closures of higher-level sector categories; Period 1-2 is September-October 2020, period 3-4 is November-December 2020, period 5-6 is January-February 2021; sectors are listed on the vertical axis, and months on the horizontal axis. Openings vary between fully open as pre-pandemic (yellow, 1) to closed (blue, 80% of values observed during the lockdown period), with optimal openings for each month over the intervention period September 2020 to February 2021 indicated.

DOI: https://doi.org/10.25561/83928



Panel S2A: Projected incidence and hospital occupancy



Panel S2B: Economic configuration across 63 economic sectors

Figure S2: Projected incidence, hospital occupancy and optimal economic configuration under scenario A (GDP maximization), hospital capacity 24,000 beds, January 2020 to February 2021

DOI: https://doi.org/10.25561/83928

Figure S2 Note: Scenario A maximizes GDP via successive bi-monthly opening and closing of 63 sectors over a six-months intervention period, subject to epidemiological and economic constraints; any economic sector including the education sector may be closed down to 80% of observed closure during the lockdown period March – May 2020 but not lower to sustain essential services; model fitted to English hospitalization data from 20th March to 30th June 2020;

Panel S2A shows projected daily infection incidence and daily hospital occupancy between January 2020 and February 2021. The three grey horizontal lines display alternative assumptions on maximum emergency hospital capacity for the treatment of COVID-19 patients. Here, hospital capacity is constrained at 24,000 beds (3rd line from below);

Panel S2B illustrates the economic configuration (bi-monthly sector openings) associated with Scenario A GDP maximization. PRE is pre-pandemic period, LD is the lockdown period March – May 2020 in the UK, plotted for comparison based on data for closures of higher-level sector categories; Period 1-2 is September-October 2020, period 3-4 is November-December 2020, period 5-6 is January-February 2021; sectors are listed on the vertical axis, and months on the horizontal axis. Openings vary between fully open as pre-pandemic (yellow, 1) to closed (blue, 80% of values observed during the lockdown period), with optimal openings for each month over the intervention period September 2020 to February 2021 indicated.

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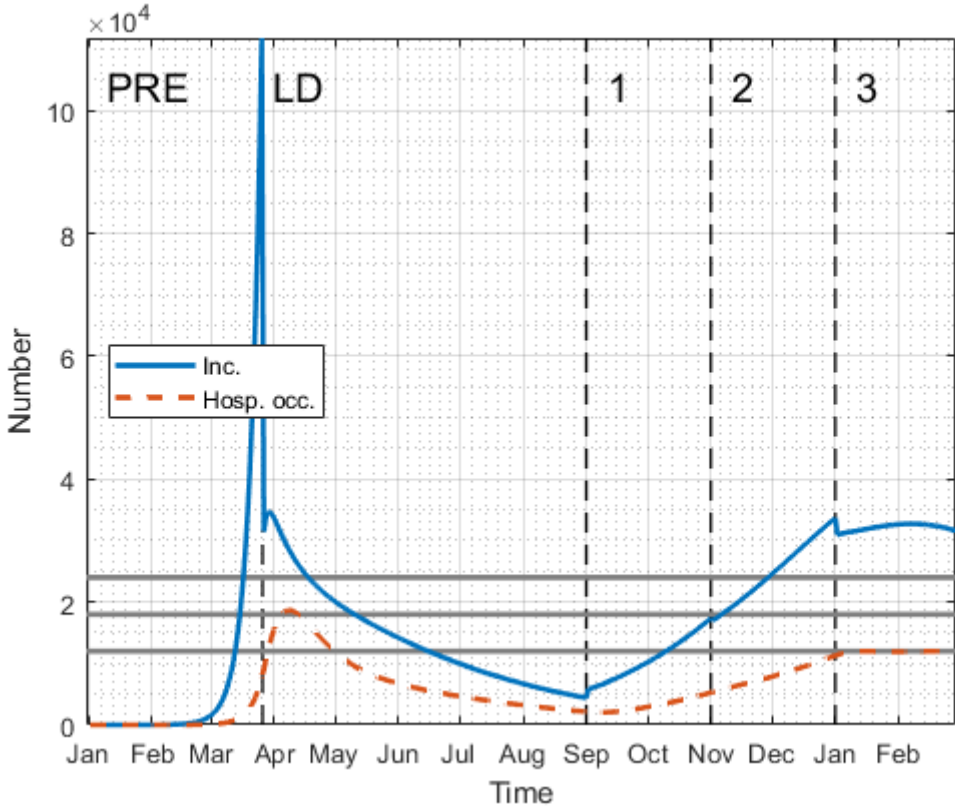

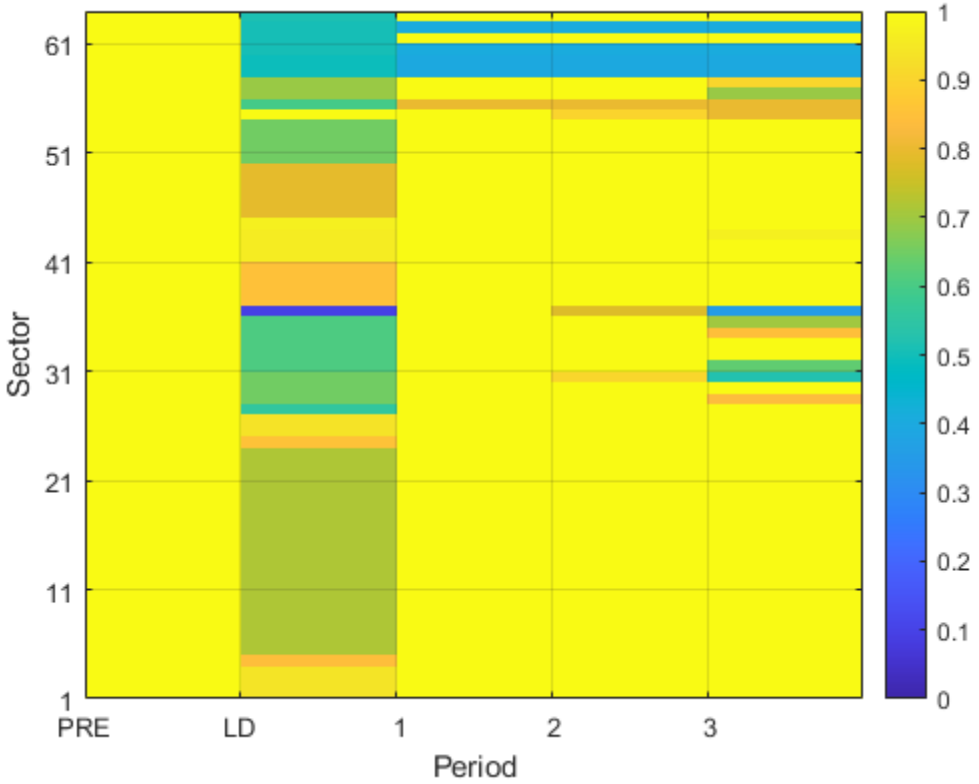

Panel S3A: Projected incidence and hospital occupancy

Panel S3B: Economic configuration across 63 economic sectors

Figure S3: Projected incidence, hospital occupancy and optimal economic configuration under scenario B (education open), hospital capacity 12,000 beds, January 2020 to February 2021

DOI: https://doi.org/10.25561/83928

Figure S3 Note: Scenario B optimizes GDP via successive bi-monthly opening and closing of 63 sectors over a six-months intervention period, subject to epidemiological and economic constraints; any economic sector except for the education sector may be closed down to 80% of observed closure during the lockdown period March – May 2020 but not lower to sustain essential services; the education sector is constrained to stay open at or above 80% of pre-pandemic production levels; model fitted to hospitalization data for England from 20th March to 30th June 2020;

Panel S3A shows projected daily infection incidence and daily hospital occupancy between January 2020 and February 2021. The three grey horizontal lines display alternative assumptions on hospital capacity. Here, hospital capacity is constrained at 12,000 beds (1st line from below);

Panel S3B illustrates the economic configuration (bi-monthly sector openings) associated with Scenario B 'education open'. PRE is pre-pandemic period, LD is the lockdown period March – May 2020 in the UK, plotted for comparison based on data for closures of higher-level sector categories; Period 1-2 is September-October 2020, period 3-4 is November-December 2020, period 5-6 is January-February 2021; sectors are listed on the vertical axis, and months on the horizontal axis. Openings vary between fully open as pre-pandemic (yellow, 1) to closed (blue, 80% of values observed during the lockdown period), with optimal openings for each month over the intervention period September 2020 to February 2021 indicated.

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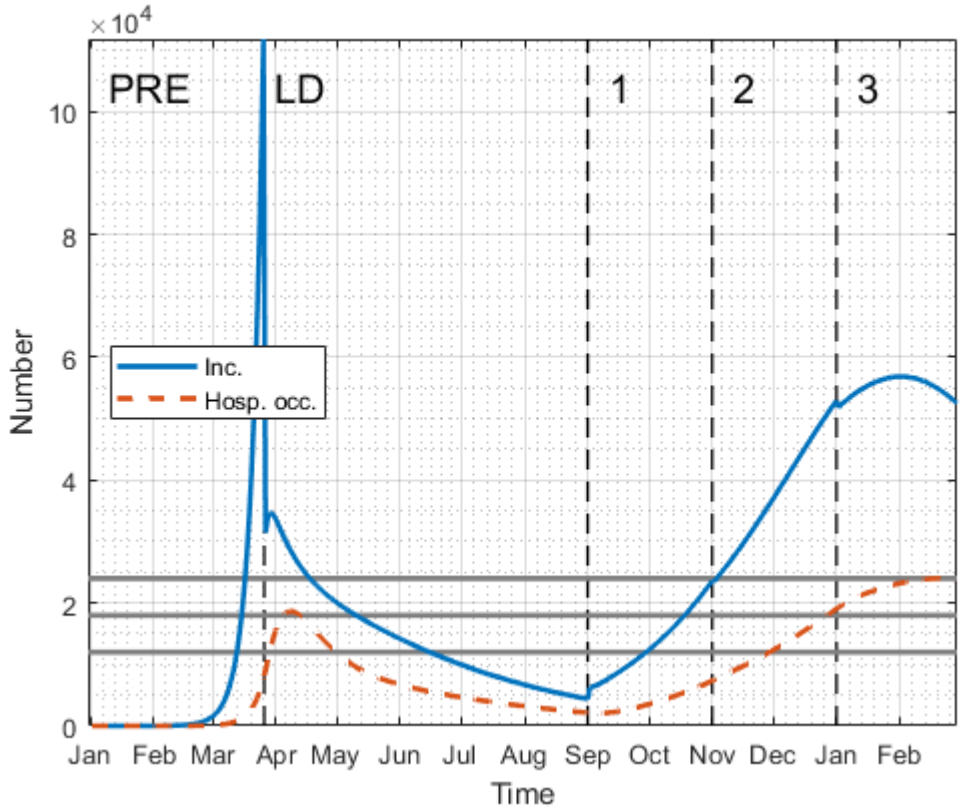
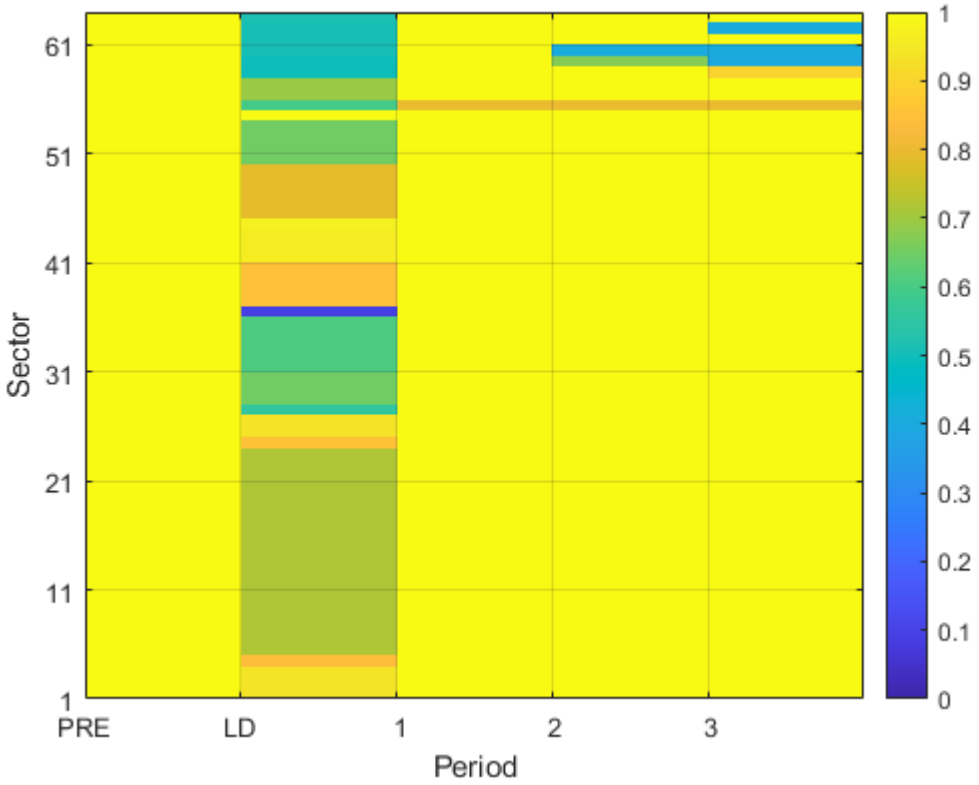


Panel S4A: Projected incidence and hospital occupancy



Panel S4B: Economic configuration across 63 economic sectorsPanel S4B: Economic configuration across 63 economic sectors

Figure S4: Projected incidence, hospital occupancy and optimal economic configuration under scenario B (education open), hospital capacity 24,000 beds, January 2020 to February 2021

DOI: https://doi.org/10.25561/83928

Figure S4 Note: Scenario B optimizes GDP via successive bi-monthly opening and closing of 63 sectors over a six-months intervention period, subject to epidemiological and economic constraints; any economic sector except for the education sector may be closed down to 80% of observed closure during the lockdown period March – May 2020 but not lower to sustain essential services; the education sector is constrained to stay open at or above 80% of pre-pandemic production levels; model fitted to hospitalization data for England from 20th March to 30th June 2020;

Panel S4A shows projected daily infection incidence and daily hospital occupancy between January 2020 and February 2021. The three grey horizontal lines display alternative assumptions on hospital capacity. Here, hospital capacity is constrained at 24,000 beds (3rd line from below);

Panel S4B illustrates the economic configuration (bi-monthly sector openings) associated with Scenario B 'education open'. PRE is pre-pandemic period, LD is the lockdown period March – May 2020 in the UK, plotted for comparison based on data for closures of higher-level sector categories; Period 1-2 is September-October 2020, period 3-4 is November-December 2020, period 5-6 is January-February 2021; sectors are listed on the vertical axis, and months on the horizontal axis. Openings vary between fully open as pre-pandemic (yellow, 1) to closed (blue, 80% of values observed during the lockdown period), with optimal openings for each month over the intervention period September 2020 to February 2021 indicated

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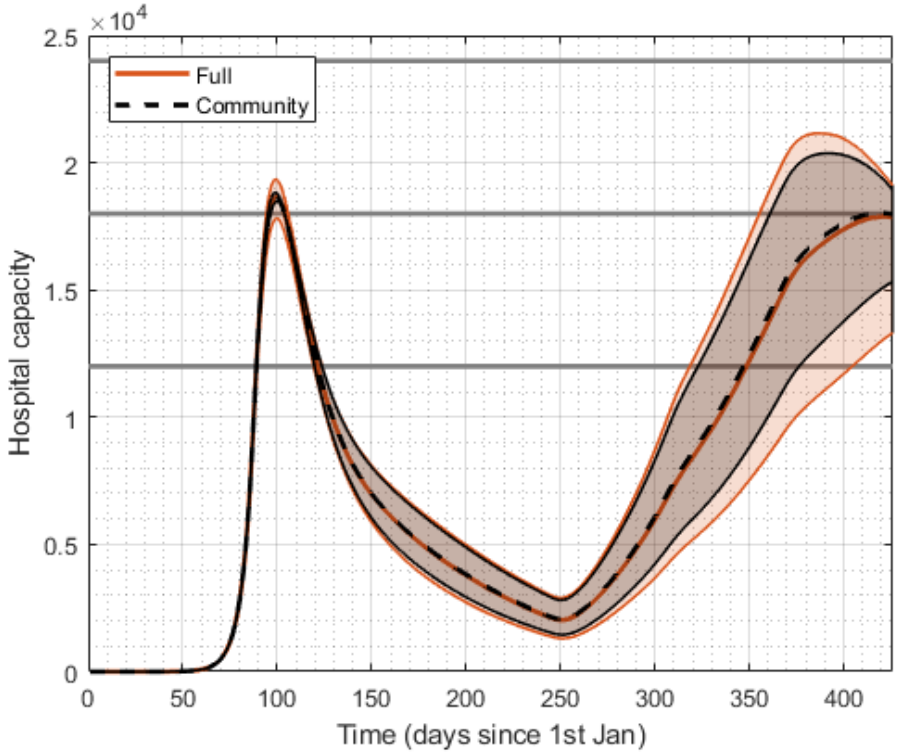
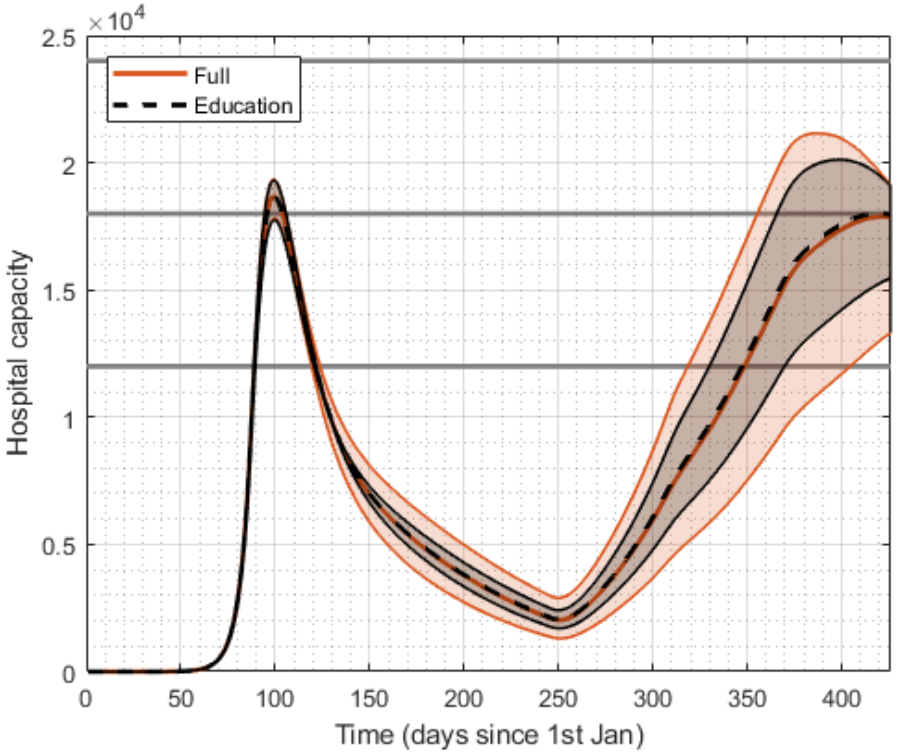


Panel S5a: contact rates in all groups and in the community



Panel S5b: Contact rates in all groups and in the education sector

Figure S5: Sensitivity analyses on contact rates, Scenario B, H_{max}=18,000

Figure S5 Notes: shown are the 5th and 95th percentiles of fitted and projected hospital occupancy when contact rates are varied by 5% standard deviations around their sector-specific means assuming contact rates are independently and normally distributed; the optimal economic configuration for scenario B (education open, H_{max}=18,000); Panel S5a shows variation in occupancy when contact rates for all groups (red) and the community group only (black) are varied; Panel S5b shows variation in occupancy when contact rates for all groups (red) and the education sector only (black) are varied; the figure demonstrates that much of the uncertainty in projected occupancy arises from variation in the community and education sectors.

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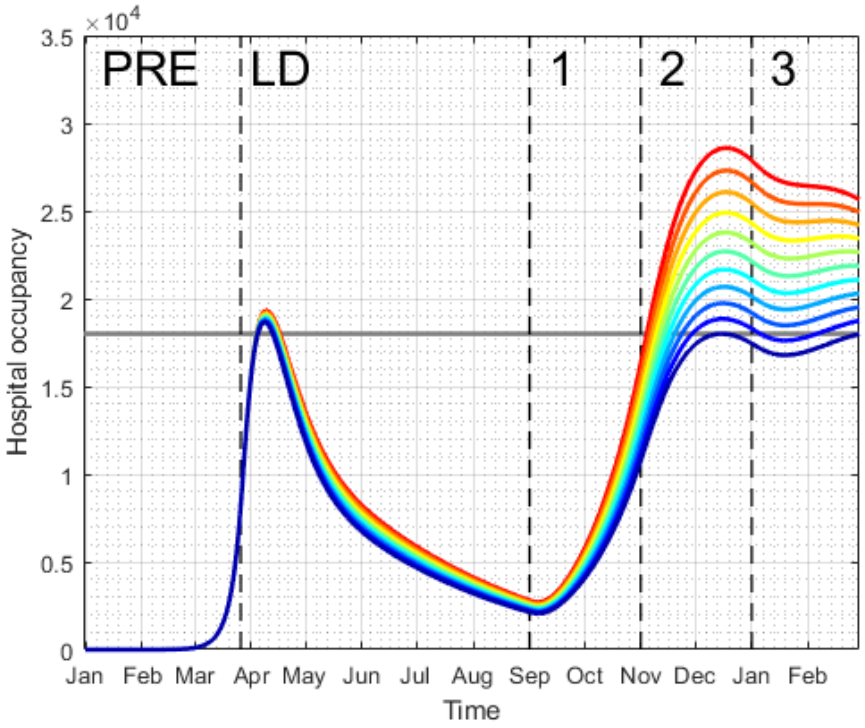

Figure S6A: Overflow of hospital capacity under Scenario A (GDP maximization)

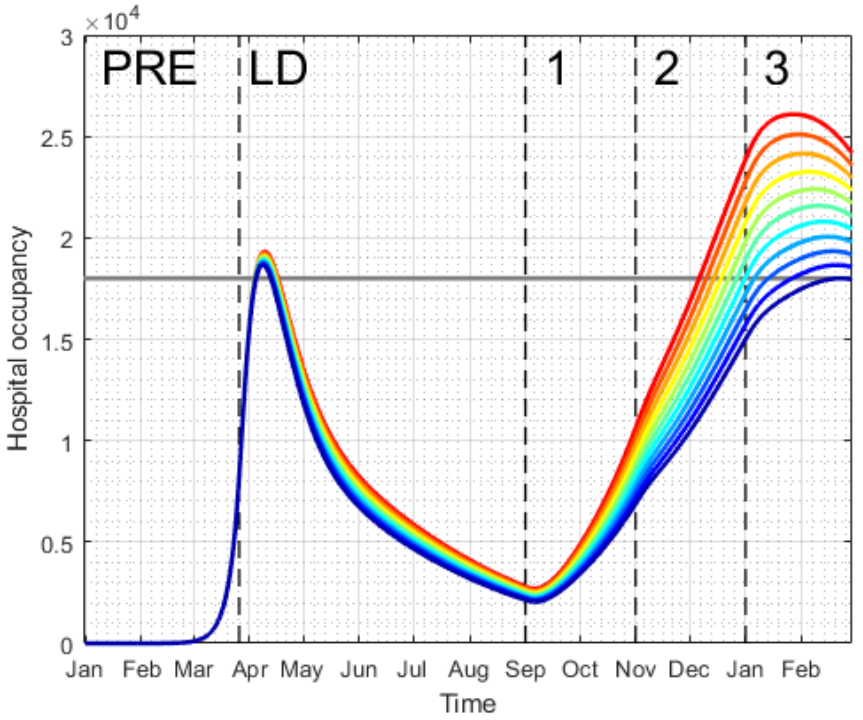

Figure S6B: under Scenario B (education open)

Figure S6: Sensitivity analyses on proportion of workers working from home

Figure S6 note: shown are fitted and projected hospital occupancy when the proportion of workers working from home is decreased in 2% steps from-our baseline assumption of the work-from-home proportions observed during the lockdown period March – May 2020 (black) to 20% fewer workers working-from-home (red);

Variations for Scenario A (GDP maximization) and B (education open), maximum spare emergency hospital capacity is set at 18,000 beds (horizontal grey line).

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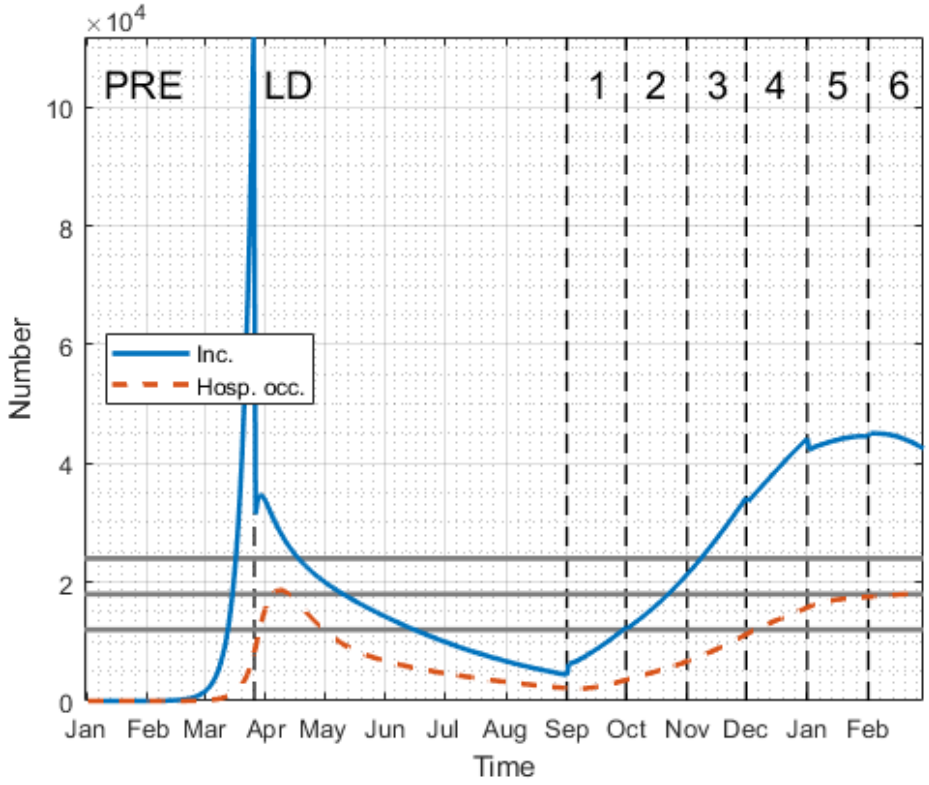
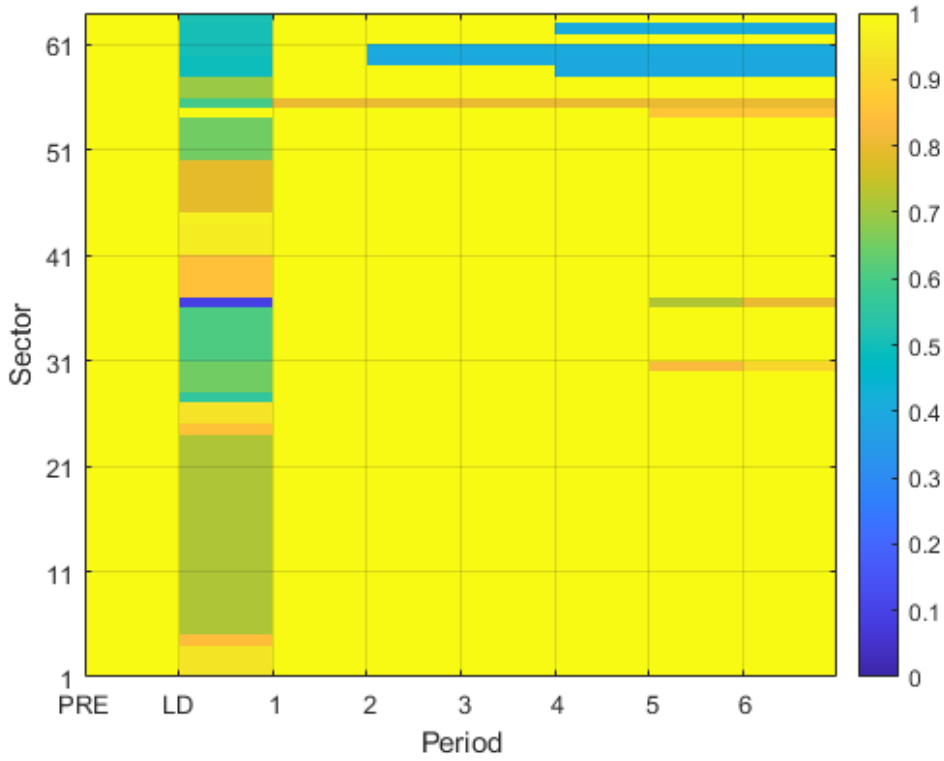


Panel S7A: Fitted and projected incidence and hospital occupancy



Panel S7B: Economic configuration across 63 economic sectors

Figure S7: Projections under a monthly optimization scenario B (education open), hospital capacity 18,000 beds, January 2020 to February 2021

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Figure S6 Note: Scenario B optimizes GDP via successive ***monthly*** opening and closing of 63 sectors over a six-months intervention period, subject to epidemiological and economic constraints; this is in contract to the baseline scenario whereby ***bi-monthly (i.e. every two months)*** opening and closing of 63 sectors over a six-months intervention period is allowed; any economic sector except for the education sector may be closed down to 80% of observed closure during the lockdown period March – May 2020 but not lower to sustain essential services; the education sector is constrained to stay open at or above 80% of pre-pandemic production levels; model fitted to hospitalization data for England from 20th March to 30th June 2020;

Panel S6A shows projected daily infection incidence and daily hospital occupancy between January 2020 and February 2021. The three grey horizontal lines display alternative assumptions on hospital capacity. Here, emergency spare hospital capacity is constrained at 18,000 beds (2nd line from below);

Panel S6B illustrates the economic configuration ***(monthly sector openings)*** associated with Scenario B 'education open'. PRE is pre-pandemic period, LD is the lockdown period March – May 2020 in the UK, plotted for comparison based on data for closures of higher-level sector categories; Periods 1 to 6 are the months September 2020 to February 2021; sectors are listed on the vertical axis, and months on the horizontal axis. Openings vary between fully open as pre-pandemic (yellow, 1) to closed (blue, 80% of values observed during the lockdown period), with optimal openings for each month over the intervention period September 2020 to February 2021 indicated.

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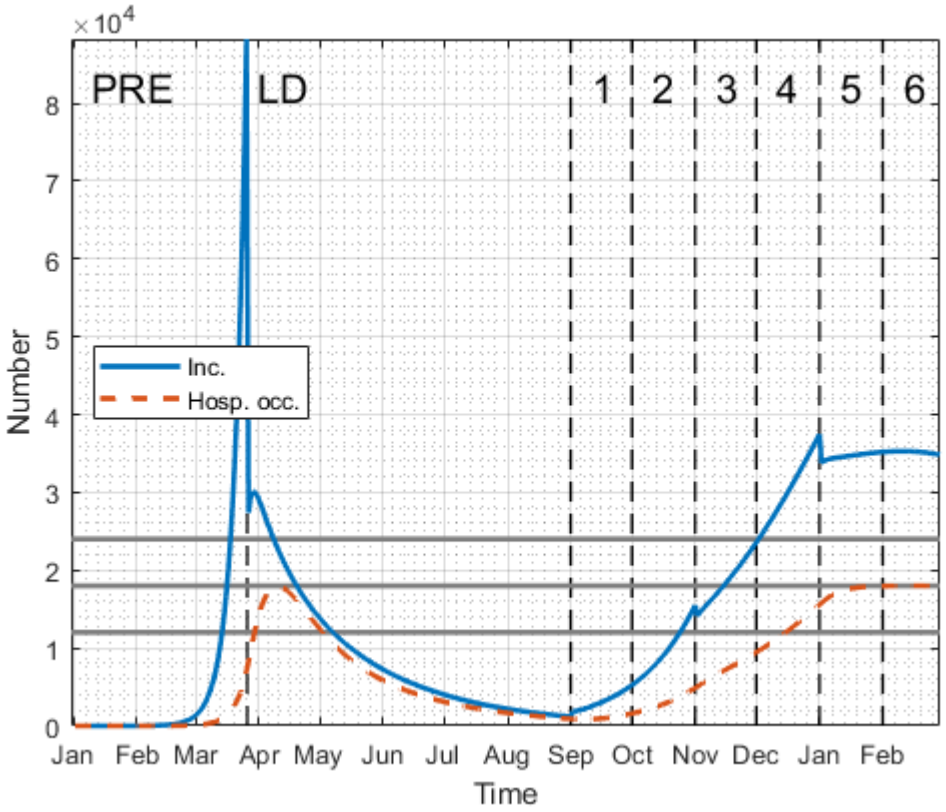
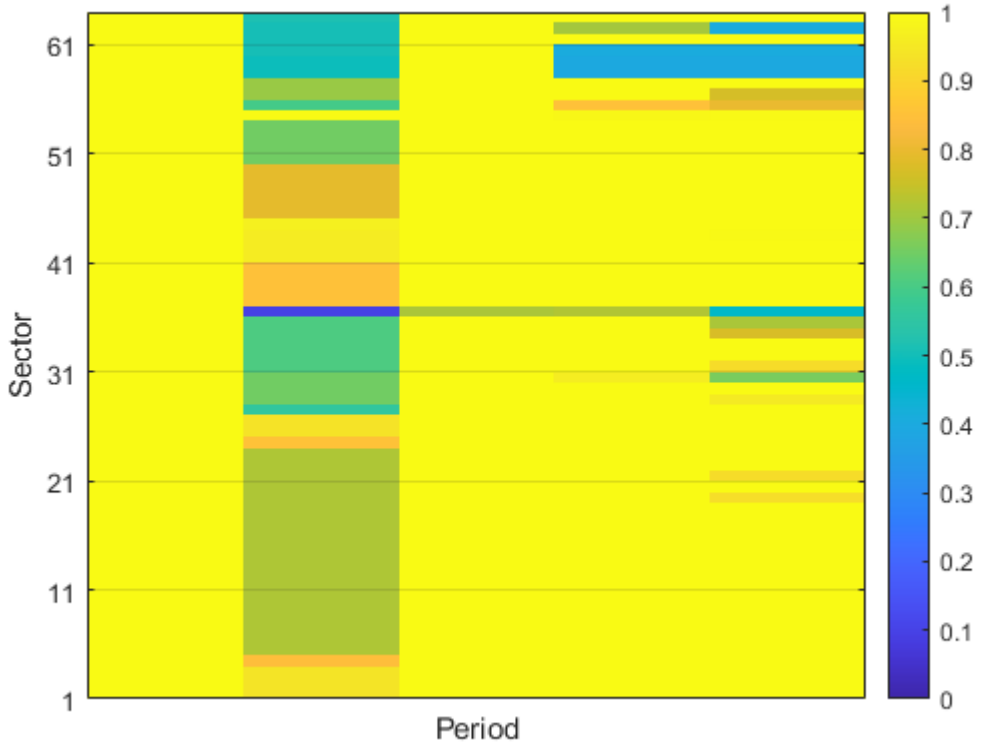


Panel S7A: Fitted and projected incidence and hospital occupancy



Panel S7B: Economic configuration across 63 economic sectors

Figure S7: Projections assuming 50% susceptibility of children under 16 years of age, optimization scenario B (education open), H_{max} 18,000 beds, January 2020 to February 2021

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Figure S7 Note: Scenario B optimizes GDP via successive bi-monthly opening and closing of 63 sectors over a six-months intervention period, subject to epidemiological and economic constraints; any economic sector except for the education sector may be closed down to 80% of observed closure during the lockdown period March – May 2020 but not lower to sustain essential services; the education sector is constrained to stay open at or above 80% of pre-pandemic production levels; model re-fitted to hospitalization data for England from 20th March to 30th June 2020 assuming children under 16 years of age have 50% less susceptibility to infection than adults (R_0=2.72, fitted δ=0.68, assumed δ=0.75); the re-fit to the initial epidemic results in the finding that there was more transmission between adults than children compared to the assumption of equal susceptibility. This implies that school closures have less impact on transmission dynamics for the projections. In order to successfully mitigate the pandemic and stay within the constraints, economic sectors need to close more strictly compared to an equal susceptibility scenario. We find that although sectors need to close more stringently, the same sectors are recommended for closure. Projected aggregate GDP is £851bn, lower than under the assumption of equal susceptibility (863bn).

Panel S6A shows projected daily infection incidence and daily hospital occupancy between January 2020 and February 2021. The three grey horizontal lines display alternative assumptions on hospital capacity. Here, emergency spare hospital capacity is constrained at 18,000 beds (2nd line from below);

Panel S6B illustrates the economic configuration associated with Scenario B 'education open' assuming children under 16 years of age have 50% less susceptibility to infection. PRE is pre-pandemic period, LD is the lockdown period March – May 2020 in the UK, plotted for comparison based on data for closures of higher-level sector categories; Periods 1 to 6 are the months September 2020 to February 2021; sectors are listed on the vertical axis, and months on the horizontal axis. Openings vary between fully open as pre-pandemic (yellow, 1) to closed (blue, 80% of values observed during the lockdown period), with optimal openings for each month over the intervention period September 2020 to February 2021 indicated.

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