An epidemiological and modelling analysis of transmission of SARS-CoV-2 at a United Kingdom electricity-generating company

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The PROTECT COVID-19 National Core Study on transmission and the environment is a UK-wide research programme improving our understanding of how SARS-CoV-2 (the virus that causes COVID-19) is transmitted from person to person, and how this varies in different settings and environments. This improved understanding is enabling more effective measures to reduce transmission –saving lives and getting society back to 'normal'.

This report describes the application of epidemiological and mathematical modelling to investigate factors influencing infection and transmission in the electricity generating sector using an extensive and detailed database of COVID-19 workforce test results complied by one large generating company. Electricity generation is part of the national critical infrastructure and has been required to keep operating throughout the pandemic.

The researchers' findings include the following. First, there were no differences in the risk of infection between job groups, although there were differences in infection risk between (geographically) different power generation sites. This was despite the fact that a contact survey suggested that there were differences in contact patterns between workers with different roles, responsibilities and working patterns. Second, data on infections suggest that the two power plants included in more detailed analyses experienced a somewhat larger epidemic wave during the autumn of 2020 compared to the nearby community. However, this was followed by relatively low reported infection rates during the subsequent community wave in January-February 2021. Overall and taking under-reporting of infections into consideration, infections at these two power plants during 2021 were broadly similar to those in the nearby community with only a minority of workforce infections acquired on-plant. Third, the risk mitigation measures introduced by the company, which included testing, contract tracing and isolation, remote working and mandatory use of face coverings, were effective in reducing the number of workplace acquired infections.

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An epidemiological and modelling analysis of transmission of SARS-CoV-2 at a United Kingdom electricity-generating company

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Executive summary

Introduction

Electricity generating is one of the national critical infrastructure sectors, as it must maintain production irrespective of external circumstances (such as the COVID-19 pandemic). The nuclear sector provides additional complications due to the safety critical nature of their operations (e.g., inability to shut reactors down at short notice). Hence, this industry has required a comprehensive risk assessment and management approach during the pandemic to avoid workplace outbreaks and minimise infection rates and sickness absence within their highly specialised workforce.

This project aimed to carry out a deep dive into the interventions and risk mitigations implemented by EDF to reduce the risk of transmissions of SARS-CoV2 in the workplace. In order to achieve this, we had the following objectives:

i. To determine the perceptions of EDF employees at one nuclear facility of the risk of transmissions at work and perception of the effectiveness of risk mitigation measures;

ii. To identify occupational risk factors within EDF for risk of infection;

iii. To carry out a contact survey at two co-located nuclear facilities;

iv. To compare the patterns of transmissions at two co-located nuclear facilities with regional patterns; and

v. To develop and implement an agent-based model for two co-located nuclear sites and assess the effectiveness of risk mitigation measures.

This report describes the results for objectives ii) – v). The results of the first objective have been reported separately.

Methods

Objective ii) Test results for SARS-CoV2 infection from across all nuclear facilities were made available to the research team. A comprehensive analysis (using a test-negative design) was carried out using these testing data to determine differences in infection rates between types of job, location, geographic and demographic and other factors, whilst taking into account potential confounders, and to compare the infection rates with the workplace control measures implemented in different physical settings.

Objective iii) An existing contact survey questionnaire developed by HSE was adapted and implemented as an online survey, which was made available to the workforce at two electricity production sites from July 25th to August 12th 2022.

Objective iv) The company testing data for two co-located sites were analysed and compared with the lower tier local authority (LTLA) testing data in the local community where most staff live using statistical models. A deterministic model capturing the essential link between the power plant and the local community was used to test two alternative hypotheses to explain the difference in the relative magnitude of the observed epidemic in the power stations and in the community: increased workplace transmission versus a more accurate case reporting. A simplified stochastic agent-based model including the essential mechanisms of screening and tracing of contacts without the complexity of a realistic contact network was used to investigate potential effects of changes in intervention measures on the realised and observed infections.

Objective v) A stochastic individually (agent) – based model for workplace transmission of SARS-CoV-2 developed in Theme 2 of PROTECT was adapted to apply to two co-located nuclear power stations. The model was applied using contact networks representing the sites developed from available data on contacts of cases identified collected via company testing and a worker questionnaire (see Objective ii), with model calibration based on available data on the secondary attack rate amongst contacts during 2021. Assumptions around mitigations were based on company risk management documents and discussions with managers responsible for the power station and parent company pandemic response. The modelling exercise focussed on January to March 2021 – a period with stringent mitigations, very low levels of workforce vaccination and with the Alpha variant dominant - and September to November 2021 – a period with reduced mitigations, high levels of workforce vaccination and with the Delta variant dominant.

Results and Conclusions

Objective ii) From an original file of 80,077 test results conducted by the company on site, there were 70,646 included in the test-negative design analysis. Women were less likely to test positive than men (OR=0.71; 95%CI 0.58-0.86). Across the pandemic, 16% of cases were first identified by routine testing, compared to 54% for symptomatic testing, and 27% for contact testing. Overall, there was little difference in positivity rates by job category. There were some differences by site, with three sites showing substantially lower risks, and one site showing higher risks in the final model. Vulnerable individuals had slightly lower risks to testing positive, while tests carried out during outages were more likely to be positive. There was no evidence for an effect of vaccination testing result. Finally, the site risk rating did not show an ordered trend in positivity rates.

Objective iii) In total, 211 participants completed the online questionnaire (response rate ~16%) split equally between the two participating electricity production sites. Both EDF workers (72%) and contractors took part. Amongst 21 EDF job categories, 'Engineers' was the largest group with 31 respondents (group size 80 workers), while only 5 respondents reported being ‘Operation technicians’ (group size 140 workers). 73% of respondents reported having had COVID, with 93% reported being doubly vaccinated. The most frequently reported control measures were hand sanitising stations, IT enabled meetings (Skype) and work from home. The median number of self-ported contacts was low at 7 per day. There was no significant difference in the number of reported contacts between the two sites. On average, the median number of self-reported close contacts with people outside of their own team (n=2) was only slightly lower to the number of self-reported close contacts in their own team (n=3). For EDF employees, working shifts and having managerial/supervisory responsibility was associated with higher contact rates. Environmental safety technicians, those in maintenance (DART/TAG) and in the nuclear safety group had statistically significantly higher contact rates than engineers (that were used as the reference group).

Objective iv) The statistical analysis showed a general synchronicity in the two surveillance curves of the power plant and the local community in the post-vaccination period, but a larger relative magnitude of the epidemics in the power plant compared to the community. The theoretical analysis, combined with the estimates of epidemic growth/decline, suggests that these trends were likely induced by better surveillance in the power plant, due to reduced under-reporting. Hence, these trends may provide a more accurate reflection of the true underlying infection spread, rather than by increased transmission risk within the workplace. In the pre-vaccination period (between September 2020 and March 2021), the statistical analysis highlighted a certain degree of asynchronicity in the growth/decline epidemic patterns. The analysis of growth/decline trends suggests that the power plant experienced a relatively larger epidemic wave compared to the local community during the fall 2020. This may indicate that there was an increased risk of transmission during the outage period (before January 2021). This wave was followed by a decline in cases and a relatively low reported incidence during the subsequent community wave in January-February 2021. This apparent lack of resurgence may be attributed to a successful implementation of more stringent measures (e.g. remote working) or to a local depletion of susceptible individuals from the first wave (October-November 2020). Finally, qualitative simulations accounting for workplace screening and contact tracing showed that a relaxation of testing and physical distancing measures could result in less reported cases but an increased number of infections that mostly go unnoticed, stressing the importance of non-pharmaceutical interventions for epidemic control.

Objective v) The agent-based model successfully reproduced the observed patterns of cases during the two periods. Total confirmed (test positive) cases at both stations during the January to March 2021 period fell within the model 90% prediction intervals. Total confirmed cases at one site during September-November 2021 were also within the prediction interval; however cases at the other site for September to November 2021 were slightly lower than predicted. The test confirmed number of cases almost certainly understates the true number of workforce infections to some degree. Workplace acquired cases were predicted to represent a minority of the total cases (19.5% and 36% in January to March 2021 and September-November 2021 respectively). Adjusting for under-reporting of community infections in the Lancaster local authority area, modelling suggests rates of infection in power station staff were slightly lower (simulated incident rate ratio 0.80) than in the wider community during January to March 2021 and very similar (simulated incident rate ratio 0.98) during September to November 2021. These findings are however sensitive to assumptions around under-reporting of local community infections. Counterfactual modelling suggested that contract tracing and isolation and remote working contributed meaningfully to reducing transmission. The mandatory use of face coverings at all times inside during January to March 2021 had an even more substantial effect – had they not been used during this period the model predicts the expected total number of cases would have been 58% higher, with the expected number of workplace acquired cases at each station increasing from 6 to 25. Limited screening testing was carried out during the two modelled periods, which was not included in the baseline modelling for the two periods. Counterfactual modelling suggests that twice weekly screening testing using lateral flow devices combined with isolation of the contacts of test positive cases might have reduced total workforce cases during September to November 2021 by around one quarter and workplace acquired cases by approximately two thirds. A similar reduction might have been achieved through once weekly testing using a high-sensitivity test method such as LAMP or point of care PCR (e.g. 'Randox).

In summary, based on the work presented in this report we conclude that:

1) There were no differences in risk of infection between occupational groups, although there were differences in infection risk between different EDF sites;
2) This was despite the fact that the contact survey showed that there were differences in contact patterns between occupational groups with different roles, responsibilities and working patterns;
3) Data on infections suggest that the two EDF nuclear power plants included in the more detailed analyses experienced a somewhat larger epidemic wave during the Autumn of

2020 compared to the nearby community. However, this was followed by relatively low reported infection rates during the subsequent community wave in January-February 2021;

4) The risk mitigation measures introduced by EDF (testing, cont~~r~~act tracing and isolation, remote working, mandatory use of face coverings) were effective in reducing the number of workplace acquired infections.

Contents

1. Introduction

Electricity generating is one of the national critical infrastructure sectors and has been required to keep producing energy throughout the pandemic. The nuclear sector provides additional complications due to the highly specialised workforce and the inability to shut reactors down at short notice. Hence, this industry has required a comprehensive risk assessment and management approach in order to avoid workplace outbreaks and limit the infection rates within its workforce during the pandemic.

Although the nuclear sector is clearly not representative of other sectors within the UK, analyses of the risk assessment and management approaches (including testing and internal track and trace programme, workplace control measures, etc) will provide important insights on effectiveness of control measures, facilitators and barriers to implementation of control measures and any unintended consequences, which will also provide important lessons for other sectors.

As part of the PROTECT programme we collaborated closely with EDF to carry out a deep dive into the interventions and risk mitigations implemented by EDF to reduce the risk of transmissions of SARS-CoV2 in the workplace. In order to achieve this, we had the following objectives:

i. To determine the perceptions of EDF employees at one nuclear facility of the risk of transmissions at work and perception of the effectiveness of risk mitigation measures;

ii. To analyse large database of company test results to identify occupational risk factors for transmission using a test negative design;

iii. To carry out a contact survey at one nuclear facility;

iv. To compare the patterns of transmissions in EDF facility with regional patterns; and

v. To develop and implement an agent-based model for one nuclear facility and assess the effectiveness of risk mitigation measures

The results of the first objective have been reported in a separate report (PROTECT- deep dive with an electricity generating company: qualitative insights from site-based workers, 2023). This report provides the results of the remaining objectives.

2. Risk factors for Covid-19 infection at a United Kingdom electricity-generating company: a test-negative design case-control study

2.1 Introduction

In July 2020, government scientific advisers and key funders identified where the UK must increase research to respond to near term strategic, policy and operational needs, and ultimately improve resilience against COVID-19 through 2021 and beyond. Six COVID-19 National Core Studies (NCS) have been established to meet these needs, including the NCS project on transmission of the SARS-CoV-2, led by the UK's Health and Safety Executive (HSE). This project is known as "PROTECT": The Partnership for Research into Occupational, Transport and Environmental Covid NCS, which brings together more than 70 researchers from 16 different institutions.

One of the six key themes of the "PROTECT" project is to collect data from outbreak investigations in a range of workplaces to understand SARS-CoV-2 transmission risk factors, potential causes for COVID-19 outbreaks and the effectiveness of a range of measures to control and prevent these outbreaks. In addition to specific outbreak investigations conducted as part of PROTECT, some companies have been identified which succeeded in assembling some detailed data on testing in their workforces including relevant data on outbreaks they have experienced. One of these is a large electricity-generating company. We here report the findings of a test-negative design case-control study conducted using the data collected by this company. The main aim of these analyses was to investigate contextual-level, workplace subgroups and individual-level risk factors for SARS-Cov-2 infections.

2.2 Methods

The large electricity-generating company which is the subject of this report, tested staff frequently on site throughout the course of the pandemic. The testing strategy and method varied over time and by facility. During some time periods, all staff were tested routinely, whereas in other periods, most workers were only tested because they had symptoms, or were identified as a contact of a positive case. These practices also varied across sites, so that at any given time, some sites may have been testing routinely, while others were only doing symptomatic and contact testing. Reason for test was collected and categorised into 4 groups: testing due to symptoms (using a lower threshold than government recommendations), testing for close contacts (using government defined criteria), testing for looser work contacts (as per company protocols) and routine testing.

Tests with a missing or inconclusive result were excluded, along with those from visitors (single tests), and any test participants with missing job type. We also excluded tests that were missing one of the following a priori confounders: age, sex, site, test date or test type.

Tests in a day with different outcomes or reasons (although only a small number were identified), we prioritised positive results over negative (as false positives are less common than false negatives), and test reason in order of strength of reason (i.e., symptoms, close contact, loose contact, screening, and then missing). For each member of staff, we used tests only up to and including their first positive result. Thus, the analyses presented here relate to the risks of a first infection, and subsequent infections were not considered.

We used a test-negative design, in which those with positive tests (cases) were compared with those with negative tests (controls) during each quarter (3-month period). This approach is intended to control for factors that affect the propensity to be tested at different time points (e.g., changing testing protocols and recognition of symptoms). It also has the advantage of being feasible, since we only had access to the test data, and not to data on individuals who were not tested. It has been widely used for assessing vaccine effectiveness, both for Covid-19 (1) and for other infections (2). More recently, it has been used for assessing risk factors for Covid-19 infection (3, 4).

Site risk rating was assessed by the Outbreak Management Team, consisting of the company doctors, occupational health advisors and site representatives for each power station, approximately once a week, based on the background prevalence of disease and the number of cases on site. The risk rating from 0 to 5 determined the Covid-19 mitigation requirements (e.g., cleaning, PPE, testing, social distancing). If there was no available risk rating for a particular week then the rating for the closest previous date was chosen. For sites with no risk rating assigned then the average risk rating across all sites was used.

An outage is a statutory period when a power station is offline and when maintenance can be undertaken. It is often a time with an increased number of external visitors/contractors to the site. We have a binary flag determining whether a test was taken during a period of outage at the relevant site.

Vulnerability status was determined by increased risk of severe disease or death from Covid due to a pre-existing health condition as determined by the literature and was based on an employee’s request for assessment. We have a binary flag for identified vulnerable staff members, who followed different protocols for their own protection (such as home working practices).

Vaccination information was captured for most employees on a voluntary basis. Where we had date of vaccine then we could determine vaccine status at the time of the test, defining vaccine immunity as beginning 10 days after the vaccination date. Partial vaccination was defined as having received one vaccine (10 days or more prior) and full vaccination as two or more. Individuals without vaccination information were assumed unvaccinated as negative information was not captured.

There were different types of tests available at different sites at different times and for different reasons. We categorised the tests as PCR LAMP (polymerase chain reaction loop-mediated isothermal amplification), other PCR (polymerase chain reaction), and LFT (lateral flow test). For PCR LAMP, all positives and 10% of negatives were then confirmed by PCR.

We fitted logistic regression models comparing tests with positive outcomes to those with negative outcomes adjusting for the time period. There may have been more than one test per person during a time period but unless the tests were very close together there would not be much dependency.

In addition to the a priori confounders of age, sex, date of test, and test type, we considered the other available information detailed above as potential confounders or other explanatory variables of interest. Some of these factors were related, e.g., routine testing was more common during site outages. All potential confounders were included in the final model, provided there were no problems of collinearity or non-convergence of the model. Ordinal variables were tested for linear trend using a likelihood ratio test and included as either categorical or continuous based on the result. The analysis used Stata version 17.

Ethical approval was obtained from the Observational/Interventions Research Ethics Committee of the London School of Hygiene & Tropical Medicine (LSHTM Ethics Ref: 28125).

2.3 Results

From an original file of 80,077 tests there were 70,878 included in the analysis (Table 2.1). Most exclusions were due to being visitor tests (5,030) or being tests for an individual after they first tested positive (2,968, of which 433 [14.6%] were also positive).

Table 2.1: Test numbers and exclusions

Exclusion reason (in order)	Excluded tests	Remaining tests
Total		80,077
Missing/invalid test outcome	200	79,877
Missing test date	0	79,877
Missing job category	267	79,610
Visitor job category	5,030	74,580
Missing site	0	74,580
Missing sex	0	74,580
Missing age group	1	74,579
Missing test type	601	74,579
Multiple tests in single day[a]	132	74,447
Tests after first testing positive	2,968	70,878

[a] duplicates deleted; 17 people had both negative and positive tests of which one positive test was kept. Of those with matching outcomes, 31 people had different test reasons of which the highest priority one was kept in this order: symptoms, close contact, loose contact, screening, missing reason.

Table 2.2 shows the demographic characteristics of the study participants. Almost 90% of the workers tested were men. There was a wide spread of ages from under 20 to over 70 and the median age group was 41-45. The largest proportion of workers were external contractors (53%), followed by engineering (16%) and operations (13%). Jobs were spread in a variety of locations, most at power stations, and there were many more tests per person at power stations 3, 7 and 8 (around 10 per person on average) than at other sites (between 2-5 per person on average).

Table 2.2: Demographic characteristics of analysis sample

Variable	Category	Test level		Individual level	
		Number	%	Number	%
Total		70,878		10,768	
Sex	Male	63,197	89.2%	9,571	88.9%
	Female	7,681	10.8%	1,197	11.1%
Age group	16-20	1,012	1.4%	189	1.8%
	21-25	4,950	7.0%	760	7.1%
	26-30	7,692	10.9%	1,184	11.0%
	31-35	8,775	12.4%	1,300	12.1%
	36-40	7,875	11.1%	1,237	11.5%
	41-45	7,037	9.9%	1,098	10.2%
	46-50	7,969	11.2%	1,231	11.4%
	51-55	9,727	13.7%	1,480	13.7%
	56-60	9,352	13.2%	1,348	12.5%
	61-65	5,106	7.2%	715	6.6%
	66-70	1,225	1.7%	193	1.8%
	71+	158	0.2%	33	0.3%
Job category	Energy operations	9,067	12.8%	1,420	13.2%
	Engineering	12,752	18.0%	1,716	15.9%
	External contractors	37,064	52.3%	5,710	53.0%
	HSE & security	2,621	3.7%	373	3.5%
	Nuclear & scientific	3,175	4.5%	460	4.3%
	Office-based	4,395	6.2%	783	7.3%
	Project management	1,804	2.6%	306	2.8%
Job site	Head Office	1,273	1.8%	576	5.4%
	Power station 1	2,573	3.6%	1,099	10.2%
	Power station 2	5,758	8.1%	1,164	10.8%
	Power station 3	5,692	8.0%	1,011	9.4%
	Power station 4	15,333	21.6%	1,494	13.9%
	Power station 5	2,926	4.1%	981	9.1%
	Power station 6	2,555	3.6%	865	8.0%
	Power station 7	18,403	26.0%	1,869	17.4%
	Power station 8	15,516	21.9%	1,357	12.6%
	Other	849	1.2%	352	3.3%
Test date	Q1-3 2020[a]	304	0.4%		
	Q4 2020	2,379	3.4%		
	Q1 2021	23,516	33.2%		
	Q2 2021	27,016	38.1%		
	Q3 2021	11,385	16.1%		
	Q4 2021	3,933	5.6%		
	Q1 2022	1,786	2.5%		
	Q2-3 2022[b]	559	0.8%		
Test type	PCR LAMP	51,935	73.3%		
	Other PCR	16,572	23.4%		
	Lateral Flow Test	2,371	3.4%		
Test reason	Symptoms	2,773	3.9%		
	Close contact	3,174	4.5%		
	Looser contact	2,666	3.8%		
	Routine screening	62,033	87.5%		
	Missing[c]	232	0.3%		
Vaccination status[d]	Not vaccinated	57,718	81.4%		
	Partially vaccinated (1)	5,078	7.2%		
	Fully vaccinated (2+)	8,082	11.4%		
Vulnerability status[e]	Not vulnerable	65,262	92.1%	9,819	91.2%
	Vulnerable (Cat1-3)	5,616	7.9%	949	8.8%
Outage[f]	Not during outage	35,580	50.2%		
	During outage	35,298	49.8%		
Site risk rating[g]	0/1[h] (lowest risk)	1,886	2.7%		
	2	15,008	21.2%		
	3	47,208	66.6%		
	4	6,776	9.6%		
	5 (highest risk)	0	0%		

PCR: polymerase chain reaction; LAMP: loop-mediated isothermal amplification; [a] 3 quarters combined due to low volumes (Q1=1, Q2=5, Q3=298); [b] 2 quarters combined due to low volumes, especially negative tests (Q2=390, Q3=169); [c] kept in sample as not all models use test reason; [d] based on vaccination date being populated and dated at least 10 days before test; [e] assumed to be not vulnerable if no vulnerability assessment took place; [f] based on statutory outage dates at the relevant site; [g] based on approximately weekly risk rating given to each site to determine Covid-19 safety protocols. If there was no risk rating for the time period, the closest available was used. If site was Other, then average risk rating for the time period was used; [h] categories 0 and 1 were combined as there were only 73 in category 0.

The number of tests varied hugely by date, reflecting different stages of the pandemic, as well as changes in regulations and protocols of testing and the general prevalence of Covid-19 in the UK. Most tests were in the first half of 2021, but most positive tests were in the first half of 2022 (Figure 2.1).

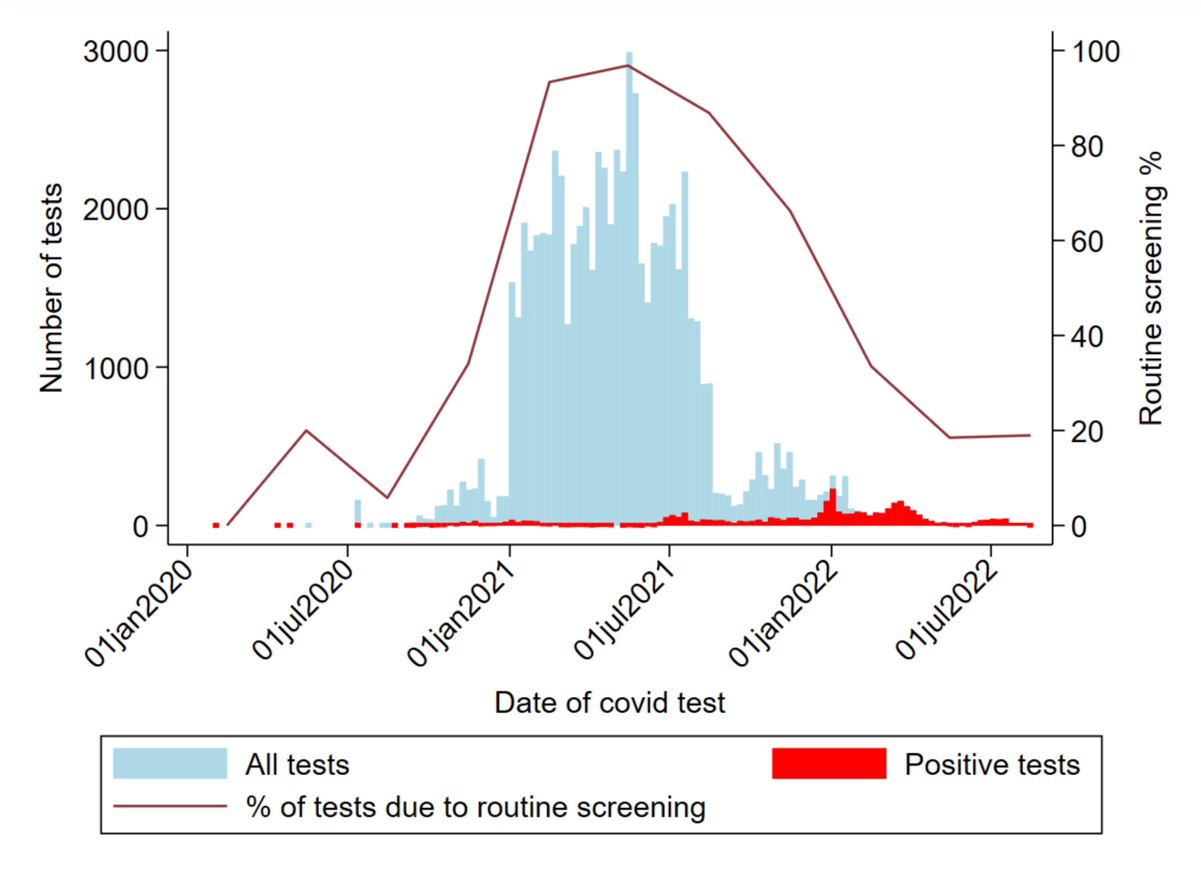

Figure 2.1: Number of tests, positive tests, and percentage due to routine screening, by date

The proportions of positive tests that were identified, according to the reasons for testing, are shown in Table 2.3. Overall, testing those with symptoms identified more than half (54%) of the positive results, whereas testing close contacts picked up 24% and looser contacts 3%. Nevertheless, a significant minority of cases (16%) were identified by routine screening. The remaining 3% had missing test reason.

Table 2.3 Proportion of positive tests by test reason in each time period

Reason	Quarter								
	Q1-3 2020	Q4 2020	Q1 2021	Q2 2021	Q3 2021	Q4 2021	Q1 2022	Q2-3 2022	All
Number of positive tests	25	183	204	120	492	742	1,324	552	3,642
% Symptoms	28%	33%	48%	37%	59%	54%	55%	65%	54%
% Close contact	44%	27%	24%	35%	20%	30%	25%	10%	24%
% Looser contact	0%	11%	10%	5%	2%	3%	2%	0%	3%
% Routine screening	4%	21%	18%	22%	18%	12%	15%	21%	16%
% Missing	24%	8%	0%	2%	1%	2%	3%	3%	3%

Table 2.4 shows the findings for the main risk factors under study. Our “base model” adjusted for test date, age-group and test type (results not shown), as well as the other risk factors shown in the table. There was strong evidence against a linear trend for time period (p<0.0001) and weak evidence for age group (p=0.05) so these were both included as categorical.

Table 2.4: Odds ratios and 95% confidence intervals of risk of testing positive on covid test

Exposure	Category	Crude job type association (n=70,878)	Base model[a] (n=70,878)	Base model[a] + test reason (n=70,646)	Fully adjusted model[b] (n=70,646)
Job category	Energy operations	0.98 (0.86, 1.12)	1.22 (0.99, 1.51)	0.91 (0.70, 1.19)	0.91 (0.70, 1.20)
	Engineering	0.78 (0.68, 0.88)	0.99 (0.81, 1.21)	0.90 (0.69, 1.16)	0.90 (0.70, 1.17)
	External	0.36 (0.32, 0.40)	0.74 (0.61, 0.89)	1.14 (0.89, 1.45)	1.05 (0.82, 1.36)
	HSE & security	0.92 (0.76, 1.10)	1.16 (0.87, 1.54)	1.10 (0.77, 1.57)	1.12 (0.78, 1.62)
	Nuclear & scientific	0.85 (0.71, 1.01)	1.09 (0.84, 1.43)	0.92 (0.66, 1.29)	0.96 (0.68, 1.35)
	Office-based	1.00 (baseline)	1.00 (baseline)	1.00 (baseline)	1.00 (baseline)
	Project management	0.92 (0.75, 1.13)	1.22 (0.89, 1.68)	1.01 (0.66, 1.53)	1.00 (0.66, 1.51)
Sex	Female		1.00 (0.85, 1.17)	0.70 (0.58, 0.86)	0.71 (0.58, 0.86)
Job site	Head Office		0.74 (0.55, 0.99)	0.67 (0.46, 0.97)	0.70 (0.48, 1.03)
	Power station 1		1.38 (1.10, 1.72)	0.61 (0.47, 0.80)	0.58 (0.43, 0.77)
	Power station 2		0.40 (0.33, 0.48)	0.44 (0.34, 0.56)	0.38 (0.29, 0.49)
	Power station 3		2.54 (2.04, 3.16)	1.12 (0.85, 1.47)	0.90 (0.67, 1.20)
	Power station 4		0.74 (0.61, 0.90)	0.57 (0.45, 0.73)	0.42 (0.32, 0.55)
	Power station 5		1.34 (1.04, 1.71)	0.93 (0.69, 1.27)	0.97 (0.70, 1.33)
	Power station 6		0.39 (0.31, 0.49)	0.26 (0.20, 0.34)	0.22 (0.16, 0.29)
	Power station 7		1.00 (baseline)	1.00 (baseline)	1.00 (baseline)
	Power station 8		4.16 (3.26, 5.31)	2.41 (1.79, 3.24)	2.05 (1.52, 2.77)
	Other		0.93 (0.69, 1.25)	0.34 (0.24, 0.48)	0.31 (0.21, 0.44)
Test reason	Symptoms			85.70 (71.37, 102.91)	94.99 (78.29, 115.24)
	Close contact			15.32 (12.75, 18.40)	16.73 (13.80, 20.29)
	Looser contact			2.51 (1.89, 3.33)	2.66 (1.99, 3.56)
	Routine screening			1.00 (baseline)	1.00 (baseline)
Vaccination status	Per vaccination[c]				0.97 (0.88, 1.06)
Vulnerability status	Vulnerable				0.78 (0.63, 0.96)
Outage	During outage				1.35 (1.12, 1.63)
Site risk rating	0/1 (lowest risk)				1.00 (baseline)
	2				0.64 (0.50, 0.82)
	3				1.30 (1.00, 1.69)
	4				1.60 (1.11, 2.31)

[a] adjusted for job category, sex, and site in the table, and also test date, test type and age group (results not shown); [b] adjusted for all variables in the table plus test date, test type and age group (results not shown); [c] up to fully vaccinated (2 or more vaccinations);

We found that the reason for testing was a strong confounder; in particular, the odds ratio for “external” workers (i.e., contractors) changed from 0.74 (95% CI=0.61-0.89) to 1.14 (0.89-1.45) after adjusting for the test reason. Also, women showed lower risks than men, after adjustment for test reason (0.70; 0.58-0.86) but not before 1.00 (0.85-1.17). As well as being a strong confounder of job type, reason for testing was a very strong factor itself (Table 2.4).

Vulnerability, outages, vaccination status and site risk rating were not identified as confounders (on introduction to the model, results not shown) but were included in the final model for completeness. There was strong evidence against a linear trend for site risk rating ($p<0.0001$) so this was included as categorical. There was no evidence against a linear trend for vaccine status ($p=0.92$) so this was included as continuous.

The final model included job type, age, sex, test date, test type, test reason, job site, vaccination status, vulnerability status, outage, and site risk rating. This model showed that there were few differences between job types and likelihood of testing positive after adjusting for all the other included factors. Women were less likely to test positive than men (0.71; 0.58-0.86).

The relationship between site and test positivity showed that power station 8 was higher risk (2.05; 1.52-2.77) than power station 7, the test site with the most tests. All other sites were estimated to be similar or lower risk than power station 7 but with varying magnitudes and levels of evidence (Table 2.4).

There was a large effect of test reason, with those testing due to symptoms having 94.99 (78.29-115.24) times the odds of those from routine screening, those testing due to a positive close contact had 16.73 (13.80-20.29), and looser contact 2.66 (1.99-3.56) times the odds of those tested in routine screening (Table 2.4).

There was no evidence of a difference in risk for vaccinated workers (0.97 per vaccination; 0.88-1.06) but vulnerable workers were at lower risk of testing positive than other workers (0.78; 0.63-0.96) and workers testing during an outage were at increased risk (1.35; 1.12-1.63). The site risk rating did not have a linear relationship with an individual worker’s risk of testing positive; category 2 was lower risk than category 1 (baseline), but categories 3 and 4 were higher risk (Table 2.4).

We additionally ran the final model separately for each reason for testing (Table S1). This showed markedly different findings according to the reason for testing, e.g., with some sites and job categories showing reduced risks if the testing was for symptoms, but increased risks if it was completed as part of routine screening. However, these findings are difficult to interpret because there is a problem with data sparsity in some time periods due to the changing testing protocols (Figure 2.1). Nevertheless, Table S1 shows large differences by site for positivity after routine testing.

2.4 Discussion

In this test-negative design study, based on data from a United Kingdom electricity-generating company, we estimated the odds ratios for infection by job category, site, reason for testing, vulnerability, sex, reason for testing and the Covid-19 risk rating for each site, adjusting for age and test date. There was little difference in risk by job category, and few differences by site. Women were less likely to be infected than men (OR=0.71). As might be expected, the reason for testing was very strongly associated with test positivity with ORs of 94.99 for those tested because of symptoms, 16.73 for those tested as close contacts of positive cases, and 2.66 for looser contacts, compared to those tested routinely. Reason for testing was also a strong confounder for the other independent variables. Thus, in studies of this type, it is important to collect information on, and adjust for, the reason for testing, as previously suggested by Vandenbroucke et al (3).

It is also notable, that despite these strong associations with symptomatic and contact testing, across the pandemic, 16% of cases were identified by routine testing. Thus, routine testing may have played an important role in identifying a significant minority of cases, and thereby also reducing the spread of infection to contacts.

One limitation of this study is that we have included multiple tests by the same people in each time period (Table S2). If the tests are well-spaced then this will not be a problem as the tests should be independent. However, tests close together on the same person will be more likely to have the same result as each other. One option is to shorten each time period and then remove multiple tests, but if the time periods are very small then there are problems of sparse data because of the large number of extra parameters in the model.

Overall, these findings showed little difference in positivity rates by job category once the analyses were adjusted for test reason. There were some differences by site, with four sites showing substantially lower risks, and one site showing higher risks in the final model. Vulnerable individuals showed slightly lower risks, possibly due to those individuals taking more care. Positivity rates were slightly higher during outages when more people were on site. The risk rating did not show consistent associations with positivity rates, which may mean that the covid rules had varying effects at the different levels. Vaccination did not show a protective effect on testing positive which is perhaps surprising.

2.5 Acknowledgements

This work was supported by funding through the National Core Study “PROTECT” programme, managed by the Health and Safety Executive on behalf of HM Government.

2.6 Section 2 References

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3. Patterns of contact between workers at a United Kingdom electricity-generating company

3.1 Introduction

Transmission of SARS-CoV-2 can occur through a combination of three routes: fomite transmission, that is transmission through the touching surfaces that have been contaminated with the virus and then the transfer of these to the mouth, nose or eyes through hand-to-face touching; large droplets that settle out of the air rapidly and so typically do not travel beyond 2m; and fine aerosols that remain suspended for longer and consequently can become more widely dispersed. Exposure to droplets and fine aerosols is strongly associated with periods of contact between individuals, however exposure to fine aerosols can also occur through 're-entry' situations, i.e., through entering a poorly ventilated space that was recently vacated by infected individual. Although fomite transmission cannot be discounted, in most settings it is not regarded as a major source of transmission [1]. Hence the patterns of contacts between individuals in a workplace are a key determinant of levels of workplace transmission.

In order to better understand the risk of transmission of SARS-CoV-2 within the nuclear energy sector, and in particular to provide inputs into micro-scale modelling of transmission, information on contact behaviours was gathered through:

1. An on-line workforce survey developed by PROTECT project researchers that was shared amongst the workforce of two electricity production sites owned by the same energy production company, EDF.
2. Extraction of information on numbers of contacts of confirmed workforce cases identified through the company's internal contact tracing process.

The online survey and company contact tracing narratives provided information for the generation of workforce contact networks for use with agent-based modelling of the transmission of SARs-CoV-2 and the evaluation of the effectiveness of mitigation measures implemented at these sites during the pandemic (see section 5). The construction of these contact networks is described in Section 3.4. The data collected using the online questionnaire complemented the information collected during a site-based consultation with workers at the same two electricity production sites that took place during July 2022 [2].

3.2 Workforce survey

3.2.1 Design

An online questionnaire was designed to collect evidence on:

1. workers' views on the effectiveness of the control measures implemented by EDF to help reduce risk factors for COVID-19 transmission.

2. the patterns of contacts amongst workers to inform simulation models for transmission of SARS-CoV-2 at electricity generation facilities.

The link to the on-line questionnaire was shared by email with the workforce at these two production sites that included EDF workers and contractors. Approximately 475 employees and 175 contractors are located at each generating site, a total of 650 workers at each site.

The on-line questionnaire was open to participants from July 25th to August 12th 2022. During this period, teams on each production sites were reminded of the importance of the work and to consider accessing the questionnaire through the on-line link shared with them by email. There were no other incentives for completion of the survey. Response rates from similar previously run surveys at EDF suggested we could expect 20% of the workforce completing the survey (or about 260 participants in total from these two sites).

3.2.2 Ethics

Workers clicking on the survey link provided by email by their employer accessed a front page that introduced the study and acted as the participant information sheet. It stated that participation was voluntary, individual responses would not be shared with the employer would be aggregated before sharing.

Participants were then able to access the questionnaire itself by simply clicking on a "next" button at the bottom of this front page. Workers accessing the questionnaire, completing the questionnaire and clicking on the "submit" button at the end, acted as their formal consent to take part in this study. A paper version of the on-line questionnaire is presented in the Annex of this report.

The questionnaire, participant recruitment process and study protocol were reviewed and approved on July 1st 2022 by the Research Ethics Committee of the University of Sheffield (reference HSE38).

3.2.3 Questionnaire structure

The questionnaire (Appendix 2) was structured around five main themes, collecting information on:

- each participant's demographic characteristics;
- job details including location;
- workplace controls in place and their effectiveness;
- vaccination status and health information; and
- typical numbers of daily contacts with co-workers, including close contacts with co-workers from their own team, outside of their own team, while travelling to work and while at their living accommodation during working week.

Close contact was defined as a situation where at least two individuals are either within 2 meters of each other for more than 15 minutes, or within 1 meter of each other for 1 minute or longer.

Two questions were included to provide additional insight to the qualitative site-based discussion with workers. These questions included:

- Which of the measures listed [within earlier question] do you believe to be most effective in preventing transmission of the COVID-19 virus currently. Why is this?
- How likely do you think it is that you will catch COVID-19 currently [Likert scale response]? Why is this?

The results of these questions have been reported previously and are not included in this report.

The questionnaire was generated and managed through Microsoft Forms.

3.2.4 Survey findings

A total of 211 participants completed a questionnaire on-line (response rate ~16%) split equally between the two generating sites. The number of respondents by individual job categories are reported in Appendix 3. The main findings from the survey in relation to contact reported contact patterns were:

- On average, the number of close contacts with people outside of their own team was slightly lower (but similar to) the number of close contacts in their own team (2 vs 3).

- The total number of contacts was not associated with site or employment, but it was associated with work pattern, i.e., the contact rate was higher for those on shift compared to day workers.

- Participants having managerial/supervisory responsibilities tended to have more contacts.

- Environmental safety technicians, those in Maintenance (DART/TAG) and Nuclear safety group had statistically significantly higher contact rates than Engineers (when adjusted for other work factors).

In-depth statistical analysis of the responses related to the number of close contacts with co-workers at these two production sites are reported in Appendix 3. The in-depth analysis was used to build a network representation of contact patterns reported in the section 3.4.

Other finds were:

- On worker health: 73% of respondents reported having had COVID, 93% reported being doubly vaccinated, 41% reported having a vulnerable family member, 5% vulnerable themselves.
- On control measures: the most frequently reported control measures included hand sanitising stations, IT enabled meetings and working from home.

3.3 Contact tracing narratives

This section summarises information on contact behaviours provided by the electricity generating company pertaining to its internal COVID-19 contact tracing. Contact tracing was undertaken following the identification, either through symptoms consistent with COVID-19 or through testing, of cases.

Contacts of confirmed cases at sites during periods of increased risk were considered in two categories: ‘A list contacts’ and ‘B list contacts’. A list contacts were defined according to the public health definition of close contacts, i.e., <2m for more than 15 minutes or <1m for more than one minute or direct contact. B list contacts were people who had interactions with the suspected/confirmed case that did not meet the public health authority criteria but were judged to at heightened risk of infection and so pose a risk to the site. Inclusion on the B list was at the discretion of site occupational health team and was influenced by the clinical picture and the local risk of disease. However, essentially B list contacts, were individuals who had been present in the same airspace as the case for an extended period.

Contact tracing identified A and B list contacts in the preceding 48 hours to the index case developing symptoms (or testing positive) and recorded these (named) individuals on a proforma. A list contacts were reported to the relevant public health authority. As part of the research the company reviewed all contact tracing narratives relating to the two power stations from 2021. The date, job category of the index case and numbers of A list and B list contacts were extracted from each narrative and these data supplied to the research study team. In total 511 narratives pertaining to 2021 were examined comprising 210 from Heysham 1 (HYA) and 301 from Heysham 2 (HYB). The greater number of narratives available for Heysham 2 is concordant with a greater number of test-confirmed cases during 2021. Table 3.1 summarises the numbers of A and B list contacts identified for the whole of 2021 and for different sub-periods.

Table 3.1: Summary of numbers of contacts per index case reported in contact tracing narratives at two electricity generating sites during 2021

Period	# A list contacts: mean (range)			# B list contacts: mean (range)		
	HYA	HYB	Pooled	HYA	HYB	Pooled
January-April	0.29 (0-5)	0.33 (0-5)	0.31 (0-5)	3.8 (0-17)	3.1 (0-15)	3.5 (0-17)
May-August	0.85 (0-7)	0.79 (0-5)	0.82 (0-7)	2.2 (0-22)	4.8 (0-25)	3.7 (0-25)
September-November	0.32 (0-2)	0.41 (0-4)	0.38 (0-4)	1.5 (0-10)	2.1 (0-15)	1.9 (0-15)
December	2.1 (0-15)	0 -	0.73 (0-15)	1.7 (0-9)	1.5 (0-14)	1.6 (0-14)
Whole of 2021	0.92 (0-15)	0.39 (0-5)	0.61 (0-15)	2.3 (0-22)	2.9 (0-15)	2.7 (0-25)

The time periods were chosen to align with those used in an investigation of the effectiveness of mitigations using an agent-based model for power station transmission (presented in section 5) also taking account of statutory power station outages. Overall, 76% of narratives reported no A list contacts and 50% no B list contacts. For all periods except December 2021 at HYA there were several times more B list contacts than A list. Several of the narratives from HYA in December 2021 reported considerably higher numbers of A list contacts (as many as 15 on four occasions) than in any narratives outside this period. Excepting this there was no compelling evidence of a difference in the numbers of contacts between the stations save for there being a greater number of B list contacts at HYB during May to August 2021. This period corresponds to a statutory (three yearly) outage of HYB during which several hundred additional contractors were on site.

Notably there were fewer B list contacts reported during September to November 2021 than between January and April 2021 (pooled mean 1.9 vs 3.5 per index case). Both sites were on a lower company COVID-19 risk rating during September to November perhaps implying that fewer contacts were classified as being B list contacts (which required the contacts to isolate) rather than this representing a genuine reduction in the number of on-site contacts occurring particularly since there were greater numbers of workers on-site during September to November (vs January to April) due to a scaling back of remote working.

Very considerably fewer A list contacts were reported in the contact tracing narratives from 2021 than self-reported, using the equivalent public health authority definition, in the online survey of power station workers during July and August 2022 (See section 5.2). The principal explanations for this discrepancy would appear to be

i) organisational changes to work activities, and associated behavioural changes, that substantially restricted the number of close contacts that occurred during the early and mid-period of the pandemic were subsequently largely phased out by summer 2022; and

ii) bias leading to over-reporting of contacts in the survey. The available information does not allow any firm conclusions to be drawn about which of these explanations is more likely, however it seems probable that both may have contributed.

3.4 Building a contact network representation

The development of networks to representing the pattern of contacts in the workforce was undertaken as a preparatory step towards the modelling of transmission of SARS-CoV-2 utilising an agent-based model (section 5). Contacts between workers were modelled by networks in which nodes of the network represent workers and an edge joining a pair of nodes represents contact between the corresponding pair of workers. Networks were encoded using a binary adjacency matrix in which a value of unity represents an edge (i.e., a contact) and zero indicates no edge/contact. The matrices were generated using a stochastic algorithm in which the probability of an edge (contact) being generated was proportional to the product of a pair of individual worker weights, where each weight represents an expected, or target number of contacts for that worker.

For each of day of a 10-day sequence, an adjacency matrix was generated and the contacts assigned to be short (distances under 2m) or medium proximity (between 2m and 5m). The relative number of short and medium proximity contacts was based on information from the employers contact tracing narratives (see section 3.3). The online survey of power station workers (see section 3.2) provided evidence for differences in numbers of contacts between different job categories. Therefore, in the contact network representation each worker was assigned to a particular job category. The typical number of workers in each job grouping at a power station was supplied by the generating company and are reproduced (with the grouping of some job categories, e.g. day operations, operations shift, operator technicians, security) into five operational shifts in Table 3.2.

Table 3.2: Number of workers per job category.

Team	Team Size	Team	Team Size
Station leaders	12	Finance	25
Human resources	5	Work management	35
Operations shift team 1	40	Outage	10
Operations shift team 2	40	Chemistry	10
Operations shift team 3	40	Nuclear safety group	20
Operations shift team 4	40	Maintenance	50
Operations shift team 5	40	Improvement & Training	25
Engineers	40	Investment	25
Fuel route	25	Contractors	175
		Total	657

Negative binomial regression analysis of the number of self-reported daily contacts per worker from the on-line survey responses provided the mean number of contacts between members of the same job group and the mean number of contacts between workers in different job groups. To generate the synthetic network each worker was assigned a target number of within-team contacts and a target number of between-team contacts (although the actual number generated is usually a little different from the target due to the stochastic nature of the algorithm). The target numbers of contacts for each were drawn from negative binomial distributions with parameters based on the regression coefficients (see Appendix 4) with an additional calibration parameter to allow tuning of the number of A list and B list contacts per index case in subsequent agent-based modelling. The numbers of between-team contacts for the workers in each team were re-ordered to generate correlation with the number of within-team contacts matching the findings from the online survey (Spearman's $\rho = 0.57$).

For each potential network edge, i.e., a contact between a pair of workers, a weight was assigned equal to the product of those workers' target number of within- or between-team contacts, depending on if the workers were in the same or different teams. The synthetic networks were generated by random assignment of edges between pairs of workers, with probability proportional to the weight assigned to each pair. Subsequently the numbers of A list and B list contacts per symptomatic case simulated using an agent-based model for workplace transmission of SARS CoV-2 were compared with the numbers recorded in the employer's contact tracing narratives, and the calibration parameter iteratively adjusted until approximate agreement was achieved. Some further details of this step are presented in sections 5.3 and 0.

Multi-day sequences of networks were derived from a baseline network comprising all short and medium proximity contacts generated using the above methodology. For each day of the sequence an alternative network was generated, using the same algorithm and generation parameters as for the baseline, but drawing different random numbers for the target number of contacts for each worker. The final network for each day was generated by duplicating the baseline network, removing 20% of the edges from it (a different 20% sample each day) and replacing them with the same number of edges sampled from the alternative network for that day. All contacts in the final network for each day were randomly assigned to be short or medium proximity, in proportion to the ratio of A list to A list + B list contacts given in the employer contact tracing narratives, where A list and B list refer to unique individuals contacted over multiple days. Additionally, on each day 10% of the short/medium assignments were swapped from those in the baseline network. Although short and medium contacts in the synthetic networks are defined differently to A list and B list contacts, in the agent-based model the A and B list contacts are derived from the synthetic short and medium contact networks.

Figure 3.1 shows the adjacency matrices representing short and medium proximity contacts for a single day. Values of unity (i.e., contacts between a pair of workers) are shown as black pixels. Workers in the same team are represented on adjacent rows/columns - within-team contacts are indicated by blue boxes on the leading diagonal. Contacts between workers of team 4 and team 15 are indicated by red boxes off the diagonal: as the matrix is symmetric both red boxes indicate the same interactions.

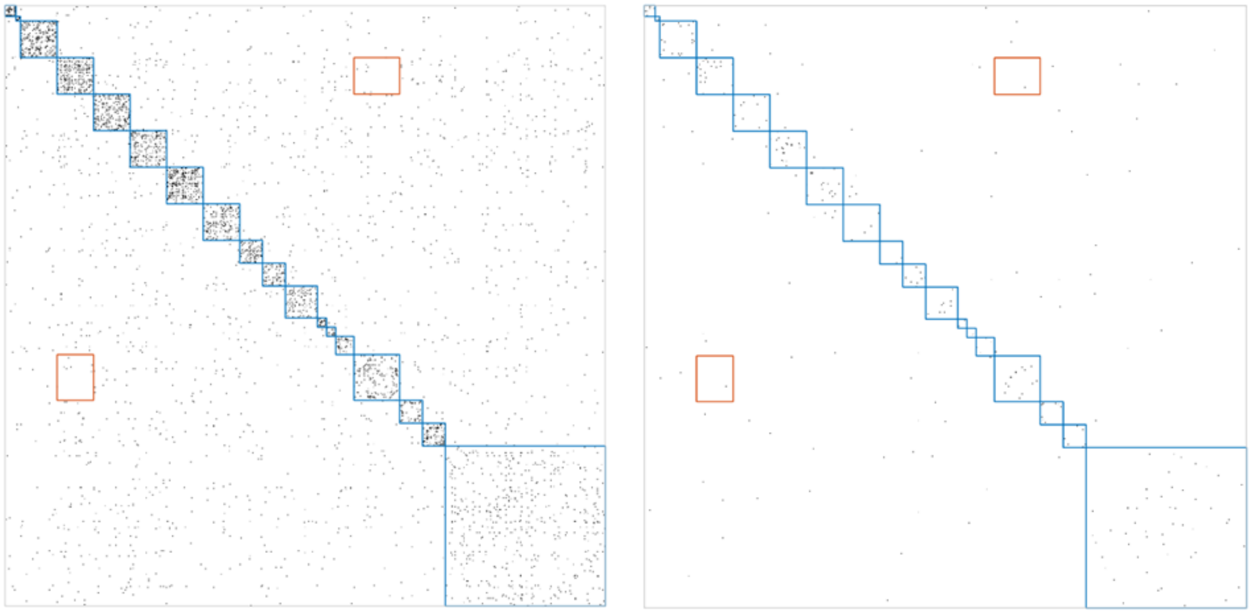

Figure 3.1: Adjacency matrices representing short proximity contacts (left) and medium proximity contacts (right) between 657 workers in 18 teams on day one of a ten-day sequence.

The mean numbers of short and medium proximity contacts per day are 0.5 and 6.7, respectively, and the most likely numbers of these type of contacts are zero and two (Figure 3.2). The agent-based model presented in section 5 accounts for remote working, work shifts and isolation by reducing the number of workers in the appropriate teams present on-site on any given day. Hence, the actual numbers of contacts per day quoted above are greater than the numbers that are actually simulated using the model.

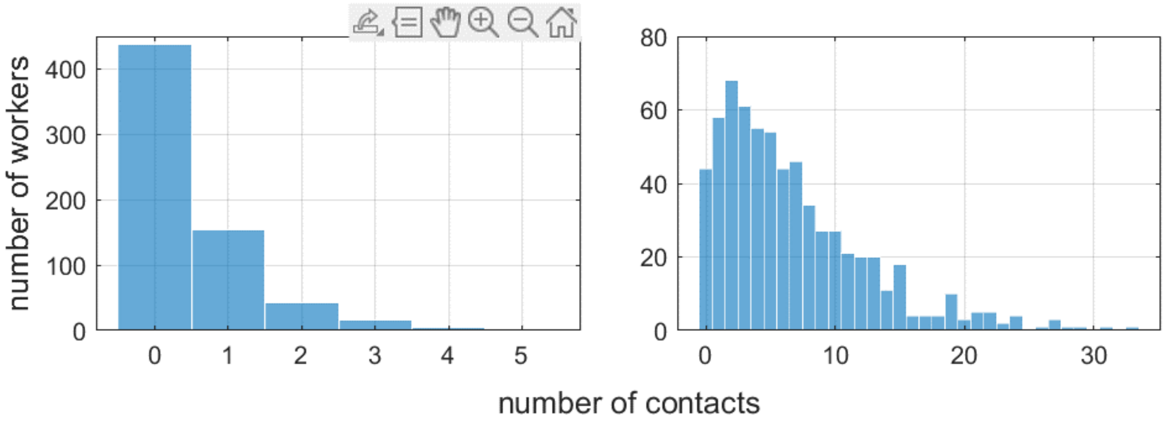

Figure 3.2: Number of contacts per worker per day – short proximity (left) and medium proximity (right).

3.5 Conclusions

- There was no evidence, either from the online worker survey or from the company contact tracing narratives, of substantial differences in contact behaviours between the two stations.
- The online survey suggested approximately equal numbers of contacts with and between teams.
- Evidence from the contact survey that shift workers (day operations, operations shift, operator technicians, security) have more close contacts than other jobs.
- Very considerably fewer close contacts were reported in narratives from 2021 than self-reported in an online survey of power station workers during July and August 2022. The principal explanations for this discrepancy are i) organisational changes to work activities, and associated behavioural changes, that substantially restricted the number of close contacts that occurred during the early and mid-periods of the pandemic were subsequently largely phased out by summer 2022 ii) bias leading to over-reporting of contacts in the survey. The available information does not allow any firm conclusions to be drawn about which of these explanations is more likely, however it seems probable that both may have contributed.
- The two information sources provided the inputs for the construction a network representation of contact patterns that was used within a simulation model for transmission of SARS-CoV-2 within a workforce.

3.6 Section 3 References

[1] Centres for Disease Control and Prevention (2021) Science Brief: SARS-CoV-2 and Surface (Fomite) Transmission for Indoor Community Environments. Release version 5th April 2021

[2] Clabon, K., Canham, R., and Coleman, A. (2023) PROTECT- deep dive with an electricity generating company: qualitative insights from site-based workers. https://documents.manchester.ac.uk/display.aspx?DocID=65318

4. Comparison of SARS-CoV-2 infections in an electricity generating company and the local community

4.1 Introduction

As employees are naturally integrated in the local community where they conduct everyday activities, an analysis was carried out to disentangle how much of the workplace epidemic can be attributed to importations from the community and how much to transmission within the workplace itself. In general, transmission in the workplace is not expected to be less than that in the community, unless the community is characterised by high-risk socio-economics factors, including for instance large low income or student communities.

To have a more significant population at risk, the analysis focused on a complex of two neighbouring electricity-generating stations in the North West of England (Heysham 1 and 2), with the population of the two stations pooled together. The maps below (Figure 4.1) show that, while external contractors are recruited from all around the UK, the majority of the employees come from locations in the neighbourhood of the two power stations under consideration.

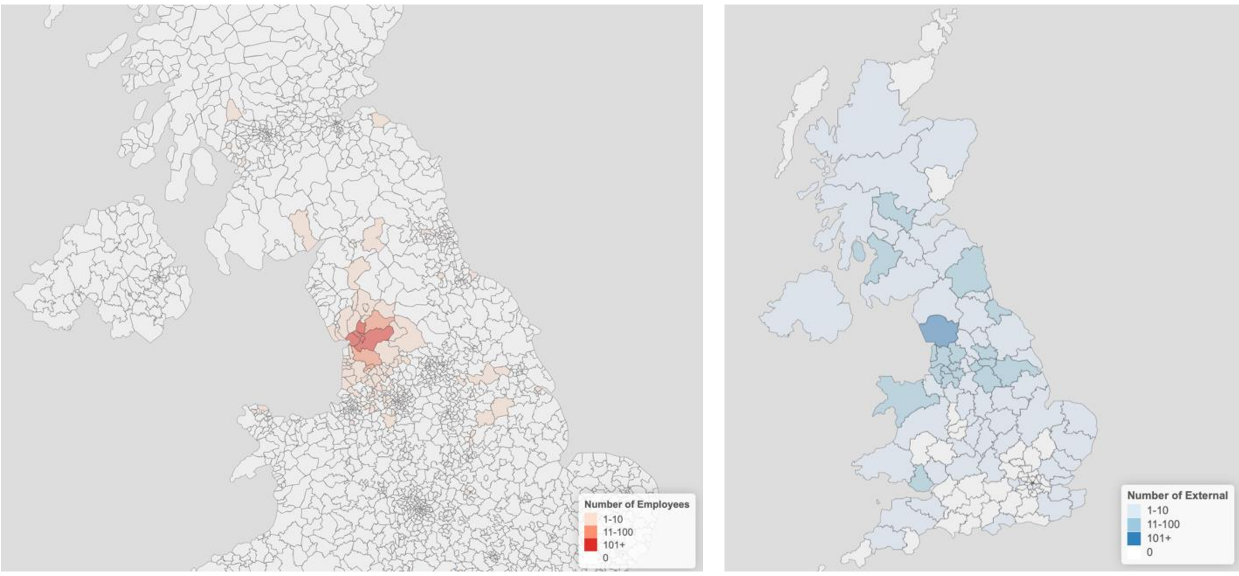

Figure 4.1: Recorded residence of individuals identified as ‘Employee’ (left, district level postcode) and others (including ‘External’ and ‘Visitor’; right, area level postcode).

4.2 Methods

To disentangle the contribution to the transmission in the power plant driven by the local community and by workplace transmission, a combination of statistical and modelling methods was used. First, suitable geographical scales with a potential link to the power plant were identified. The case data time series at the local community level and in the power plant were analysed using generalised additive modelling to allow comparison of the instantaneous growth rates and the magnitude of the epidemics relative to the total population sizes. To support simple theoretical observations, a two-compartment deterministic model was used to test different hypotheses (increased workplace transmission versus lower under-reporting). Finally, a simple stochastic model accounting for workplace screening and contact tracing of detected cases was used to investigate theoretically the effect of relaxing interventions in the workplace on the realised and observed infections, in a theoretical framework with well-mixed contacts in the workplace.

4.2.1 Identification of the local community geographical scale

Reported daily cases of SARS-CoV-2 in the community for each Lower Tier Local Authority (LTLA) were obtained from data provided to the Scientific Pandemic Influenza Group on Modelling – Operational (SPI-M-O) by the UK Health and Security Agency (UKHSA) as part of the pandemic response, not publicly available.

The correspondence between the postcode data recorded in the power plant database (in the form of district-level postcode) and LTLAs is not exact. The LTLAs of Lancaster, Wyre and Craven were identified following a broad correspondence provided by the ONS [1], as they cover (together with South Lakeland) the five postcode districts with the highest number of employees. The LTLA of South Lakeland was excluded as this is a very wide LTLA that covers most of the Lake District area [2].

Three geographical scales were considered: a small geographical scale comprised of Lancaster LTLA only, representing the major city in the neighbourhood of the power plant; a medium scale comprising Lancaster, Wyre and Craven LTLAs; and a large scale comprising the North West of England. To compare populations with similar characteristics, the analysis was restricted to the adult population, aged 20-64, in order to reduce the impact of outbreaks in the school populations and in the vulnerable senior age groups. The population size of the three geographical scales is summarised in Table 4.1.

Table 4.1: Geographical scales considered in the analysis and corresponding population [3].

Geographical scale	*Total population*	*Population aged 20-64*
Small scale (Lancaster)	142,900	81,200
Medium scale (Lancaster, Wyre, Craven)	311,700	170,900
Large scale (North West of England)	7,417,300	4,294,800

4.2.2 Generalised additive model with day-of-the-week effect

Typically, an infection that spreads from person to person will grow exponentially in the early phase of epidemic. This exponential growth can be measured through the real time growth rate r so that, loosely speaking, the incidence of infection is $y(t) = y_0 e^{rt}$ + noise. To allow, in a semi-parametric manner, time variation in growth rates, a generalised additive model (GAM) was used, where $y(t) \propto e^{s(t)}$ for some smoother $s(t)$. The instantaneous local growth rate is then taken as the time derivative of the smoother, $r(t) = \dot{s}(t)$. To account for the weekly reporting patterns (e.g. reduced case reporting at weekends, followed by a back-log of cases at the start of the week), additional explanatory variables for the day-of-the-week effect were included. Thus, denoting by $y(t)$ the random number of new cases on day t, the expected value is $E[y(t)] = \exp(d_j + s(t))$, where d_j takes on a different value for each day of the week ($j = 1, \dots, 7$) corresponding to time t. As output, the method returns both a spline for the growth rate and a fit to the data, including day-of-the-week effect. A smooth fit to the daily cases was obtained by a weighted average accounting for the estimated day-of-the-week effect in each setting, which could be used to infer a smoothed time series representing the underlying community incidence. The analysis was performed using the R package mgcv [4, 5], using a Negative Binomial family with GP spline to capture the noise inherent in the data. Asymptotic confidence intervals are derived for $r(t)$.

4.2.3 A simplified compartmental model for the community-power plant interaction

To have a minimalistic description of the relation between the epidemic in the community and in the power plant, a simplified deterministic compartmental model was considered and used to simulate the essential dynamical patterns. A simplified representation has the advantage to capture the essential dynamical aspects without including the detailed fine-grained mechanisms of individual events.

Consider a simple SIR model, with individuals partitioned into Susceptible (S), Infected and infectious (I), and Removed (R) (either by recovery, isolation or death). Denote with a subscript p

and c the variables related to the power plant and the local community, respectively. Let N_p and N_c denote the total number of individuals in the two settings. The compartmental model is described by the equations

$$I_c'(t) = \beta_{cp}\frac{S_c}{N_c}I_p + \beta_{cc}\frac{S_c}{N_c}I_c - \gamma I_c$$
$$I_p'(t) = \beta_{pp}\frac{S_p}{N_p}I_p + \beta_{pc}\frac{S_p}{N_p}I_c - \gamma I_p$$

(4.1)

with $\beta_{ij} = p_i c_{ij}$ $(i, j = p, c)$, where c_{ij} denotes the contact rate of one individual in the setting j with individuals in setting i, and p_i is the transmission probability upon contact (possibly time-dependent).

To capture the fact that the power plant population is a small fraction of the local community ($N_p \ll N_c$), it is convenient to reformulate system (4.1) in terms of the *fractions* of individuals in each setting, that are denoted for simplicity with small letters, e.g., $s_c = S_c/N_c$. With this notation, (4.1) is equivalent to

$$i_c'(t) = \beta_{cp}s_c i_p\frac{N_p}{N_c} + \beta_{cc}s_c i_c - \gamma i_c$$
$$i_p'(t) = \beta_{pp}s_p i_p + \beta_{pc}s_p i_c\frac{N_c}{N_p} - \gamma i_p$$

(4.2)

Assuming that a generic individual in the community c contacts per day, one can assume that the infectious contacts β are proportionally distributed between individuals in the power plant and in the community according to

$$\beta_{cc} = \frac{\beta N_c}{N_p + N_c}\,, \qquad \beta_{pc} = \frac{\beta N_p}{N_p + N_c}.$$

Combining with the assumption $N_p \ll N_c$ results in the following approximations:

$$\beta_{cc} \approx \beta, \qquad \beta_{pc}\frac{N_c}{N_p} \approx \beta.$$

It is also reasonable to assume that workers in the power station are relatively conscious of the risks of community transmission, so their infectious contact rate with individuals in the community is not larger than β. For a conservative estimate, the approximation $\beta_{cp} \approx \beta$ was considered. However, since workplace transmission (β_{pp}) depends intrinsically on the nature of the jobs and on the safety measures in the workplace, this parameter cannot be naturally linked to the community transmission parameters, and indeed can drive workplace transmission.

With these approximations in place, (4.2) simplifies to

$$
\begin{aligned}
i_c'(t) &= \beta s_c i_c - \gamma i_c \\
i_p'(t) &= \beta_{pp} s_p i_p + \beta s_p i_c - \gamma i_p
\end{aligned}
\qquad (4.3)
$$

From (4.3) it is clear that, under the previous assumptions, the epidemic in the community is independent of the epidemic in the power plant, as it is negligibly influenced by the relatively small workforce population.

The local instantaneous epidemic growth rate is obtained via a standard method by linearising the system assuming that the susceptible population is locally constant, so that the corresponding linear system is defined by the (possibly time-dependent) matrix

$$
\begin{pmatrix} \beta s_c - \gamma & 0 \\ \beta s_p & \beta_{pp} s_p - \gamma \end{pmatrix}
$$

which is lower triangular with eigenvalues

$$
\lambda_c \approx \beta s_c - \gamma, \qquad \lambda_p = \beta_{pp} s_p - \gamma.
$$

If $\lambda_c > \lambda_p$, the epidemic in the power plant tends to synchronise with the epidemic of the community. The larger relative number of positive individuals can be explained by a higher detection rate in the power plant following the stricter testing/monitoring measures.

If $\lambda_c < \lambda_p$, then the power plant should show a larger growth than the community, which instead tends to align with an exponential growth with coefficient λ_c.

To use system (4.3) to study the impact of the community of the power plant, the time series of the community incidence, $inc(t) = \beta s_c i_c$ was assumed to be known, obtained by the smoother of the daily cases obtained from the GAM analysis. System (4.3) was then solved for $t \geq t_0$ assuming $s_c \approx 1$ (negligible immunity in the community) and by computing the susceptible population in the power plant from the equation $s_p'(t) = -\beta_{pp} s_p(t) i_p(t) - s_p\, inc(t)$, with $s_p(t_0) = 1$.

4.2.4 A simplified stochastic model including screening and contact tracing

While the simple deterministic compartmental model captures the feedback mechanisms between the power plan and the local community and the (de)synchronicity phenomena, it is insufficient to capture the effect of intervention measures aimed at reducing workplace transmission and isolating positive individuals. To this aim, a simple stochastic model including essential mechanisms of screening (by symptomatic or routine asymptomatic testing) and tracing of contacts was considered. The model, which is a stochastic version of the deterministic model proposed in the literature [6], is a simple agent-based stochastic model (ABM) on a homogeneous contact network, capturing three main processes:

- Infection spread, in which every individual is assigned a generation time (Gamma-distributed with mean 6.84 days and standard deviation 4.48 [7]), a reproduction number R_0, and an incubation period drawn by a given distribution (Gamma-distributed with mean 3.49 days and standard deviation 1.2 [7], assuming that 30% of cases are asymptomatic [8, 9]);

- Screening, such that every infected individual can test positive with a certain probability according to a given distribution;

- Contact tracing, for which each secondary contact of a positive case is tested with a certain probability and removed if positive.

Although the model is not refined enough to capture the realistic contact network, it can be used to broadly assess the impact of intervention measures on the underlying infection spread and the cases reported through screening and tracing. The model was simulated in the period from September 2021 to March 2022, accounting for daily importation of cases generated from the local community.

Random importations from the local community into the power station were generated as follows:

- The smoother obtained from the GAM analysis on the local community (medium scale) is taken as approximation of the reported community cases;
- Each reported case is assigned a time since infection, randomly drawn from a uniform discrete distribution from 1 to 14 days, and therefore a day of infection;
- The time series of daily infections is obtained by multiplying the obtained time series times an amplifying factor to account for underreporting, (varied between 1 and 1.5);
- Daily importations into the power plan are obtained by sampling daily a Poisson random variable with parameter equal to the time series of the community infections scaled proportionally to the population size of the power plant.

Detection of infected individuals via screening is obtained by assigning a probability distribution of detection to each individual. For symptomatic screening, detection happens upon symptom onset. For routing screening, the probability of detection also follows the incubation period distribution, which is taken as proxy for the test positivity profile. For each detection route, the cumulative probability of being detected was taken as a parameter ε, which is reduced by the percentage of asymptomatic individuals in the case of symptomatic screening only. Taking into account that individuals in the power plant were immediately sent for testing and isolation upon symptom onset and that testing machines were available onsite, no delay was assumed between testing and isolation.

Given a positive test, all the individuals infected by the index case within the last 48h are immediately tested and detected (and isolated) with a probability ε (assumed to be the same as the detection probability for illustration purposes). For similar considerations about testing and isolation in the workplace, no tracing delay was considered.

The model ignores the isolation of healthy individuals upon contact tracing, which would slightly overestimate the number of infections (by overestimating the number of susceptible people). However, traced contacts would test and return back to work after the second negative test, effectively returning to the susceptible population.

For each parameter choice, $n = 50$ simulations of the model were run for each choice of the screening and tracing parameters and workplace reproduction number to compute the average total number of infections and reported cases in the selected period (September 2021 to March 2022). The simulations give an indication of the consequences of scenarios where interventions are relaxed or intensified.

4.3 Comparison of the instantaneous growth rates in the power plant and the local community

The instantaneous growth rate for the positive cases in the power plant and the community (at the three geographical scales) was computed using the GAM with day-of-the-week effect, considering the adult population in the community, aged 20-64 years. The analysis over the whole period of interest (September 2020 to March 2022) in Figure 4.2 shows that, for all geographical scales, the growth rates seem in good agreement after July 2021, while the trends of the epidemics in the power station seem to differ substantially from that of the local community in the period before June 2021. The latter time frame is characterised by several aspects: the start of the vaccination campaign in the spring/summer 2021, the establishment of different variants (Alpha, Delta) from November 2021, and various changes in the work conditions, including periods of outages (e.g. from September 2020 to January 2021) with many external contractors coming into the power plant, as well as increased interventions with large fractions of the office workers working from home, and periods of low testing.

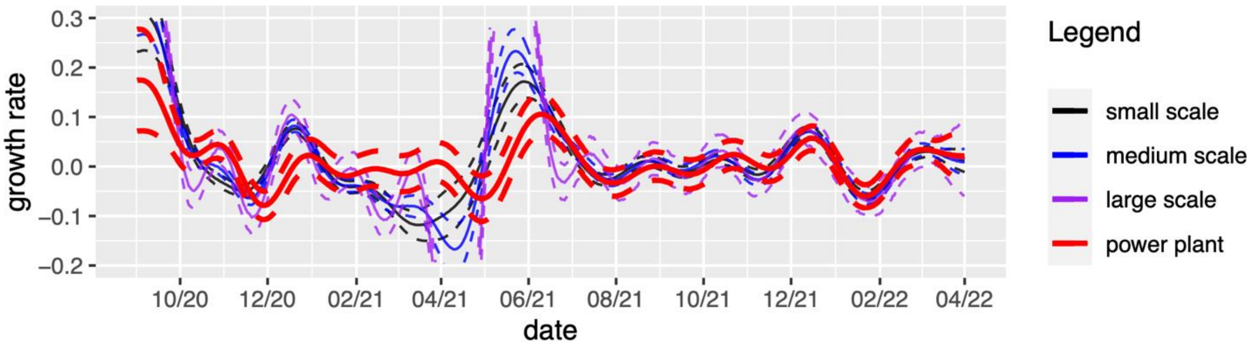

Figure 4.2: Estimated growth rate, all time. Instantaneous growth rate estimated via GAM accounting for day-of-the-week effect, for the power plant (red) and the local community at three geographical scales (small/medium/large community), for the population aged 20-64 years. Continuous lines represent the mean estimate, dashed lines the 95% confidence intervals.

To compare the magnitude of the epidemics relative to the total population at risk, a suitable denominator should be selected for each setting. While the total populations are known for the local community (Table 4.1), identifying the population at risk for the power plant is a nontrivial task. This was achieved by counting the number of individuals classified as 'Employee' in the database, which we take as a proxy for the stable workforce, plus the number of other workers ('Visitors' or 'Externals') recorded in a given time frame, taken as a proxy for workers hired on a temporary basis for maintenance jobs particularly during the outage periods. For this reason, two different time frames were isolated for a more detailed analysis: one in a 'pre-vaccination' period, from September 2020 to March 2021, and the other in a 'post-vaccination' period, from September 2021 to March 2022. The total number of tests performed in these two time frames is shown in Figure 4.3. Figure 4.4 shows the output of the GAM when fitting the cases in the power plant in the two identified time frames (average of the day-of-the-week effect). To note is that the period between December 2020 and January 2021 is characterised by very low testing levels, which are likely partly responsible for the low reported cases in that time period.

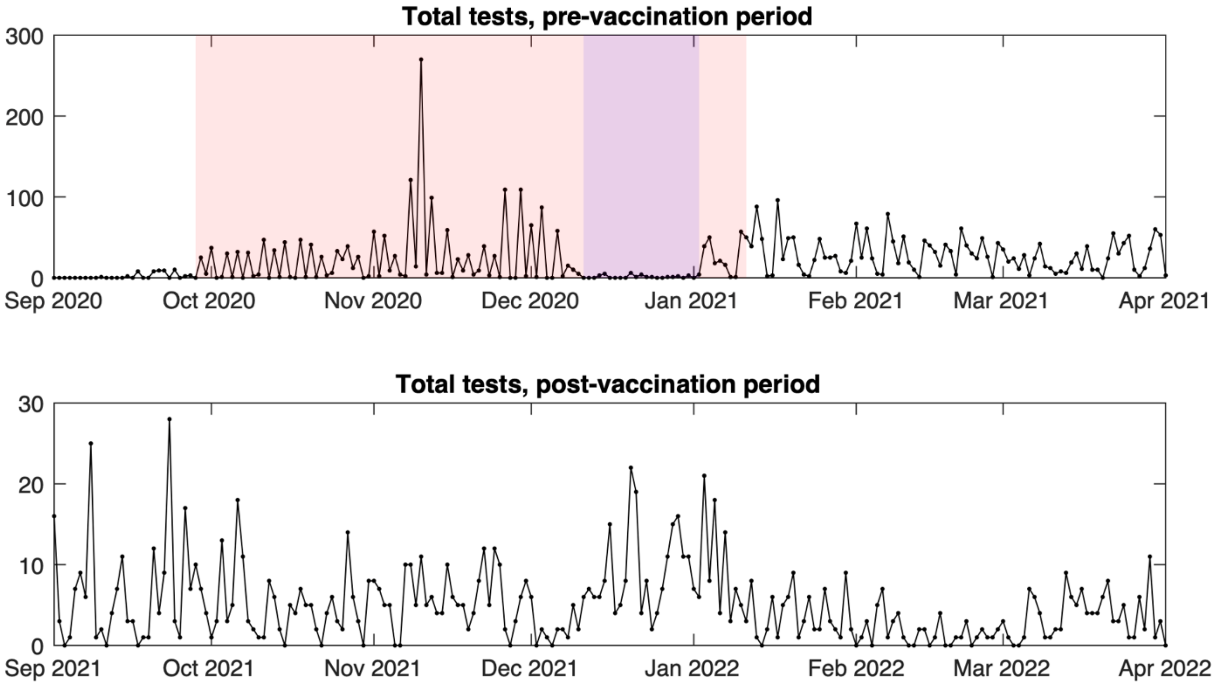

Figure 4.3: Total daily number of reported tests, for the selected pre-vaccination (top) and post-vaccination (bottom) time frames. For the pre-vaccination period, the red region indicates the period of outage, and the violet region indicates the time frame with low numbers of recorded tests.

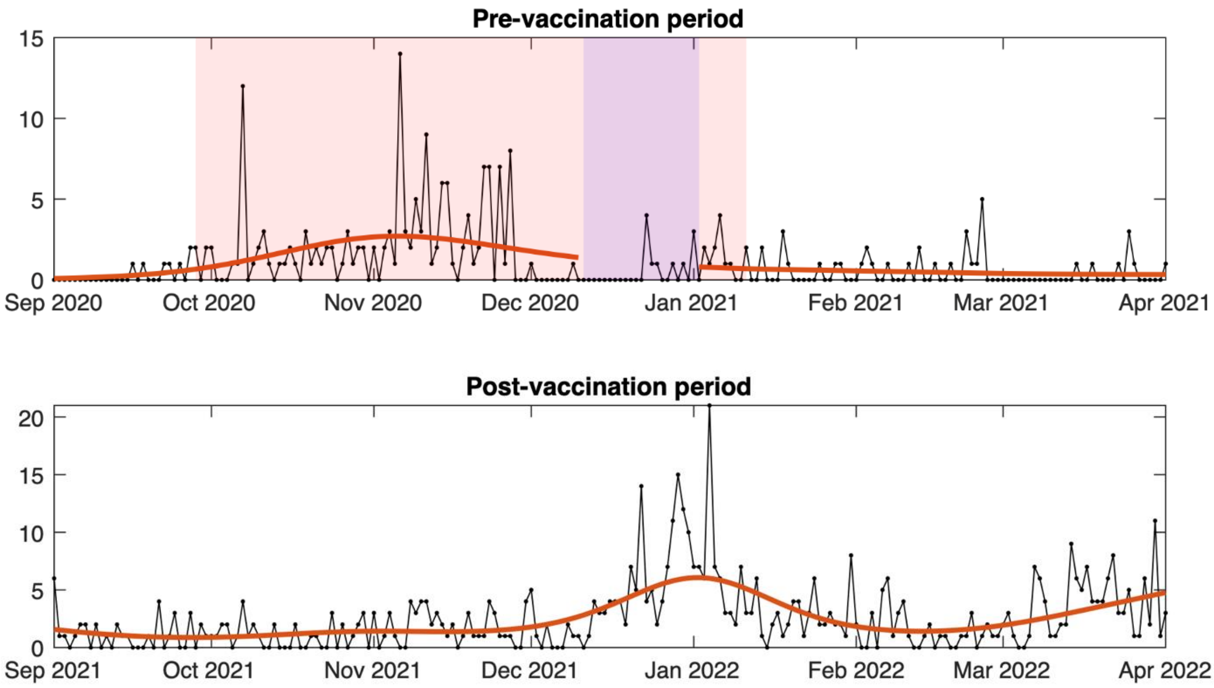

Figure 4.4: Smoothed curve (red) fit to reported cases in the power plant (black dots) using GAM and averaging the day-of-the-week effect, for the selected pre-vaccination (top) and post-vaccination (bottom) time frames. For the pre-vaccination period, the red region indicates the period of outage, and the violet region indicates the time frame with low numbers of recorded tests (excluded from the GAM analysis).

4.3.1 Pre-vaccination period

For the pre-vaccination period, it was not easy to isolate a suitable period outside outage dates, so the whole window from 01/09/2020 to 01/04/2021 was considered. The population for the power station was taken as 1586 workers (including individuals recorded as 'Employee" and others recorded in that time frame). The estimated instantaneous growth rate (top panel) and the corresponding smoothed incidence curves normalised per 10,000 individuals (bottom panel) are shown in Figure 4.5. The period under consideration is characterised by one of the power plants being in outage (time frame highlighted in red), and by a period of consistently low testing, with less than five tests per day conducted and most days seeing no recorded tests (highlighted in violet). The period of low testing was removed from the time series used to compute the GAM fit, as the GAM applied to the time series of positive tests would not be able to distinguish low positive tests due to lack of testing from a true signal of low prevalence. Compared to the local community (at each of the three geographical scales, although the difference is more pronounced for the smaller geographies), the power plant shows a higher and delayed wave of transmission extending to November 2020, followed by a relatively controlled period during January 2021, when the local community shows a resurgence of infections.

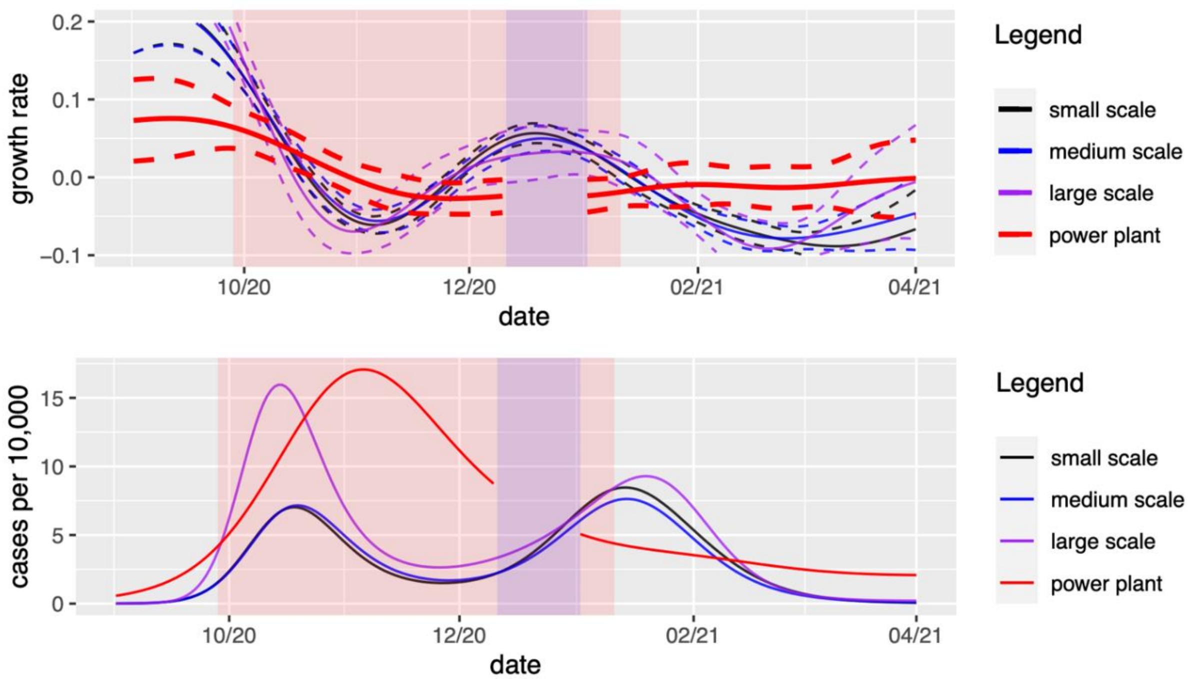

Figure 4.5: Estimated growth rate and smoothed incidence curve, pre-vaccination period (01/09/2020 to 01/04/2021). Instantaneous growth rate estimated via GAM with day-of-the-week effect, for the power plant (red) and local community at three geographical scales (small/medium/large), aged 20-64 years. Continuous lines represent the mean, dashed lines the 95% confidence intervals. Red region indicates period of outage, violet region indicates time with low numbers of recorded tests (excluded from the GAM analysis of the power plant).

4.3.2 Post-vaccination period

To determine the population at risk in the post-vaccination period, a suitable time window from 21/09/2021 to 15/03/2021 was identified as no outages were recorded. The total population at risk for the post-vaccination period was taken as 1265. Figure 4.6 shows the estimated instantaneous growth rate (top panel) and the corresponding smoothed incidence curves normalised per 10,000 individuals (bottom panel) in the time interval from 01/09/2021 to 01/04/2022. The time frame of interest (between outages, for which the population of the power plant is estimated) is from 21/09/2021 to 15/03/2022. The growth rates are never substantially different, suggesting that the outbreaks in the workplace were broadly synchronised to those in the community.

The larger confidence intervals for the power plant are due to the lower recorded numbers. When normalised to cases per 10,000 individuals, the ratio of the epidemic in the power station in the analysed period is approximately two, suggesting that the relative magnitude of the cases reported in the power plan was substantially larger than what reported in the local community. This behaviour can be explained by at least two different mechanisms: a higher risk of transmission in the workplace compared to the community, due for instance to close contact of workers or high-risk enclosed environments, or instead a similar or reduced risk of transmission in the workplace, but a more accurate case finding strategy that reduces the under-reporting of cases and gives an estimated of the epidemic closer to the true underlying transmission. These two hypotheses are investigated in the next section using a simplified compartmental model.

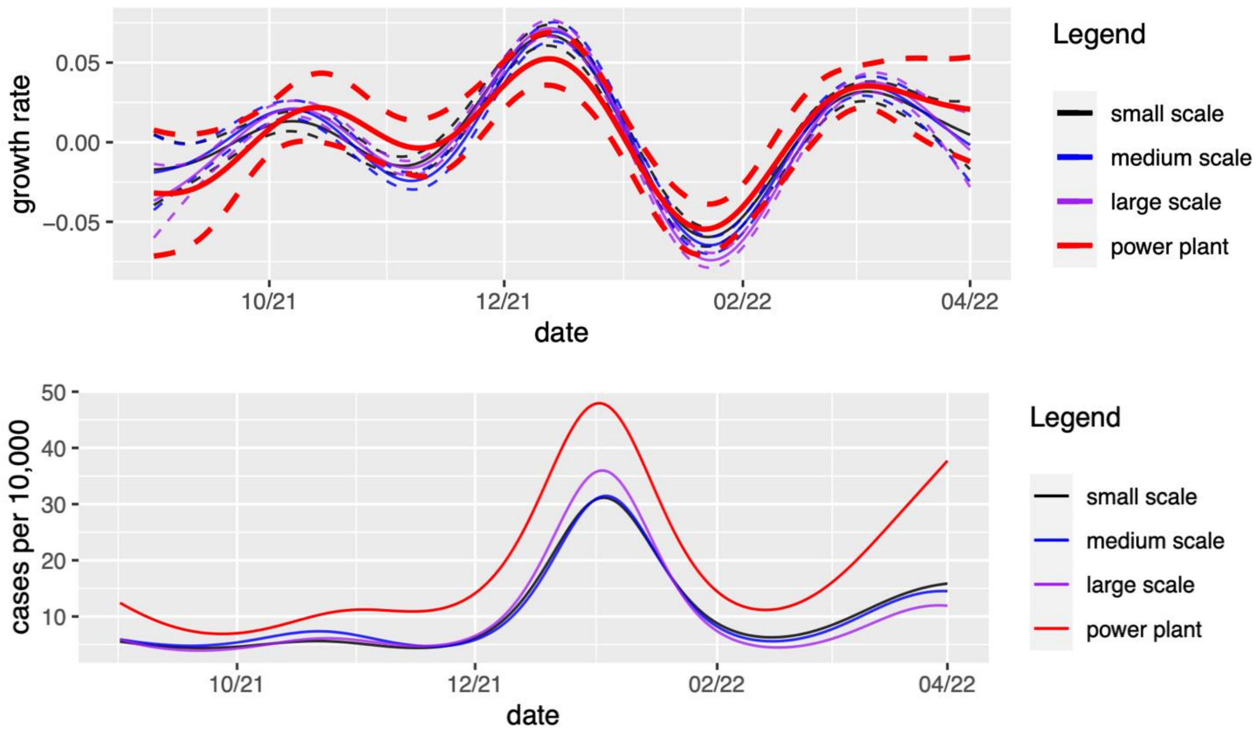

Figure 4.6: Estimated growth rate and smoothed incidence curve, post-vaccination period (from 01/09/2021 to 01/04/2022). Instantaneous growth rate estimated via GAM with day-of-the-week effect, for the power plant (red) and the local community at three geographical scales (small/medium/large community), for the population aged 20-64 years. Continuous lines represent the mean estimate, dashed lines the 95% confidence intervals.

4.4 Hypothesis testing and model simulations

To explain the observed patterns of similar epidemic growth rates but different relative magnitude of the epidemics in the post-vaccination period (after September 2021), the simple compartmental model (4.3) was used to compare two hypotheses:

a) Increased workplace transmission risk, leading to larger epidemic outbreaks in the workplace;

b) Similar or lower transmission in the workplace compared to the community, but lower under-reporting implying a more accurate description of the true underlying epidemic.

Hypothesis a) corresponds to assuming $\beta_{pp} > \beta$ in equation (4.3). In this case, assuming that the fraction of susceptible population, which is determined by the previous infections and vaccination levels, is comparable in the two settings, i.e. $s_c \approx s_p$, the instantaneous growth rates defined by the eigenvalues λ_p and λ_c satisfy the relation $\lambda_p > \lambda_c$, suggesting that generally we should observe larger instantaneous growth rates in the power plant than what observed in the community. In the post-vaccination period, this goes against the observed trends, which are not substantially different (Figure 4.6). Therefore, similar trends of the instantaneous growth rate after June 2021 suggest a larger detection rate rather than an increased risk of transmission. Under-reporting factors of 1.5-2.5 are in agreement with estimates obtained by comparison of cases reported on the gov.uk dashboard and the (cumulative) ONS incidence estimates for England.

Another important aspect to take into consideration is the timing of the epidemic peak. Simulations of the simple model (4.3) help visualise the effect of higher workplace transmission versus lower under reporting. Figure 4.7 shows how hypothesis a) (higher workplace transmission) would lead to an epidemic peak in the power plant that is either substantially anticipated compared to the community peak, if the workplace transmission is extremely high (top panel), or a delayed peak followed by a slower decay due to the transmission inertia in the workplace (middle panel). This behaviour is even more evident when depletion of susceptible in the workplace is ignored (bottom panel). Lower under-reporting, in contrast, induces synchronicity of the two epidemic peaks as well as in the growth/decline phases.

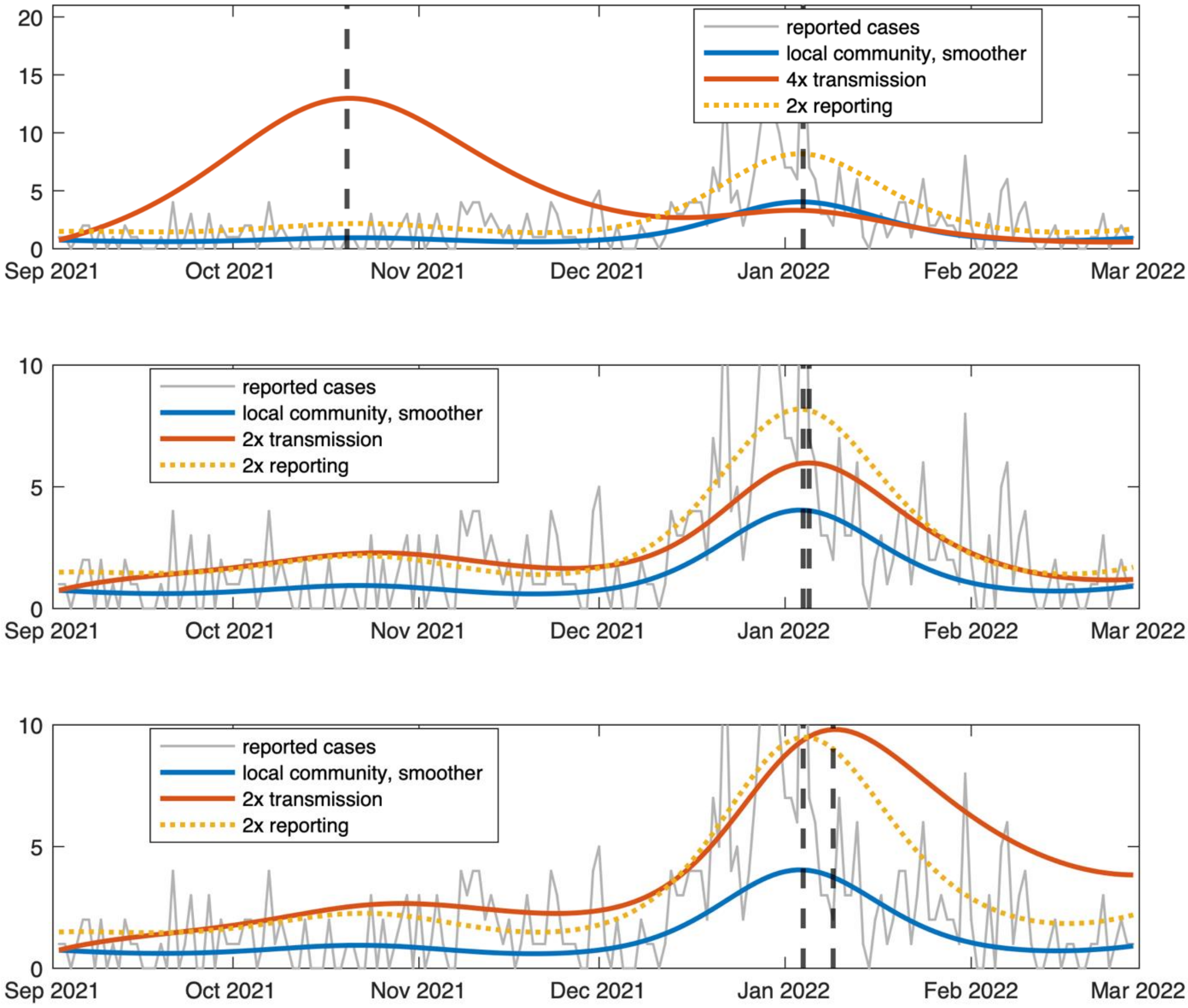

Figure 4.7: Simulations of different scenarios for the post-vaccination period, from the simple two compartment model (4.3), using the estimated community incidence from the GAM analysis on the medium geographical scale (weighted average with day-of-the-week effect). The incidence cases in the y-axis are normalised to the assumed population in the power station (to help comparison with data). Parameter values are $\gamma = \frac{1}{7}$, $s_c = 1$, $\beta = 0.05$, with total population representing the medium scale local community and the power plant in the post-vaccination period. Given the incidence in the local community (blue), the model simulates workplace transmission assuming larger workplace transmission (red) or higher reporting (yellow, dashed). Dashed grey lines indicate the simulated peak incidence. Top panel: 4x higher workplace transmission; middle panel: 2x higher workplace transmission; bottom panel: 2x higher workplace transmission without depletion of susceptibles.

Considering the pre-vaccination period, the large and delayed peak observed around November 2020 in Figure 4.5 (bottom) may suggest that the power plant suffered from increased workplace transmission during that period. To note is the fact that the power plant was under outage during the last months of 2020, suggesting that the essential nature of the work and the increased workforce contributed to the spread of infection. However, the measures put in place to control transmission, including an increase in risk level and remote working of office workers may have contributed to prevent the resurgence of the infection during the following community wave in January 2021. Figure 4.8 illustrates the mechanisms of increased reporting versus increased transmission in the pre-vaccination settings, with importations from the community showing two subsequent waves. While a relatively low workplace transmission reproduces the two-wave pattern within the workplace (bottom panel), a higher transmission coefficient can explain the higher and delayed wave without resurgence of the second wave (top panel).

It is important to stress that the simulations in Figures 4.7 and 4.8 are not obtained by fitting the data, but simply by fixing parameters in order to illustrate the different mechanisms.

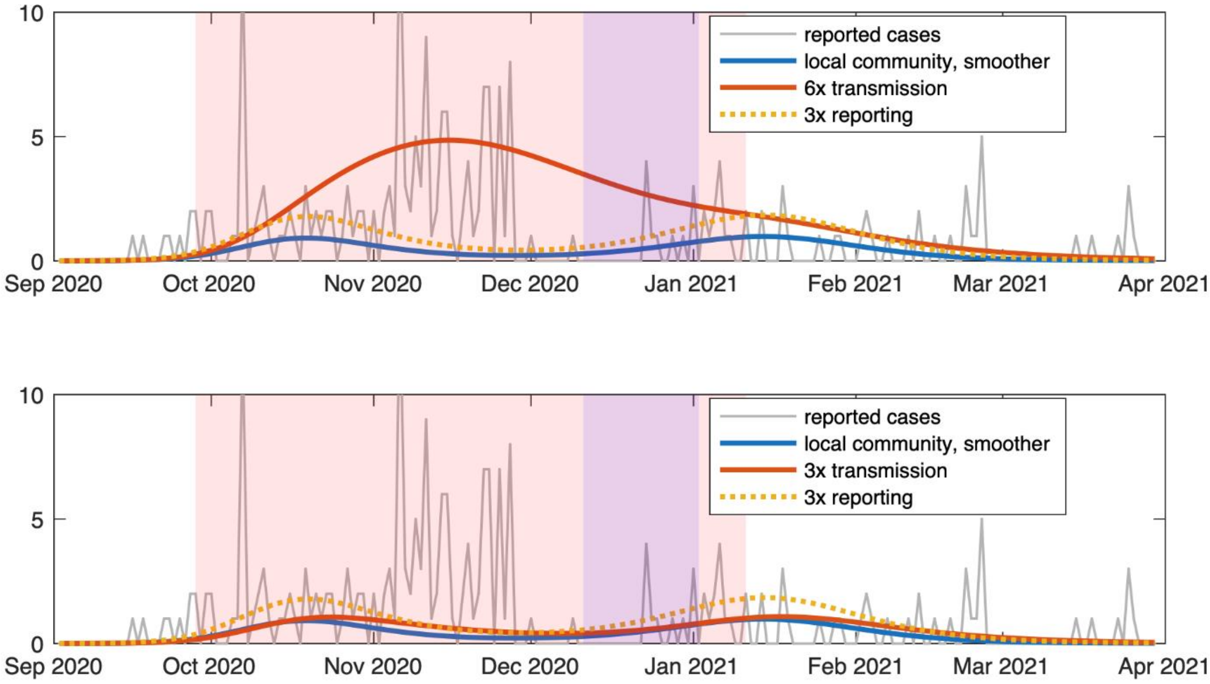

Figure 4.8: Simulations of different scenarios for the pre-vaccination period, from the simple two-compartment model (4.3), using the estimated community incidence from the GAM analysis on the medium geographical scale (weighted average with day-of-the-week effect). The incidence cases in the y-axis are normalised to the assumed population in the power station (to help comparison with data). Parameter values are $\gamma = \frac{1}{7},\ s_c = 0.6,\ \beta = 0.05$, with total population representing the medium scale local community and the power plant in the pre-vaccination period. Given the incidence in the local community (blue), the model simulates workplace transmission assuming larger workplace transmission (red) or higher reporting (yellow, dashed). Top panel: 6x higher workplace transmission; bottom panel: 3x higher workplace transmission. The red region indicates the period of outage, and the violet region indicates the time frame with low numbers of recorded tests.

4.5 Impact of screening and contact tracing on workplace transmission

We simulated the stochastic ABM with screening and contact tracing, focusing on the post-vaccination period. An example of the modelled community infections (top panel) and the modelled introduction of new infections from the community into the power plant (bottom panel) is given in Figure 4.9.

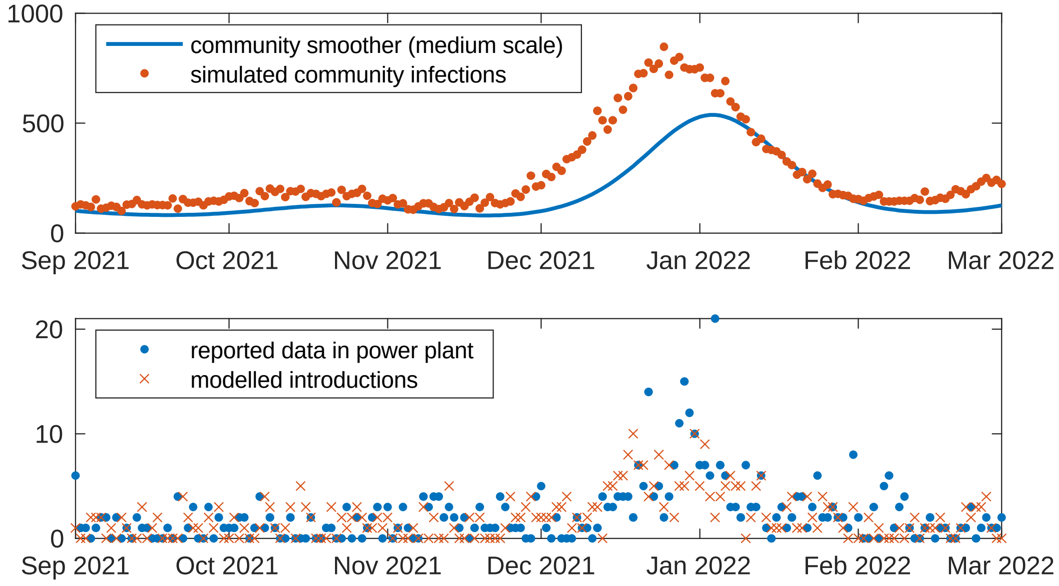

Figure 4.9: Modelled community infections (top panel) and modelled introductions in the power plant (bottom panel). The simulated community infections (red dots) are out of phase with the reported cases because each reported case was attributed a random infection time between 0-14 days; infections are further inflated by an under-reporting factor (equal to 1.5 in this example).

The screening of both symptomatic and asymptomatic individuals was considered first, with a certain efficacy ϵ of screening and contact tracing (describing both the cumulative probability of an individual being detected because of screening and of an infected contact being actually detected). Figure 4.10 shows an example of simulation of the ABM (with within-workplace transmission $R = 1.1$ and $\epsilon = 0.8$). Here, the reproduction number is assumed to account not only for the effect of workplace transmission but also for the reduction of susceptibility and transmissibility due to vaccination.

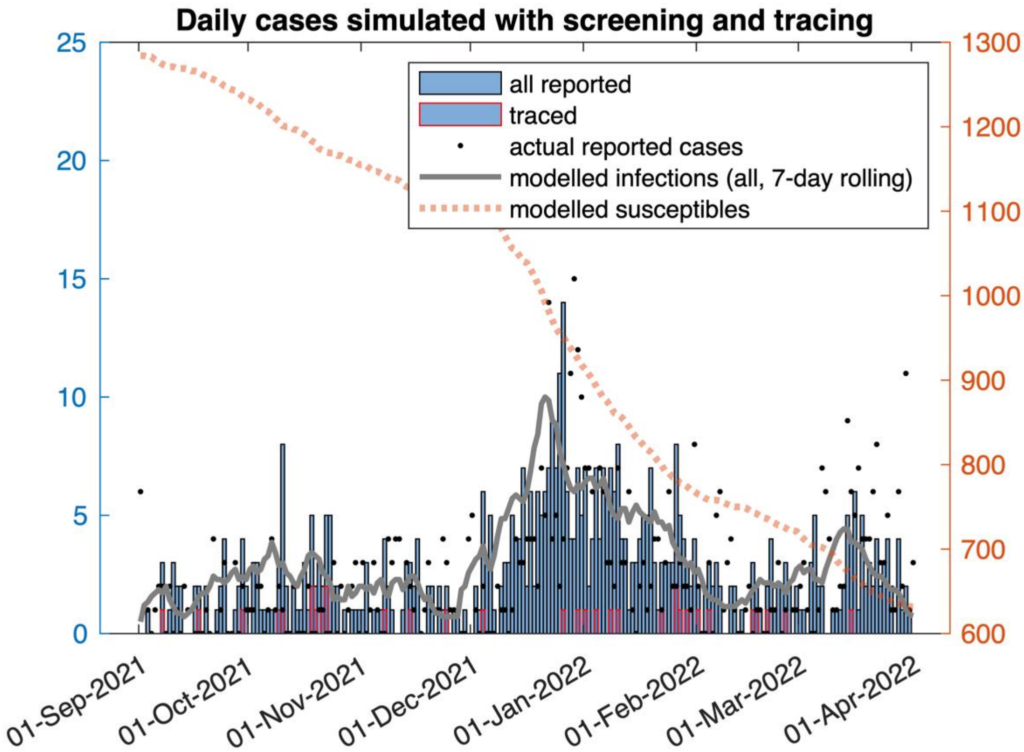

Figure 4.10: Example of an ABM simulation run, with screening of symptomatic and asymptomatic individuals. Simulation for $\mathrm{R} = 1.1$ and $\epsilon = 0.8$.

Table 4.2 shows the modelled relative increase (or decrease) in reported cases compared to the actual reported cases in the period from September 2021 to March 2022 (424 reported cases). The total number of modelled infections in addition to the modelled introductions from the community is reported in brackets.

The sensitivity analysis on the fraction of detected cases (rows) and the workplace reproduction number (columns) shows that expected infections could substantially increase either by relaxing screening of individuals or by relaxing social distancing in the workplace. It is interesting to stress that, even if a reduction in testing can result in less reported cases (moving bottom to top in each column), it is also associated with increased number of realised infections, that mostly go unnoticed. The additional infections can quickly scale up of the order of hundreds.

Table 4.3 considers the case of a delay of one day between emergence of symptoms and isolation, and between detection of a case and isolation of the secondary contacts. The introduction of a delay increases the number of modelled infections but reduces the number of detected cases.

Quantitative results substantially depend on the assumed parameters (e.g., under-reporting community factor, transmission and incubation period distribution, delays in detection) and, as such, these results are not meant to provide an estimation of the parameters ϵ and R in the workplace, but rather to give an indication of the effect of an increased transmission risk (R) or reduced testing and isolation effort (ϵ) on the realised infections.

Table 4.2: Modelled excess reported cases from 09/2021 to 03/2022 as percentage of the actual reported cases (424), and total number of modelled infections in addition to the modelled introductions from the community (in brackets). Orange shading highlights the simulations where the average relative difference with respect to the total actual reported cases is <5%. Introductions are modelled assuming a community under-reporting factor of 1.5 and no delay between symptoms and diagnosis and tracing of contacts is assumed.

		Workplace reproduction number														
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
Fraction of detected cases	10%	-92% (+28)	-91% (+62)	-90% (+92)	-90% (+143)	-89% (+181)	-87% (+235)	-85% (+295)	-84% (+353)	-82% (+424)	-81% (+489)	-80% (+558)	-78% (+619)	-76% (+691)	-74% (+741)	-73% (+793)
	20%	-83% (+25)	-82% (+56)	-80% (+87)	-79% (+123)	-77% (+167)	-74% (+212)	-71% (+261)	-69% (+317)	-67% (+373)	-64% (+439)	-60% (+507)	-58% (+561)	-55% (+617)	-52% (+683)	-49% (+734)
	30%	-74% (+24)	-72% (+50)	-70% (+81)	-68% (+109)	-65% (+151)	-62% (+186)	-60% (+230)	-55% (+285)	-51% (+333)	-49% (+389)	-44% (+432)	-40% (+495)	-36% (+560)	-31% (+609)	-28% (+664)
	40%	-66% (+21)	-64% (+44)	-61% (+69)	-58% (+96)	-56% (+134)	-52% (+164)	-49% (+201)	-45% (+242)	-40% (+281)	-35% (+338)	-30% (+386)	-27% (+430)	-20% (+479)	-16% (+532)	-10% (+581)
	50%	-57% (+18)	-56% (+41)	-52% (+67)	-49% (+86)	-46% (+115)	-41% (+147)	-38% (+174)	-34% (+215)	-29% (+248)	-25% (+284)	-20% (+329)	-14% (+368)	-9% (+411)	-4% (+451)	2% (+501)
	60%	-50% (+17)	-47% (+35)	-44% (+56)	-40% (+80)	-38% (+98)	-33% (+126)	-29% (+156)	-26% (+179)	-21% (+209)	-16% (+244)	-11% (+272)	-6% (+314)	0% (+349)	4% (+371)	11% (+415)
	70%	-41% (+14)	-38% (+32)	-36% (+47)	-33% (+64)	-29% (+87)	-26% (+105)	-21% (+129)	-18% (+150)	-14% (+169)	-10% (+196)	-5% (+224)	0% (+253)	5% (+276)	10% (+310)	16% (+343)
	80%	-33% (+13)	-31% (+27)	-28% (+41)	-25% (+57)	-22% (+73)	-19% (+86)	-15% (+106)	-12% (+121)	-8% (+141)	-3% (+161)	0% (+180)	5% (+208)	9% (+226)	13% (+244)	18% (+272)
	90%	-25% (+11)	-23% (+21)	-21% (+33)	-18% (+46)	-15% (+59)	-12% (+70)	-9% (+84)	-6% (+99)	-3% (+111)	0% (+125)	3% (+141)	6% (+154)	11% (+175)	14% (+191)	18% (+208)
	100%	-18% (+9)	-16% (+18)	-13% (+27)	-11% (+37)	-9% (+47)	-6% (+56)	-4% (+66)	-1% (+78)	1% (+87)	3% (+97)	6% (+107)	9% (+121)	11% (+129)	13% (+140)	17% (+155)

Table 4.3*: Same as Table 4.2 with different assumptions: introductions are modelled assuming a community under-reporting factor of 1.5, with a 1-day delay between symptoms and diagnosis and tracing of contacts.*

	Workplace reproduction number														
Fraction of detected cases	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
10%	-95% (+21)	-94% (+45)	-93% (+74)	-92% (+105)	-92% (+145)	-90% (+193)	-89% (+241)	-88% (+305)	-86% (+369)	-84% (+444)	-83% (+506)	-81% (+598)	-78% (+665)	-78% (+733)	-76% (+789)
20%	-88% (+20)	-87% (+44)	-86% (+71)	-84% (+98)	-83% (+132)	-81% (+173)	-79% (+217)	-76% (+268)	-74% (+329)	-70% (+393)	-66% (+475)	-64% (+530)	-60% (+600)	-57% (+667)	-53% (+735)
30%	-83% (+18)	-81% (+39)	-80% (+63)	-77% (+89)	-75% (+118)	-72% (+155)	-69% (+199)	-66% (+239)	-62% (+293)	-58% (+343)	-53% (+409)	-48% (+474)	-45% (+519)	-39% (+594)	-35% (+652)
40%	-77% (+16)	-74% (+36)	-72% (+59)	-70% (+77)	-68% (+106)	-65% (+133)	-61% (+170)	-57% (+212)	-52% (+261)	-47% (+303)	-43% (+353)	-36% (+423)	-32% (+455)	-27% (+517)	-20% (+581)
50%	-71% (+15)	-69% (+32)	-66% (+51)	-64% (+71)	-60% (+95)	-58% (+119)	-54% (+149)	-51% (+179)	-46% (+220)	-40% (+261)	-34% (+308)	-29% (+348)	-22% (+395)	-15% (+452)	-10% (+503)
60%	-65% (+14)	-62% (+29)	-60% (+44)	-58% (+62)	-54% (+84)	-52% (+105)	-47% (+131)	-43% (+159)	-38% (+188)	-34% (+223)	-29% (+257)	-23% (+299)	-17% (+333)	-10% (+372)	-4% (+421)
70%	-60% (+12)	-56% (+27)	-55% (+40)	-52% (+56)	-48% (+76)	-45% (+92)	-41% (+114)	-38% (+133)	-33% (+161)	-29% (+185)	-25% (+209)	-19% (+239)	-15% (+267)	-7% (+305)	-2% (+338)
80%	-54% (+11)	-51% (+24)	-49% (+35)	-46% (+50)	-43% (+65)	-41% (+77)	-37% (+95)	-34% (+111)	-29% (+134)	-25% (+155)	-23% (+167)	-18% (+194)	-13% (+215)	-8% (+244)	-3% (+265)
90%	-48% (+9)	-46% (+19)	-44% (+32)	-41% (+44)	-38% (+55)	-35% (+69)	-33% (+81)	-29% (+97)	-27% (+110)	-24% (+123)	-20% (+139)	-15% (+162)	-12% (+175)	-9% (+191)	-4% (+214)
100%	-43% (+8)	-41% (+18)	-39% (+26)	-36% (+37)	-34% (+46)	-32% (+56)	-29% (+69)	-26% (+80)	-24% (+89)	-22% (+99)	-18% (+113)	-16% (+123)	-13% (+137)	-9% (+152)	-6% (+165)

We also investigated the effect of a screening procedure that tests symptomatic individuals only. We assumed a probability of showing symptoms compatible with results for Omicron (Gamma-distributed with mean 3.49 days and standard deviation 1.2 [7], assuming that 30% of cases are asymptomatic [8, 9]). The probability of being diagnosed by testing is then further reduced by the probability of being asymptomatic, while the probability that a contact is effectively traced is still taken equal to ϵ. Table 4.4 shows the outcome on detected cases and realised infections, with a community under-reporting factor equal 1.5 and no delay in detection. It is again clear how the absolute numbers strongly depend on the details of the screening procedure, with a less intense screening resulting in more infections under the same conditions on transmissions, but with a potentially less accurate detection.

Table 4.4: Same as Table 4.2, with screening of symptomatic individuals only (detection probability by screening is reduced by a factor 0.3).

	Workplace reproduction number														
Fraction of detected cases	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
10%	-94% (+28)	-94% (+64)	-93% (+102)	-92% (+144)	-92% (+194)	-91% (+249)	-89% (+309)	-89% (+371)	-87% (+439)	-86% (+512)	-85% (+575)	-84% (+638)	-83% (+706)	-82% (+763)	-81% (+809)
20%	-88% (+26)	-87% (+61)	-86% (+92)	-84% (+139)	-83% (+182)	-81% (+232)	-79% (+278)	-77% (+351)	-75% (+404)	-73% (+467)	-71% (+542)	-68% (+607)	-67% (+659)	-64% (+719)	-63% (+770)
30%	-82% (+26)	-80% (+57)	-79% (+90)	-76% (+130)	-75% (+166)	-72% (+218)	-69% (+267)	-67% (+316)	-63% (+380)	-61% (+434)	-57% (+495)	-54% (+553)	-50% (+617)	-48% (+679)	-46% (+729)
40%	-76% (+24)	-74% (+53)	-71% (+80)	-70% (+118)	-67% (+153)	-64% (+199)	-61% (+241)	-57% (+292)	-52% (+346)	-50% (+397)	-45% (+458)	-41% (+514)	-37% (+567)	-34% (+614)	-31% (+683)
50%	-70% (+23)	-66% (+49)	-65% (+75)	-62% (+108)	-59% (+143)	-55% (+178)	-52% (+219)	-48% (+264)	-44% (+312)	-40% (+354)	-35% (+417)	-30% (+464)	-26% (+525)	-21% (+564)	-17% (+629)
60%	-63% (+21)	-61% (+45)	-58% (+73)	-55% (+100)	-51% (+132)	-47% (+167)	-44% (+200)	-41% (+235)	-35% (+282)	-31% (+324)	-25% (+373)	-21% (+421)	-16% (+467)	-11% (+507)	-6% (+563)
70%	-57% (+19)	-54% (+43)	-51% (+65)	-48% (+93)	-44% (+117)	-41% (+151)	-37% (+178)	-33% (+215)	-27% (+255)	-23% (+292)	-18% (+332)	-12% (+372)	-7% (+423)	-2% (+464)	4% (+507)
80%	-52% (+18)	-48% (+39)	-45% (+62)	-42% (+85)	-38% (+108)	-34% (+131)	-30% (+164)	-26% (+192)	-21% (+229)	-16% (+266)	-11% (+295)	-6% (+330)	0% (+372)	5% (+411)	11% (+450)
90%	-45% (+16)	-42% (+35)	-39% (+55)	-35% (+75)	-32% (+100)	-29% (+119)	-25% (+145)	-20% (+171)	-16% (+196)	-12% (+224)	-6% (+262)	-2% (+285)	4% (+324)	9% (+361)	15% (+387)
100%	-39% (+15)	-36% (+32)	-33% (+49)	-30% (+67)	-26% (+88)	-22% (+105)	-19% (+129)	-14% (+152)	-10% (+176)	-7% (+198)	-1% (+225)	3% (+252)	8% (+276)	12% (+302)	17% (+330)

4.6 Concluding remarks

- Comparison of the epidemic trends within the power plant and the local community show evidence of similar patterns of growth/decline in the post-vaccination period (after September 2021), but higher level of observed infections in the power plant compared to the community. The combination of a larger relative epidemic with similar growth/decline patterns can be more likely explained with better case reporting in the workplace, rather than with an increased transmission risk.

- The statistical analysis highlighted asynchronous growth/decline epidemic trends in the pre-vaccination period (between September 2020 and March 2021). The larger relative epidemic in the power plant in October-November 2020 could indicate an increased risk of transmission during outages, while the apparent lack of resurgence of a second wave in the power plant during January-March 2021 may be attributed to a successful implementation of more stringent measures (e.g. remote working) or to a local depletion of susceptibles from the first epidemic wave (October-November 2020).

- Qualitative simulations including screening and contact tracing show that a relaxation in testing and physical distancing measures (including social distancing, remote working) could result in less reported cases but an increased number of infections that mostly go unnoticed.

4.7 Section 4 References

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5. Agent-based modelling of power station transmission

5.1 Introduction

This section describes the development of an agent-based model for transmission of SARS-CoV-2 within the workforce of a nuclear generating facility and its application to assess the effectiveness of risk mitigation measures in place during the COVID-19 pandemic.

5.2 Model overview

The model comprises a variation of the SIR (Susceptible, Infected, Recovered) approach applied in an agent-based simulation in which individuals can transition from the Susceptible to Infected state on a stochastic basis. These transitions are decided in 24-hour steps depending on the degree of contact (proximity and time within each 24-hour period) with other workers already in the Infected state, and other factors including environmental characteristics, vaccination status and workplaces controls. If infected, individuals may isolate following symptom onset and recover, or remain infectious at work (e.g. if pre-symptomatic or asymptomatic) and then recover.

The model comprises five main elements:

1. Workplace contact networks that determine the occurrence, duration and distance of daily contacts between workers. The model characterises contacts at two different distance scales with a separate contact network for each: short proximity, meaning < 2m (i.e., 'near-field' exposure) and medium proximity, nominally 2-5m (i.e., 'far-field' exposure). Contact patterns may vary day-to-day and this is simulated by selecting each day's pair of networks at random from a set of pairs of up to 10 days of contact patterns. The duration of each worker's contact is the aggregate of all individual interactions between those two workers, at a given proximity, in a 24-hour period.

2. A disease model that represents individuals' transition from the susceptible to the recovered state and their isolation status. Figure 5.1 illustrates the states that individuals may transition between in 24-hour steps.

3. A within-host viral kinetics model, which is used to simulate the viral load and degree of infectivity for infected individuals during each 24-hour period. An exponential growth and decay model is used to represent viral loads trajectories with individual-level parameters for the time to peak viral load, peak viral load and the growth and decay rates. The predicted daily viral culture probability is calculated from an individual's viral load and time since

infection [1] is used as a proxy for their infectiousness on that day. Viral loads are used to determine a person and time specific test (lateral flow, PCR etc.) sensitivity where applicable. The within-host viral kinetics model is based upon findings from the Human Challenge Study [2] and other modelling from PROTECT [3].

4. An exponential dose-response model for estimating individual infection probabilities between daily contacts to allow the simulation of which susceptible workers become infected during each 24-hour step. The probability of each susceptible agent becoming infected during each day depends on the duration of close and medium proximity contact with infected persons in that period, as well as other relevant factors such as the environmental and the immunological status of the susceptible individuals.

5. Simulation of community-acquired 'seed' cases that introduce SARS-CoV-2 into the workplace. The model may be run either with a single randomly selected worker as the seed case or with continual seeding according to an age-dependent and time varying incidence. The latter should be based upon data relating to the relevant local authority area(s) from which the workforce is drawn.

The calculation of the 24-hour infection probabilities outlined in step 4 involves two transmission rate parameters (β_{short} and β_{medium}) that determine the rate of transmission at the two proximities per unit time. Thus, two terms appear within the exponential expression, each of which is the product of the contact time, the transmission rate parameter and an individual level parameter that represents the potency/quantity of the viral material generated by the infected individual. This has the same mathematical form as a stochastic exponential dose-response in which the infection probability depends on the intake dose and probability of the virus surviving within the susceptible host [4]. Whilst these two factors do not appear explicitly in the calculation, they are implicitly incorporated within the two viral transmission rate parameters, along with other factors such as room volume and the level of ventilation that affect the intake dose.

Other parameters are also included within the exponential expression to represent the protection conferred by vaccination and the use of face coverings. The 24-hour probability of a susceptible individual becoming infected from contact with an infectious individual is given by:

$$P = 1 - \exp\left(-\varphi_{i,j}\theta(s_1 w_1 \beta_{short} t_1 + s_2 w_2 \beta_{medium} t_2)\right) \qquad (1)$$

Where:

t_1 and t_2 are the cumulative durations of short and medium proximity contacts respectively between the pair during the 24-hour period.

β_{short} and β_{medium} are the transmission rate parameters for short and medium proximity contacts *in the workplace environment under consideration*.

S_1 and w_1 are the reductions in virus exposure when face coverings are used by the infected (*s*, source protection) and susceptible (*w*, wearer protection) individuals respectively for short proximity contacts; s_2 and w_2 are the equivalent for medium proximity contacts. These protection factors may differ due to different aerosol size distributions at the two distances.

$\varphi_{I,j}$ is the infectivity of infectious individual i on day j (using the calculated culture probability as a proxy).

θ is the reduction in susceptibility conferred by vaccination, equivalent to 1 – vaccine efficacy, assumed to remain constant during the period of the simulation.

The infection probability in equation 1 above is calculated based upon the cumulative contact time with each specific infected individual that a susceptible individual has contact with on that day. During an outbreak, multiple infected individuals might be encountered, and the effects of these are combined as independent probabilities to determine an individual's overall risk of becoming infected that day.

A comprehensive description of the model is provided in Warren et al. [5].

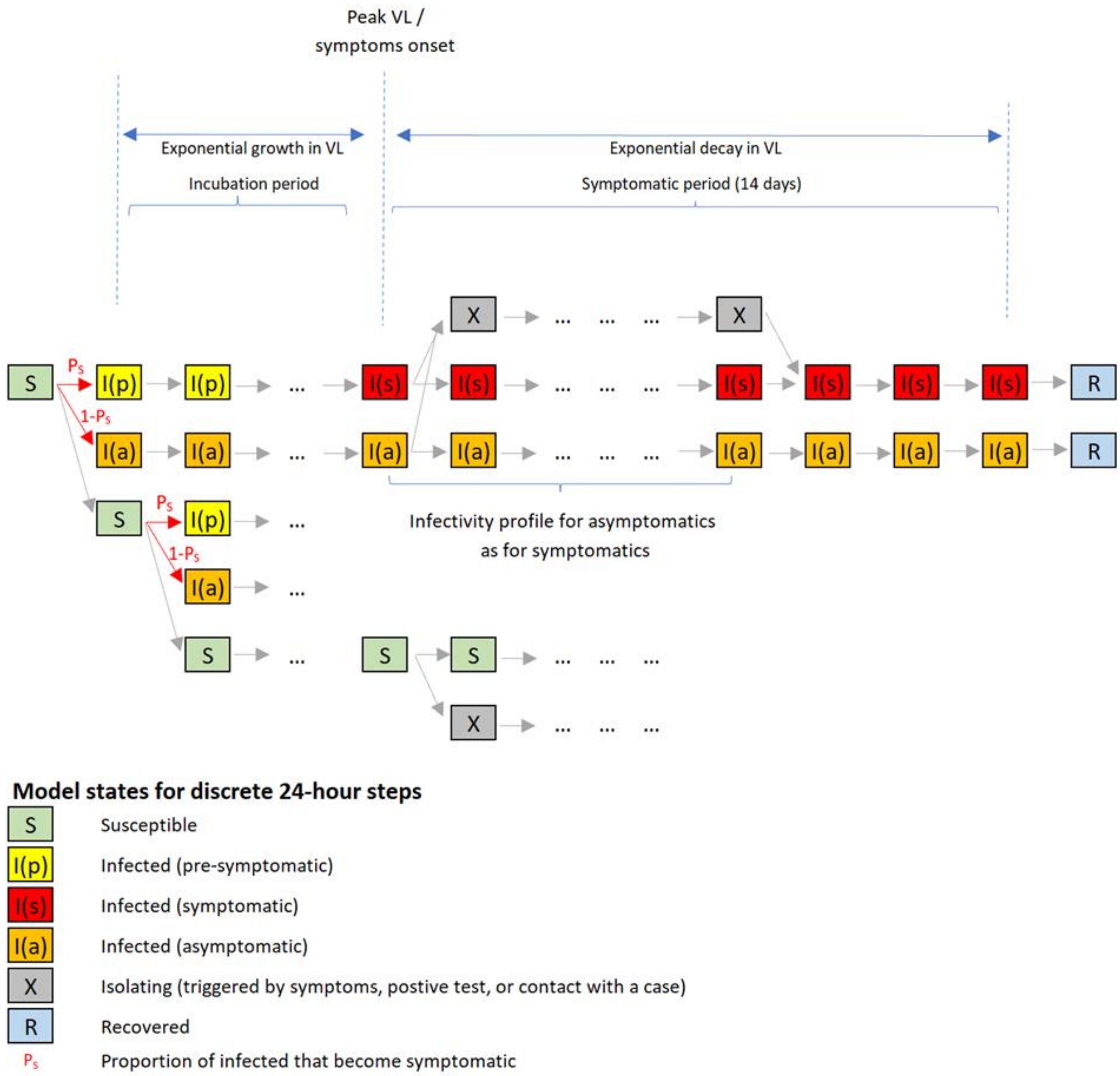

Figure 5.1: 24hr-transition and SIR states

5.3 Application of the agent-based model to electricity generation plants

5.3.1 Introduction

Much of the agent-based model is generic in that it can be applied to any workforce and workplace setting by adjustment of global model parameters. In particular, this applies to the in-host viral kinetics model, which encapsulates assumptions around time to symptom onset, viral loads, the length of the infectious period and the proportion of infections that are asymptomatic. Contact patterns however may vary substantially between workplaces and so efforts were made to construct suitable contact networks that were specific to nuclear power stations (see section 3.5). As no there was no clear evidence of differences between the two power stations in terms of the site risk ratings and mitigations, contact behaviours (from both the research survey and company contact tracing narratives), or the pattern of known infections (see section 2), a single generic power station was modelled.

A 10-day sequence of short proximity (<2m) and medium proximity (nominally 2-5m) networks waqs constructed (section 3.4). Resampling within the ABM was carried out to generate longer sequences of contact patterns as necessary. The ABM is designed such that every contact in the network has an associated duration of contact. As virtually no power station specific information was available on the distribution of contact durations (save for close / A list contacts by definition being greater than 15 minutes) variation in the duration of contacts was not included in this application. Instead, all short proximity contacts were assigned a nominal duration of 15 minutes and all medium proximity contacts a duration of four hours.

Available information on contacts of confirmed cases at the power stations was considered in two categories: ‘A list contacts’ and ‘B list contacts’. A list contacts were defined according to the public health definition of close contacts with a suspected/confirmed case, i.e., <2m for more than 15 minutes or <1m for more than one minute or direct contact. B list contacts were people who had interactions with the suspected/confirmed case that did not meet the public health authority criteria but were judged to at heightened risk of infection and so pose a risk to the site. Inclusion on the B list was at the discretion of site occupational health team and was influenced by the clinical picture and the local risk of disease. However, B list contacts can essentially be considered as individuals who had been present in the same airspace as the case for an extended period. In the simulations, A list contacts were correspondingly defined as any workers having short proximity (<2m) contact with a symptomatic and isolating index case in the 48 hours prior to their symptom onset, and B list contacts as workers having medium proximity contact but without short proximity contact in the same 48-hour period.

A database of company testing information provided estimates of the secondary attack rates in A and B list contacts and an indication, albeit subject to under-reporting, of the total numbers of infections. This was subsequently used to confirm that the ABM provided a reasonable representation of the level of transmission. A fuller description and analysis of these data is presented in Section 2.

5.3.2 Modelling approach

The overall modelling approach was as follows:

1. Selection of time periods of interest. January to March 2021 was selected as this was the period with the highest site COVID-19 risk ratings for the two stations being studied ('4' on a 0-to-5-point scale devised by the company), the Alpha variant was dominant and levels of (double) vaccination in the workforce were negligible. September to November 2021 was chosen because the two power stations were at a lower risk rating (1 or 2) during this period meaning that some mitigation measures had been relaxed, the initial vaccination campaign was largely complete for adults, and the delta variant was dominant. The intervening period had several features that rendered it more complex to model including a steadily increasing number of doubly vaccinated workers due to the on-going vaccination programme, a transition between the Alpha and Delta variants being the preeminent strain of the virus in circulation; and a statutory outage at one of the stations meaning that several hundred additional contractors were on-site potentially leading to altered contact patterns. Around the beginning of December 2021 the more transmissible Omicron variant began to displace the Delta variant which would require further adjustment to some of the parameters.

2. Specification of power station workforce contact patterns. Contact networks representing daily short and medium proximity contacts at the sites were constructed using results from the online worker survey to determine the degree of contact within and between 18 different job groups. Tuning of a calibration parameter used within the network generation algorithm (described in section 3.5) to control the overall level of contacts was informed by preliminary runs of the ABM that determined the mean number of identified A and B list contacts per symptomatic case. These were compared against the mean numbers of A and B list contacts reported in company contact tracing narratives (see section 3.4) and the calibration parameter was recursively adjusted until the simulated and observed numbers of A and B list contacts were similar.

3. Specification of other model assumptions for the two periods. Model assumptions relating to transmission risk mitigations, including testing and isolation, were based upon company COVID-19 risk management documentation, and supplemented by discussion with the power station pandemic leads and the company Chief Medical Adviser. Importantly, no attempt was made to explicitly include all aspects of the company testing protocol(s) in the model but sought to represent the major processes through which testing influences power station transmission. For instance, symptomatic workers were required to take a high sensitivity test before or after leaving the site (either an on-site or back-to-laboratory PCR test, or a LAMP test processed at the on-site laboratory) and to isolate at home until receiving their test result. A positive test result required them to isolate for 10 days from their first day of symptoms. If the test result was negative, a second test would be arranged after at least a further 48 hours. If the second test was negative then the worker could return work. The rate of false negatives from high sensitivity PCR tests is low and it is therefore sufficient to model the high proportion of symptomatic cases (95%, see Table 5.1) isolating for 10 days. What this implementation fails to correctly represent, is the treatment of individuals who have symptoms but who are not infected with SARS-CoV-2. These individuals would isolate from work until the receipt of a second negative test. This non-modelled behaviour has minimal impact on the transmission of SARS-CoV-2 within the workforce (save for temporally isolating one susceptible worker from the site) but clearly leads to increased levels of worker absence. As the focus of the modelling exercise was ultimately to investigate the effect of mitigation measures on transmission and numbers of infections and not investigate staff absence levels, the chosen approach was considered adequate.

4. Calibration of transmission model parameters. The transmission rate parameters β_{short} and β_{medium} were recursively adjusted to achieve secondary attack rates (SARs) for A and B list contacts (see section 3.3) that were approximately equal to those observed in the company testing data for the two stations during 2021 (25.5% and 7.1% in A and B list contacts respectively). These transmission rate parameters were then adopted for all simulations for the period January to March 2021. For simulations relating to September to November 2021, a period when the Delta variant was dominant, the transmission rate parameters were increased by 50% to account for the extra transmissibility of the Delta variant relative to the Alpha variant [6]. Whilst immunity, either from previous infection or vaccination, also affects rates of transmission (and would have differed between the two study periods) since

this is implemented through a separate individual-level susceptibility parameter it does not require adjustment of β_{short} and β_{medium}.

5. Simulation of transmission during the two periods. For each period, two sets of simulations were conducted: a 'single seed case' simulation (20,000 iterations of 50 days) and a 'continual seeding' simulation (10,000 iterations of 90 days). The former used a single index case to introduce infection into the workforce on day one whilst the latter used continual stochastic seeding of cases into the simulated workforce according to the incidence of cases in the local community. The local community incidence of infection was adjusted to account for under-reporting and to remove the work-related component – the latter to avoid 'double counting' the work-related contribution when simulating workplace acquired infections using the ABM. Additionally, 40% of the resulting community infections were assumed to be already isolating before becoming infectious through being household or social contacts of known cases. These community cases therefore cannot infect co-workers and were therefore excluded as potential seed cases. They were however included in estimates of the total workforce cases.

6. Counterfactual modelling Counterfactual modelling was used to investigate the effect of various mitigation measures that were in place during the pandemic by turning off or altering those measures within the simulations - e.g. no isolation of B list contacts or no wearing of face coverings - and then comparing the predicted numbers of infections against the predictions from the baseline simulations.

Further details and results from steps 2 to 5 are presented in section 5.4. Details of the counterfactual scenarios, their assumptions and results are presented in section 5.5.

5.3.3 Model outputs

The agent-based model outputs the complete day-by-day history of the disease and isolation state for every worker, along with various other characteristics of the individuals, including their viral load, adherence to wearing face coverings (if applicable) and vaccination status. Consequently, a rich collection of model outputs is calculable. For this study the following key transmission and infection metrics are presented:

- $R_{workplace}$ – the mean number of direct secondary infections per index case. This is a workplace equivalent of the widely recognised 'Reproduction number'. As with the societal R value, values greater than one imply exponential growth and values less than one lead to reducing numbers of infections. However, the agent-based model is a stochastic simulation of transmission in a small finite population (657 individuals). In these circumstances the stochasticity is very considerable meaning that sizeable outbreaks are possible even when R<1. Conversely, transmission may quickly become extinct even when the average number of secondary infections is greater than one ($R_{workplace}$ >1).

- A and B list SAR – the simulated secondary attack rates in A list and B list contacts. The transmission rate model parameters were chosen to replicate the positivity rate in EDF A and B list contact tests for HYA and HYB during 2021 overall. These are only presented for the baseline scenarios corresponding to the period January to March 2021 and September to November 2021 and not for the counterfactual scenarios. Only contacts identified through contact tracing and isolating are included in the calculation.

- Mean number of A and B list contacts per symptomatic case – for comparison with the mean number recorded in the company contact tracing narratives for the two stations during 2021. These are only presented for the baseline scenarios representing actual conditions during the periods January to March and September to November 2021 and not for the counterfactual scenarios.

- Total downstream cases per introduced case – the mean total number of secondary infections per index case, i.e. including the second and any subsequent generations of infections caused by the direct secondary infections of the index case.

- Total period cases – the mean and a 90% prediction interval for total workforce infections during the periods January-March 2021 and September-November 2021. This included both workplace and community acquired cases.

- Total workplace acquired infections – the mean and a 90% prediction interval for the number of workplace-acquired infections during January-March 2021 and September-November 2021.

- Probability of a cluster – the probability of >=20 identified cases in any 10-day period. Both community and workplace acquired cases are included in these calculations. However, the 40% of community infections that are assumed to be already isolating from before they became infectious due to being known household or social contacts of cases are excluded, as are infections in those working exclusively from home. Note that such clusters do not require all the cases to be linked but represent a temporal clustering of cases strongly suggestive of workplace transmission from one or more community introductions.

- Relative incidence of infection (incident rate ratio) – the ratio of community infections (adjusted for under-reporting) vs. total simulated workforce infections. This is a measure of the level of infections in the workforce relative to those in the local community. This metric is sensitive to additional assumptions around the community force of infection into the power station workforces.

The mean numbers of A and B list contacts per symptomatic case, $R_{workplace}$, and the total number of downstream cases per introduction were all obtained from the single seed case simulations. All other outputs were derived from the continual seeding simulations.

5.4 Reproducing HYA/HYB power station infection patterns during January to March 2021 and September to November 2021

5.4.1 Baseline assumptions

The power station specific model assumptions and parameters are set out in detail in Table 5.1 for the two study periods. These include assumptions around shift and contact patterns, mitigations including testing and isolation, and immunological factors such as previous infection, vaccine uptake and vaccine effectiveness. Model assumptions relating to mitigations, including testing and isolation, were based upon company COVID-19 risk management documentation, and supplemented by discussion with the power station pandemic leads and the company Chief Medical Adviser.

5.4.2 Sensitivity study: additional untraced contacts

A sensitivity study was carried out to explore the potential impact of transmission through additional contact not included with the A and B list contact criteria. The criteria were designed by the company to include the situations where transmission could occur, and the networks constructed to represent these contact patterns in the workforce in turn reflect those contacts for which a transmission risk is represented in the agent-based model – namely the short and medium proximity risk elements with the dose-response. Combined with the baseline assumption for January to March 2021 that 95% of the A and B list contacts isolate (the remaining 5% representing unidentified contacts rather than deliberate non-compliance), this set-up implies that the model should capture almost all of the transmission risk in the workforce.

However, in reality some degree of transmission could occur outside the A and B list contact definitions. For example, short proximity contact of a duration of less than 15 minutes could still pose some degree of transmission risk, albeit lower than durations required to meet the definition of an A list contact. Similarly, individuals may have occupied the same air space (but further than 2m apart) but for a sufficiently short time that they were not classified as B list contacts. Such contacts would carry an even lower risk of transmission, but in aggregate this might still contribute significantly to the overall levels of infection. The sensitivity study addressed the potential impact these additional contacts might have.

In principle additional shorter duration contacts (short and medium proximity) could be incorporated into the contact networks used with ABM but below the duration thresholds used to define A and B list contacts. However, for ease of implementation a simpler approach was taken where all short and medium proximity contacts remained the same nominal durations (15 minutes and four hours respectively) but the isolation probability for A and B list contacts was reduced from 0.95 to 0.66, i.e., one third of contact were now assumed to go unidentified. The calibration parameter used to scale the average numbers of short and medium proximity contact in the networks was then adjusted so that the simulated numbers of A and B list contacts *identified* and isolated were again approximately equal to those reported in the contact tracing narratives for the two power stations during January to April 2021. Although in this implementation one third of A and B list contacts go unidentified, these unidentified contacts can be regarded as a proxy for a greater number of shorter duration contacts that would not have qualified as A or B list contacts. In this manner additional untraced contacts were introduced into the simulations that contributed to elevated levels of workplace transmission. A simple interpretation of this sensitivity study is that it assumes contact tracing only identifies contacts that represent two thirds of workplace transmission.

In all other respects the sensitivity adopted the same assumptions as the baseline January to March 2021 scenario (Table 5.1).

Table 5.1: Power station specific assumptions for the two study periods

Property		January – March 2021	September – November 2021
Contact patterns	Shift patterns	Non-shift teams: standard 5-day working week Five combined operational shifts (see section 2.4) working 4 days on 5/6 (alternating) days off Two operational shifts per day, 7 days per week	
	Remote working	100% for support function teams[1] 50/50 rota for technical teams[2] Operations teams[3] on-site	50/50 remote working rota for support teams Technical teams on-site Operational teams on-site
	Average simulated type A and type B contacts per symptomatic case. (Actual from contact tracing narratives during 2021)	Type A: 0.29 (0.31) Type B: 3.5 (3.5)	Type A: 0.36 (0.38) Type B: 2.6 (1.9)
	Simulated on-site weekday workforce size excluding those isolating	405 – applies to both sites (Actual[4]: HYA: 461, HYB: 537)	497 – applies to both sites (Actual[4]: unavailable)
Controls	Site risk rating	4	2 decreasing to 1
	Face coverings	Mandatory all times inside 95% uptake compliance, worn for 90% of short and medium proximity contact time Assumed 50% effective for both source and exposure control [7]	Required for close proximity working only Assumptions otherwise as per January-March 2021
Isolation	Symptomatic	Probability 95%; for 10 days; half isolating from and including day of symptom onset, half from day after symptom onset	
	Workplace type A contact of symptomatic case	Probability 95%; assumed to isolate from the day after symptom onset in the index case; isolate for 10 days (increased to 10 days from their symptom onset with probability 0.95 if they become symptomatic whilst isolating)	
	Workplace type B contact of symptomatic case	Probability 95%, assumed to isolate from the day after symptom onset in the index case, isolate for 10 days (increased to 10 days from their symptom onset with probability 0.95 if they become symptomatic whilst isolating)	Probability 55%[5], otherwise as per January to March 2021
	Contacts of contacts	Type A and B contacts of isolating contacts that turn symptomatic are assumed to isolate with the same probabilities as type A and type B contacts of primary cases	
Testing	Symptomatic	Symptomatic cases were tested by high sensitivity PCR which confirmed they had SARS-CoV-2 and must isolate. This testing does not need to be explicitly modelled for transmission purposes.	
	Contacts	Not explicitly modelled	
	Screening	Limited screening testing at both power stations during this period (HYA 573 HYB 1094) – not included in model	Very limited screening testing at both power stations during this period (HYA 30 HYB 96) – not included in model
Virus and immunological	Virus variant	Alpha	Delta
	Vaccination (double vaccinated)	Uptake: 0%	Uptake: 88.2%[8] 75% reduction in risk of infection No Reduction in onwards transmission in breakthrough infections [9][10][11]
	Previous infection	20.0%[6] representing infection to original or Alpha variants within last 10 months. 100% immunity (initialised in the Recovered state)	June-Aug 2021: 4.2%[6] representing recent Delta infections with assumed 100% immunity (initialised in the Recovered state) Pre- June 2021: 22.8%[6] primarily representing infection to original strain and Alpha variant more than 3 months previously. Immunity assumed equivalent to double vaccination[9]

Property		January – March 2021	September – November 2021
	Incidence of seed cases	Smoothed Lancaster local community infection rate for working age adults (see Section 4) with multiplicative adjustments for under-reporting of community rate (Jan-Mar 1.87[7], Sep-Nov 2.54[7]), to discount the contribution from work (0.66, based on the odds ratio for infection for working from home vs. not working from home [13]), and isolation if already a known household or social contact (0.60 [14])	
	Transmission rate parameters b_{short} , b_{medium}	b_{short} =0.148, b_{medium}=0.0017 Chosen to simulate observed secondary attack rates in A and B list contacts at HYA and HYB	b_{short} =0.222, b_{medium}=0.0026 January to March parameter values adjusted for the delta variant being 1.5 times more transmissible than Alpha variant [6]
Known power station infections	Total positive tests	HYA 25, HYB 24	HYA 40, HYB 72
	Positivity of workplace contacts[8]	Both stations over the whole of 2021 Type A: 12/47 (25.5%) Type B: 17/238 (7.1%)	

[1] HR, Finance and Supply Chain, Performance Improvement and Training, and Investment Delivery.
[2] Engineering, Chemistry, Environmental Safety/ Nuclear Safety Group, Fuel Route, and Outage Planning.
[3] Station Leadership, Day Operations, Operations shift Operator Technicians, Security, Maintenance, Work Management, Radioactivity monitors and Contractors.
[4] From company weekday 10am footfall data.
[5] Based upon the reduction in type B contacts reported in the company contact tracing narratives during September to November 2021 relative to January to March 2021 and assuming that this reduction represents a relaxation in the rigour of the contact tracing for type B contacts, i.e., reduced identification or classification as type B contacts, rather than a change in the underlying contact patterns.
[6] Derived from the MRC-PHE Nowcast report of September 7th 2021 [12]. The Nowcast reports provide two relevant sources of information: the estimated cumulative attack rate nationally by age and by English region; and estimates of cumulative infections, including reinfections, by English region. Estimates of the cumulative attack rates are only available for the date of the report and as the methodology changed between reports are consistent with one another. First an estimate of the cumulative attack rate in NW England to September 7th 2021 in adults aged 25-64 was derived by scaling the Nowcast estimate for NW England (all ages) by the ratio of the average national attack rate aged 25-64 and the all age national attack rate, yielding an estimate of 27%. Second, the age adjusted cumulative attack rate to January 1st 2021 was obtained by multiplying the estimate for Sept 7th (27%) by the ratio of estimated cumulative infections (including reinfections) to January 1st 2021 vs September 7th 2021. Estimates of the age-adjusted cumulative attack rate to May 31st and from June 1st to September 7th were derived similarly.
[7] Calculated as the ratio of the cumulative ONS infection incidence for England [15] over the period multiplied by the ONS 2021 population estimate for England [16] to pillar 1 and 2 infections for England [17].
[8] Contact positivity defined as number of individuals testing positive in either their first or second workplace contact test divided by the number of tested individuals.

5.4.3 Results

Model outputs for the baseline simulations of the two study periods are presented in Table 5.2 below. A good but not exact agreement was achieved between the simulated numbers of A and B list contacts for January to March 2021 and the mean numbers of such contacts reported through the company contact narratives (0.29 vs 0.31 and 3.5 vs 3.5 for A and B list respectively, see also Table 5.1). The numbers of A and B list contacts for September to November were not directly tuned to the observations from the contact tracing narratives and so (as expected) there were greater discrepancies for this period (0.36 vs 0.38 and 2.6 vs 1.9 for A and B list respectively). Similarly for the period January to March there was good agreement between the simulated secondary attack rates (SARs) for A and B list contacts (27.1% simulated vs 25.5% observed and 7.6% simulated vs 7.1% observed for A and B list contacts respectively).

The transmission rate parameters had been chosen to achieve this. The same transmission parameters were used to the period September to November but with adjustment for the extra transmissibility of the Delta variant. Further, the SARs for this period were also influenced by the assumptions around increased immunity, both from vaccination and previous infection, and from the changed behaviours around the wearing of face coverings, which during the later period were only mandatory for close proximity working. It is this change in the model assumptions around the use of face coverings that lies behind the elevated SAR for B list contacts during September to November relative to the earlier period.

Table 5.2: Model predictions for the periods January to March and September to November 2021

	January-March	September-November
# type A contacts identified per symptomatic case	0.29	0.36
# type B contacts identified per symptomatic case	3.5	2.6
Secondary attack rate type A contacts	27.1%	23.2%
Secondary attack rate type B contacts	7.6%	13.6%
$R_{workplace}$	0.32	0.58
Total downstream cases per introduction	0.46	1.32
Total period cases: mean and 90% prediction interval	31.7 (20-45)	71.7 (48-100)
Total workplace acquired cases: mean and 90% prediction interval	6.2 (1-15)	25.6 (8-50)
Expected community cases	39.7	72.9
Relative incidence of infection	0.80	0.98
Probability of a cluster[1]		
10+ cases within 10 days	0.34	0.85
20+ cases within 10 days	0.01	0.20

[1] Defined as 10/20 or more identified cases within 10 days, excluding cases in exclusively remote workers and known community acquired infections, i.e., those individuals already isolating as a household or social contact of a known case.

Predicted levels of workplace transmission for both periods were low with $R_{workplace}$ considerably less than one for both periods but especially for January to March 2021. This implies that sustained transmission was highly unlikely with transmission lineages quickly becoming extent. The total downstream cases per introduced case were correspondingly small, although for the period September to November still amounted to more than one workplace acquired case on average per introduction via community infection.

The predicted number of secondary cases ($R_{workplace}$) and total downstream cases per index case were highly skewed (Figure 5.2). During both periods a substantial majority of SARS-CoV-2 introductions to the workforce were predicted to generate no onwards transmission (80% and 69% in January to March and September to November respectively). Further, the predicted number of downstream cases was heavily dependent upon the symptom status of the index case: during

January to March 2021 asymptomatic and symptomatic index cases were predicted to generate an average of 0.37 and 0.65 downstream cases respectively). The greater level of transmission caused by asymptomatic cases reflects these workers being present on-site for the totality of their infectious period (in contrast to symptomatic cases, of which the majority isolate).

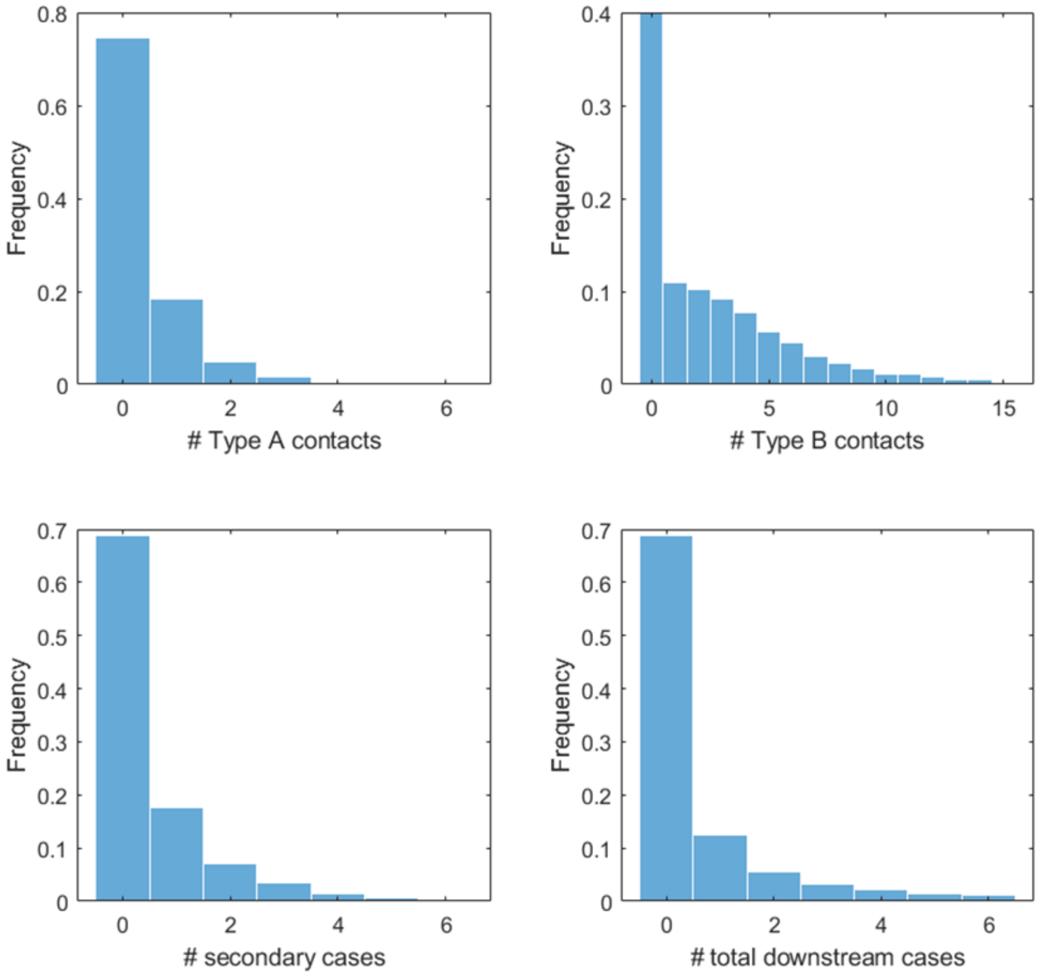

Figure 5.2: Distribution of numbers of contacts and infections resulting from an index case during September to November 2021

The 90% prediction interval for total workforce cases during January to March 2021 was 20-45 cases, compared with 25 and 24 confirmed positive cases identified at HYA and HYB respectively (Figure 5.3, top panel, blue bars and red lines).

The 90% prediction interval for total workforce cases during September to November 2021 was 48-100 cases, compared with 40 and 72 confirmed positive cases at HYA and HYB respectively

(Figure 5.3, bottom panel). The number of confirmed cases at HYB for this period lies in the second quartile of predictions, however, the confirmed number is likely to be an underestimate due to some asymptomatic cases not being identified. The number of confirmed cases at HYA during September to November 2021 lies below the modelled 90% prediction interval, though again it is highly probable that the confirmed number of cases understates the true number due to under-reporting (especially of asymptomatic cases).

The predicted proportion of total workforce cases that were workplace acquired for the two periods was 19.5% and 36% for January to March and September to November 2021 respectively (though there was considerable variation around these estimates for individual simulations, results not shown).

Infections from contacts of known household and social contacts, who are assumed to already be isolating as a contact prior to becoming infectious, on average comprised 33.0% of the total simulated workforce cases for the period January to March 2021 and 26.8% of simulated cases during September to November 2021. These predictions compare with 89 out of 440 (20.2%, 95% confidence interval 16.6% to 24.3%) of positive tests at the two stations during the whole of 2021 being household or social contact tests.

Comparison of the predicted workplace incidence of cases with that in the local community yielded estimated incidence rate ratios (IRR) of 0.80 and 0.98 for January to March and September to November 2021 respectively. This implies that the number of workforce infections was slightly lower than would be expected in people of working age in the local community. It should be noted, however, that these estimates are sensitive to the adjustments made to the local community incidence in order to derive the effective incidence of community seed cases introduced into the workforce (i.e. the 0.66 reduction to remove the contribution of work, the assumption that for 40% of cases the worker would already be isolating before they became infectious as a consequence of being a household or social contact of a known case, and the assumed level of under-reporting in the community infections).

Clusters of 10 or more cases within 10 days, excluding cases in those who were working exclusively from home and cases who were known household or social contacts of confirmed community cases and who are assumed to have isolated before becoming infectious, were predicted to be probable for both periods. The estimated probabilities of at least one such cluster were 0.34 and 0.85 for January to March and September to November respectively. Several such clusters were actually observed, namely, 13 cases at HYA between January 1st and 7th, and at

HYB, 10 cases between February 16th and 25th, 10 cases between October 24th and Nov 1st, 13 between November 8th and 14th and 12 cases between November 22nd and 30th. However, a small number of these cases were in household contacts and thus would be excluded under the definition applied to the simulations. Clusters of 20 or more cases within 10 days were predicted to be highly unlikely for January to March 2021 (p=0.01) but moderately likely for September to November 2021 (p=0.20).

Figure 5.4 depicts the simulated rolling 7-day average daily infections for the workforce of one power station (657 workers) for each study period. The figure shows the average, 90% prediction interval and a sample of individual simulations, alongside the expected number of cases based upon the incidence of infections in the local community (corrected for under-reporting). The average number of simulated infections exhibits the same temporal pattern as those in the local community, which reflects limited workplace transmission in both periods – meaning, for instance, that most workplace introductions cause either zero or one additional cases (Figure 5.2). However, there is considerable stochastic variation between individual simulations (light grey lines) with a small proportion of simulations exhibiting peak daily numbers of cases exceeding three times the average (and the level in the local community). As Figure 5.4 depicts the 7-day rolling average, such peaks represent a moderately sized cluster of cases within the simulated workforce.

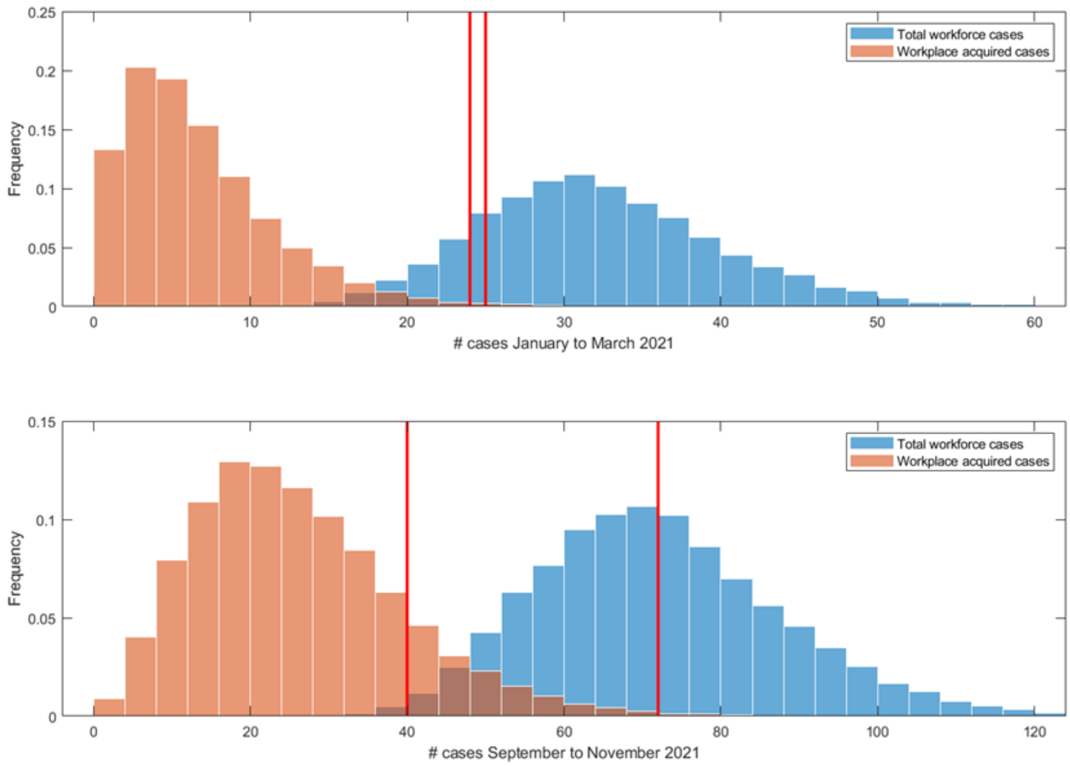

Figure 5.3: Simulated number of work-acquired and total infections for a single power station January to March 2021 (top) and September to November 2021 (bottom); redlines are the total test positive cases at HYA and HYB

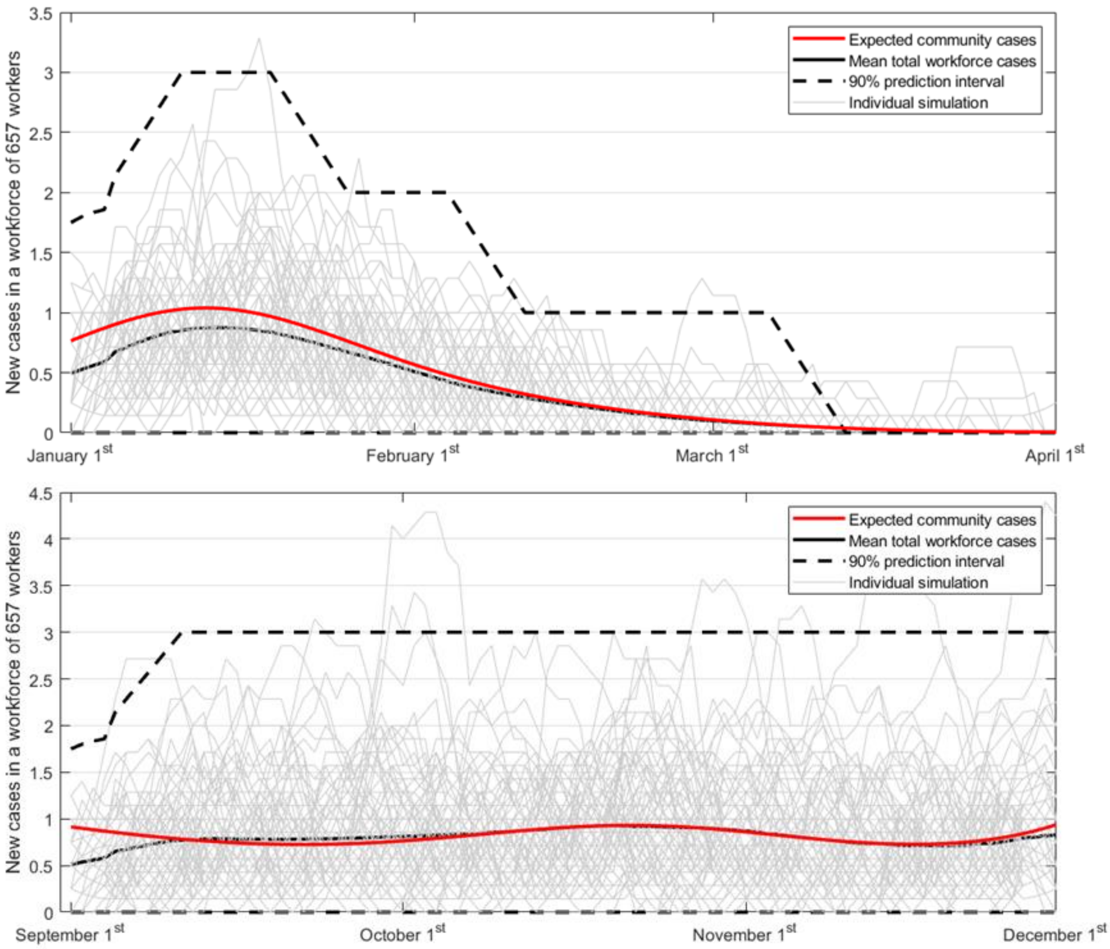

Figure 5.4: Time series of simulated daily infections (7-day rolling average) for January to March 2021 (top panel) and September to November 2021 (bottom panel).

5.4.4 Sensitivity study

Table 5.3 presents the simulation results for the sensitivity study with higher levels of workplace contacts, but a correspondingly lower proportion of contacts identified and isolated through contact tracing.

The simulated numbers of (identified) A and B list contacts after re-calibration of the contact networks were slightly greater than actually reported (0.34 vs 0.31 and 3.7 vs. 3.5 for A list and B list respectively). Similarly to the baseline simulations for the same period, the simulated secondary attack rates remained close to but slightly higher than their target (observed) values: 26.5% vs 25.5% and 8.5% vs 7.1% for simulated and observed A list and B list contacts respectively. All these simulated outcomes were comfortably within the ranges of uncertainty (confidence intervals) associated with the observations (not presented).

As would be expected, all measures of the levels of transmission/infection in the workforce were increased compared to the baseline predictions for January to March 2021. However, transmission within the workforce was still predicted to be relatively well controlled with $R_{workplace}$ equal to 0.5. The predicted number of workplace-acquired cases, although nearly double that of the baseline prediction, remained a substantial minority of total cases, and the predicted overall incidence of infection was approximately the same as in the local community (adjusted for under-reporting).

The confirmed numbers of cases at the two stations lie at the lower end of the 90% prediction interval for total cases. Overall, assuming substantial levels of additional and unidentified workplace contact increases the predicted level of workplace transmission considerably but only has a modest impact upon the predicted total workforce cases.

The numbers of confirmed cases at the two power stations are consistent with both the baseline and sensitivity scenarios. The sensitivity study does not therefore provide a strong basis for preferring a different set of model assumptions about levels of contact (which are partly bound up with the assumed effectiveness of contact isolation). Ultimately these model assumptions must be judgement-based and informed by discussions with company representatives.

Table 5.3: Model predictions for sensitivity study of the period January to March 2021 with additional workplace contacts

	January-March
# type A contacts identified per symptomatic case	0.34
# type B contacts identified per symptomatic case	3.7
Secondary attack rate type A contacts	26.5%
Secondary attack rate type B contacts	8.5%
$R_{workplace}$	0.50
Total downstream cases per introduction	0.95
Total period cases: mean and 90% prediction interval	37.3 (22-58)
Total workplace acquired cases: mean and 90% prediction interval	11.0 (1-29)
Expected community cases	39.7
Relative incidence of infection	0.94
Probability of a cluster	
10+ cases within 10 days	0.553
20+ cases within 10 days	0.064

5.5 Counterfactual modelling

5.5.1 Counterfactual scenarios

The following counterfactual scenarios were investigated and output transmission/infection metrics for each compared against those for the relevant baseline scenario (i.e., scenarios 1-7 vs the January to March 2021 baseline; scenarios 8 and 9 vs the September to November 2021 baseline). The scenarios are also summarised visually in Table 5.4 and the results are shown in Table 5.5. Scenarios 1-7 represent relaxations of particular mitigations used during the period January to March 2021 and scenarios 8 and 9 represent additional mitigations (screening tests) that could have been introduced during September to November 2021 to further reduce transmission.

1. January to March 2021 without tracing and isolation of B list contacts of symptomatic and test positive cases.

2. January to March 2021 without remote working for support and technical teams. This increases the mean weekday on-site workforce to 537 (+33%) for each station.

3. January to March 2021 without remote working and without isolation of B list contacts. This is a combination of scenarios 1 and 2 above.

4. January to March 2021 without face coverings worn at any time on-site.

5. January to March 2021 without face coverings and with delayed isolation of symptomatic cases. All symptomatic cases that isolate do so from the day after their symptom onset rather than the baseline assumption that half isolate from and including their day of symptom onset and half from the following day. As per the baseline assumptions it is assumed that their A and B list contacts isolate from the following day.

6. January to March 2021 without face coverings and with reduced isolation compliance for symptomatic cases. Here adherence was reduced to 75% to represent a lower achieved level of isolation of true cases had a more restrictive definition (as per government guidance) of symptoms been adopted.

7. January to March 2021 without face coverings and without tracing and isolation of B list contacts of symptomatic and test positive cases. This is a combination of scenarios 1 and 4.

8. September to November 2021 with additional once weekly screening tests using either high sensitivity LAMP or point-of-care PCR[1] tests and including isolation of A and B list contacts of those testing positive. Screening tests are assumed to take place in the morning with a negative test result being required for full access to the site meaning that positive cases are assumed to isolate from the day of the test. A and B list contacts during the previous 48 hours are assumed to be identified and to (fully) isolate from the *following* day with the same probabilities as assumed for contacts of symptomatic cases (namely 0.95 and 0.55 for A and B list contacts respectively). This assumes that any contacts would already be on-site by the time they were identified through contact tracing and so their first full day of isolation would not commence until the day after the test was performed. Shift workers receive their test on the first day of each four-day block; non-shift workers are tested on either Monday or Wednesday (50/50 split).

9. Sep-Nov 2021 with additional twice weekly lateral flow device (LFD) screening tests and including isolation of A and B list contacts of those testing positive. Lateral flow device tests have lower sensitivity[2] than PCR based methods but are cheaper and more rapid than the more sensitive tests considered in Scenario 8 (above), which may make more frequent testing practical. Shift workers undergo testing on the first and third days of each of their four-day blocks; non-shift workers either Monday and Wednesday or Tuesday and Thursday (50/50 split). Isolation of positive cases and their contacts as per scenario 8 above.

5.5.2 Results

Scenarios 1-7: January to March 2021

All mitigations were found to make a meaningful contribution to transmission: all output metrics were higher than baseline for counterfactual scenarios 1-7, meaning that transmission would have been higher during January to March 2021 had each of mitigation measures not been implemented. Nevertheless, $R_{workplace}$ remained below 1 in all seven of the March to January 2021 scenarios, and the probability of a cluster of 20 or more cases within a 10-day period was below 0.5 in all but scenario 7.

Of the three mitigation measures removed separately in scenarios 1, 2 and 4 (B list contact isolation, remote working, and face coverings, respectively) with all other measures retained, removing face covering usage led to the largest increase in transmission with, for example, a four-fold increase in total workplace acquired cases. This was followed by removal of remote working

(56% increase in total workplace acquired cases) and then by removing B list contact isolation, which had only a modest effect (32% increase). Whilst the removal each mitigation was predicted to increase the total number of downstream cases per introduced case (by a similar percentage to the predicted increase in total workplace acquired cases) removal of B list contact isolation did not affect the estimate of $R_{workplace}$. The workplace reproduction number is the average number of direct infections caused by one workforce case, which is not influenced by whether their contacts isolate. Instead, isolation of contacts reduces the likelihood and number of subsequent tertiary (second generation) infections.

Removing the isolation of B list contacts in combination with also removing remote working (scenario 3) or face covering usage (scenario 7) led to much larger increases in transmission than the effects when considered separately: total acquired workplace cases increased 10-fold with no B list isolation and no face coverings, and 4-fold with no B list isolation and no remote working. The probability of a cluster of 20 or more cases being identified within a 10-day period increased very substantially for these scenarios (over 40-fold), though in both scenarios $R_{workplace}$ remained below 1. This implies that while clusters of several tens of cases may have occurred in these situations, these would usually have died out rather than cases growing exponentially in number.

The results for scenarios 3 and 7 suggest that while removing the requirement for isolation of B list contacts when transmission is relatively well controlled would have had only a modest detrimental impact, in higher transmission situations, a much larger detrimental impact would have been seen.

The counterfactual scenarios for January to March 2021 in which face covering usage was removed in combination with less rapid isolation of cases (scenario 5) and reduced compliance with isolation requirements and (scenario 6) demonstrate the importance of rapidly identifying and isolating as many symptomatic cases and their contacts as possible. Even a modest delay in these risk management processes can have a significant impact upon transmission (though in both these scenarios the effect on transmission was considerably less severe than removing face mask usage in combination with removing B list contact isolation, scenario 7). The use of a broader symptom definition for the identification of potential symptomatic cases (backed by in-house testing of those symptomatic individuals that did not meet the government definition) may have assisted in achieving a high case identification and isolation rate (assumed 95% for symptomatics).

Scenarios 8 and 9: September to November 2021

The implementation of once-weekly high-sensitivity screening tests in combination with isolation of A and B list contacts of test positive cases (scenario 8) led to a large reduction in transmission: for example, predictions for total workforce acquired infections reduced by 73% and $R_{workplace}$ reduced by 60%. A comparable reduction was predicted with twice weekly screening testing using lower sensitivity lateral flow device (LFD) tests (scenario 9) with total workforce acquired infections reduced by 68% and $R_{workplace}$ by 55%.

The two charts shown in the top row of Figure 5.5 represent the scenario with the highest impact on transmission (scenario 7: no face covering usage and no B list contact isolation) for the period January to March 2021. Distributions for predicted total workplace acquired cases and total period cases are shown for the baseline (blue bars) scenario and scenario 7 (orange bars). These distributions show the substantial variability these outcomes across the simulations, particularly for scenario 7: the 90% prediction interval for total workplace acquired cases was 6-125 (i.e., 95th percentile = 125) and for total period cases the prediction interval was 29-151 (i.e., 95th percentile = 151, nearly one quarter of the workforce of one power station). This again shows that while outbreaks would have tended to die out even in scenario 7, in some cases these may have become large in size and affected a substantial minority of workers at a site.

The two charts in the bottom row of Figure 5.5 show the distributions of total workplace acquired cases and total period cases for September to November 2021 for scenario 9 (twice weekly LFD testing) vs baseline. The 90% prediction interval for workplace acquired cases with testing was 2-17 compared with 40-70 without, illustrating the substantial expected typical reduction in transmission but also reduced variability in transmission across the simulations.

Figure 5.6 shows the simulated rolling 7-day average daily infections for the workforce of one power station (657 workers) for January to March 2021 for scenario 7 (no face covering usage and no isolation of B list contacts (solid black line). The 90% prediction interval (black hashed lines) and a sample of individual simulations (light grey solid lines) are also included, alongside the expected number of cases based on the incidence of infections in the local community, corrected for under-reporting (red solid line).

During most of January 2021, the 7-day average total number of simulated infections in this relatively high-transmission counterfactual scenario increases more rapidly than the expected numbers based on local community incidence, and by late January, total simulated infections are more than double the expected number. Average total simulated infections then reduce in a similar manner to the expected number over the remainder of the period, though at a much higher level.

As Figure 5.4 showed for the baseline scenario, there is again considerable stochastic variation between individual simulations (light grey lines) with a small proportion of simulations exhibiting peak daily numbers of cases several times the average, and in some cases around 10 times the expected number based on community infection rates. Given that these lines show 7-day averages, some of these peaks imply clusters of several tens of infections, or over 100 in a small number of cases (i.e., the simulations corresponding to the right-hand tail of the distribution shown in the top row of Figure 5.5).

Table 5.4: Summary of counterfactual scenarios

	Tracing and isolation of contacts	Remote working	Face coverings	Case isolation timing	Case isolation compliance	Screening tests
January to March 2021 scenarios (Alpha variant, no vaccination immunity)						
Baseline (see Table 5.1 for full details)	***Case, A list and B list contacts isolate***	***Support staff 100% remote, technical staff 50% rota***	***Mandatory, 95% compliance on site***	***50% on day of symptoms, 50% day after***	***95% compliance***	**-**
1. No isolation of B list contacts	Case and A list only	Baseline	Baseline	Baseline	Baseline	-
2. Without remote working	Baseline	No remote working	Baseline	Baseline	Baseline	-
3. No B list isolation of remote working	Case and A list only	No remote working	Baseline	Baseline	Baseline	-
4. No face coverings	Baseline	Baseline	No face coverings	Baseline	Baseline	-
5. No face coverings, delayed isolation	Baseline	Baseline	No face coverings	All isolation from the day after symptom onset	Baseline	-
6. No face coverings, reduced isolation	Baseline	Baseline	No face coverings	Baseline	75%	-
7. No face coverings, no isolation of type B contacts	Case and A list only	Baseline	No face coverings	Baseline	Baseline	-
September to November 2021 scenarios (Delta variant, majority vaccinated)						
Baseline (see Table 5.1 for full details)	***A list and B list (55%) contacts isolate***	***50% of support staff remote***	***Close proximity contacts only***	***50% on day of symptoms, 50% day after***	***95% compliance***	***None***
8. Once per week high sensitivity screening	Baseline	Baseline	Baseline	Baseline	Baseline	Once a week screening and isolation of cases
9. Twice per week LFD screening	Baseline	Baseline	Baseline	Baseline	Baseline	Twice a week Screening and isolation of cases

[1] Loop Mediated Isothermal Amplification (LAMP) assays were a rapid diagnostic method that were deployed on-site by the generating company during outage periods. Additional rapid testing capacity was provided by Bosch Vivalytic point-of-care PCR tests. Evaluation studies have suggested limits of detection as low as 10 RNA copies per ml for the LAMP method [18] and ≤1000 RNA copies per ml for the Bosch Vivalytic. Real-world diagnostic, sensitivity, which is limited by the reliability of nasopharyngeal swabbing, was 95% and 88% for the LAMP and Bosch Vivalytic methods respectively [19][20], which are comparable to those estimated for the Office for National Statistics Infection Survey [21]. For modelling purposes, the sensitivity of these tests is assumed to be zero below a limit of detection of 100 RNA copies per ml and 90% at higher viral loads.
[2] The sensitivity of lateral flow device tests is assumed to depend via a logistic function upon the viral load of the individual with 50% sensitivity achieved at a viral load of approximately 10^5 RNA copies per ml [22] corresponding to a cycle threshold (Ct) value of around 25. A maximum sensitivity of 90% is assumed, consistent with the assumptions for LAMP and RANDOX tests, to reflect the reliability of nasopharyngeal swabbing as opposed to the assay sensitivity.

Table 5.5: Key epidemiological metrics for counterfactual scenarios and their % change from baseline values

Scenario	$R_{workplace}$	Avg. downstream cases per introduction	Total period cases	Total workplace-acquired cases	Probability of cluster*	Relative incidence of infection
0. Jan-Mar 2021 baseline	0.32	0.46	31.7	6.2	0.01	0.80
0. Sep-Nov 2021 baseline	0.58	1.32	71.7	25.6	0.20	0.98
1. Jan-Mar 2021 without isolation of B contacts	0.33 (+3%)	0.60 (+30%)	33.7 (+6%)	8.2 (+32%)	0.02 (+190%)	0.85 (+6%)
2. Jan-Mar 2021 without remote working	0.47 (+47%)	0.72 (+57%)	35.2 (+11%)	9.7 (+56%)	0.03 (+290%)	0.89 (+11%)
3. Jan-Mar 2021 without remote working and without isolation of type B contacts	0.47 (+47%)	1.06 (+130%)	39.4 (+24%)	14.0 (+126%)	0.10 (+1100%)	0.99 (+24%)
4. Jan-Mar 2021 without face coverings	0.83 (+159%)	2.2 (+380%)	50.1 (+58%)	24.7 (+300%)	0.34 (+4100%)	1.26 (+58%)
5. Jan-Mar 2021 with delayed isolation of type A & B contacts	0.88 (+175%)	2.6 (+440%)	52.2 (+64%)	26.9 (+330%)	0.39 (+4700%)	1.31 (+64%)
6. Jan-Mar 2021 with no face coverings and reduced isolation for symptomatic cases	0.85 (+166%)	2.9 (+530%)	55.7 (+75%)	30.4 (+390%)	0.37 (+4500%)	1.40 (+75%)
7. Jan-Mar 2021 without face coverings and without isolation of type B contacts	0.82 (+156%)	7.3 (+1500%)	96.2 (+200%)	62.3 (+900%)	0.70 (+8600%)	2.42 (+200%)
8. Sep-Nov 2021 with once weekly screening tests and isolation of A/B contacts of LFD positives	0.23 (-60%)	0.31 (-70%)	53.3 (-26%)	6.9 (-73%)	0.02 (-88%)	0.73) (-26%)
9. Sep-Nov 2021 with twice weekly LFD screening tests and isolation of A/B contacts of LFD positives	0.26 (-55%)	0.34 (-74%)	54.6 (-24%)	8.1 (-68%)	0.01 (-94%)	0.75 (-24%)

* Defined as 20 or more identified cases within 10 days, excluding cases in exclusively remote workers and known community acquired infections, i.e., those individuals already isolating as a household or social contact of a known case.

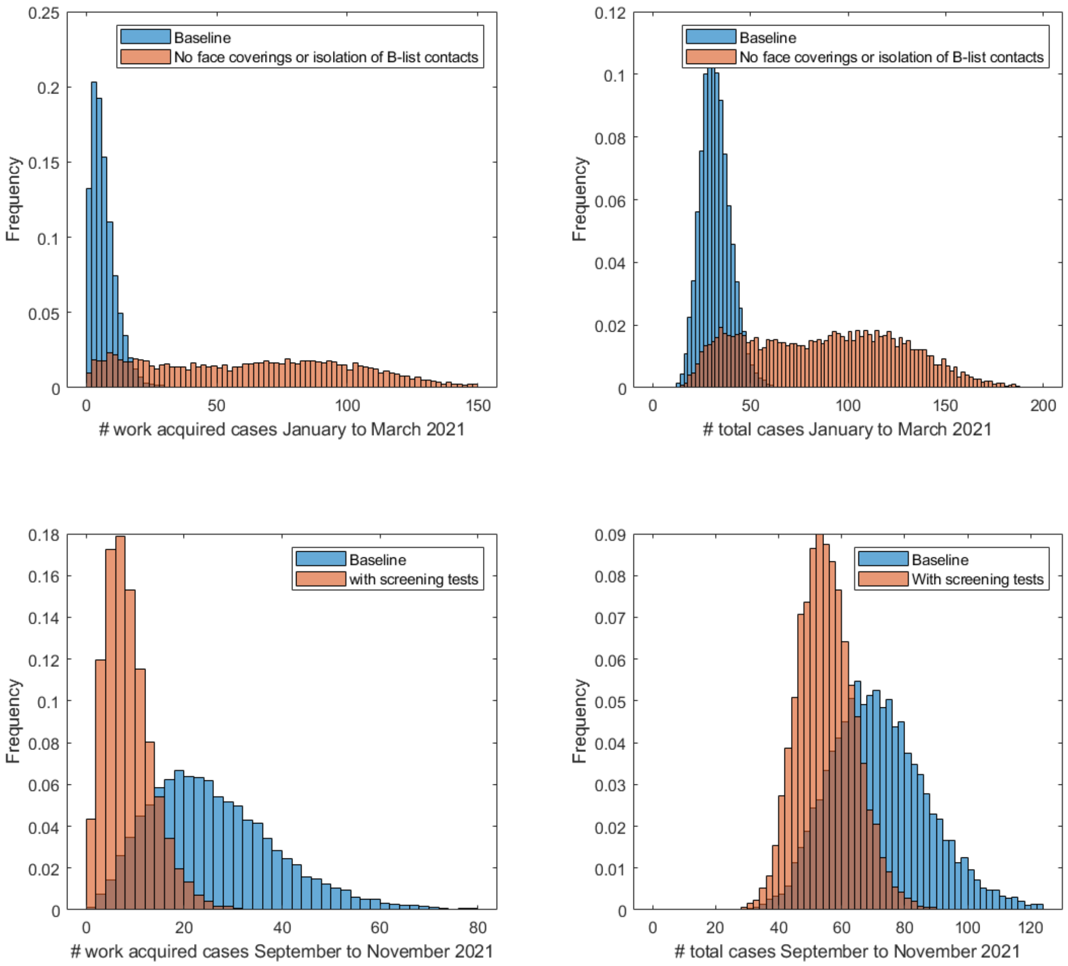

Figure 5.5: Counterfactual modelling of the potential impact of mitigations: the impact of the wearing of face coverings January to March 2021 (top row); the impact of twice weekly LFD screening tests had they been deployed during September to November 2021 (bottom row)

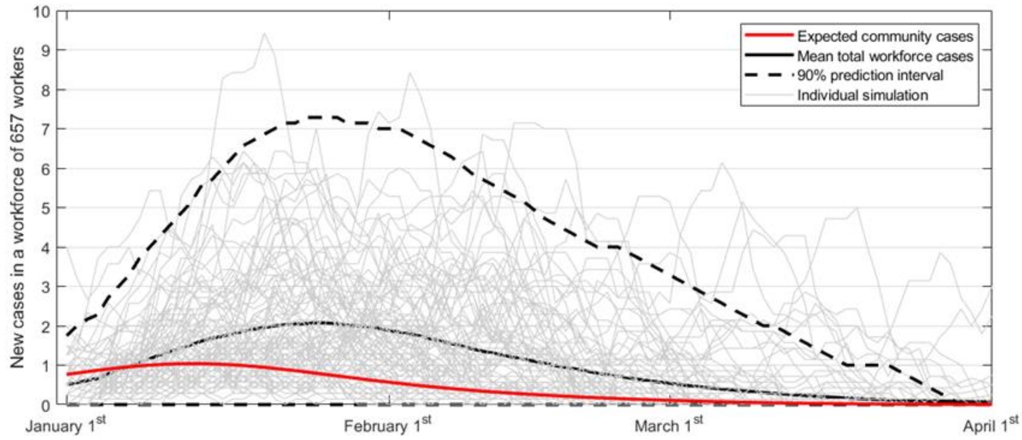

Figure 5.6: Time series of simulated daily infections (7-day rolling average) for the counterfactual scenario January to March 2021 without face coverings and without tracing and isolation of B list contacts.

5.6 Discussion

A stochastic agent-based model for workplace transmission of SARS-CoV-2 was configured for two electricity generating sites through the inclusion of site-specific data on contact patterns, mitigations and secondary attack rates in workforce contacts. The model was applied to two periods from 2021: January to March, during which time the Alpha variant was dominant, site risk ratings were high and vaccination levels were low; and September to November, during which time the Delta variant was dominant, most of the workforce was double vaccinated, and some mitigations had been relaxed.

The modelling predicted limited workplace transmission during both periods (workplace reproduction number <1) with most workforce infections being community acquired. Overall levels of infection in the workforce were comparable (September to November 2021) or slightly lower (January to March 2021) than those in the local community levels (adjusted for estimated under reporting). Modelling predicted that the number of infections at the two power stations over the two three-month periods analysed would have been highly stochastic, meaning that with the mitigation measures in place during the two periods considerably fewer or greater numbers of infections than observed were possible just by chance alone.

Overall, there was a good level of consistency between the baseline simulations for both periods and the known patterns of infection at the two generating sites. This provides confidence that the model provides a reasonable basis for investigating the impact of workplace mitigations through counterfactual modelling.

All the mitigations investigated through counterfactual modelling, namely remote working, contact tracing and isolation of B list contacts, the wearing of face coverings and asymptomatic screening testing, were predicted to make meaningful contributions to reducing transmission. Taken in isolation the wearing of face coverings was predicted to be the most impact of these measures - had this measure not been in place during January to March 2021 total work force infections may have been around 60% higher.

Even for the highest transmission counterfactual scenario (January to March 2021 without face coverings and without isolation of B list contacts) the predicted workplace reproduction number ($R_{workplace}$) remained less than one. This implies that outbreaks in the workforce would naturally abate without needing further mitigations. However, such outbreaks might achieve a substantial size before subsiding, for instance, the 95th percentile of the distribution of predicted total workforce cases was 151 or around a quarter of the workforce.

Counterfactual modelling suggests that had contract tracing and isolation of B list contacts not been undertaken during January to March 2021 there would likely have been a modest increase in the number work workplace acquired infections from an average of 6.2 to 8.2 (+33%). In actuality, three positive B list contacts were identified at each station between January and March 2021. Based upon the model prediction of 0.60 downstream cases per workplace introduction (without isolation of B list contacts) then the number of cases identified through testing of B list contacts appears consistent with the modelled impact. The predicted impact of tracing and isolation of B list contacts is modest during this period primarily because the levels of workplace transmission were low (estimated $R_{workplace}$≈0.3, i.e., each index case creating an average of 0.3 direct secondary cases). In these circumstances few additional downstream cases will be caused by the limited number of secondary infections and so the interruption of these lines of transmission through contact tracing and isolation has only a modest impact.

Further counterfactual modelling explored this issue through consideration of two higher transmission scenarios (January to March 2021 without remote working and January to March without face coverings) also without the tracing and isolation of B list contacts. Even with only modestly higher transmission (without remote working, $R_{workplace}$≈0.5) the impact of not tracing and isolating B list contacts was markedly increased with the mean predicted number of workplace-acquired cases over the three month period increasing from 9.7 to 14 (+44%). With even higher levels of transmission (without face coverings, $R_{workplace}$≈0.8) workplace-acquired cases were forecast to increase from an average of around 25 with the tracing and isolation of B-list contacts to more than 60 (+150%) without.

The impact of tracing and isolation of A list (close) contacts was not investigated. During 2021 there was a legal obligation for close contacts of COVID-19 cases to isolate for 10 days, although as part of step 4 of the government's COVID-19 roadmap from August 16th 2021 the requirement ceased for those who had received two vaccine doses (and those under 18 years of age). Based upon company contact tracing records from 2021 A list contacts were approximately 10 times less numerous but with a test-confirmed secondary attack rate approximately three and a half times higher (25.5% vs. 7.1%). The isolation of A list contacts may therefore have had a more modest impact than the isolation of B list contacts.

Counterfactual modelling for September to November 2021 suggested that asymptomatic screening testing would have had a substantial impact in reducing levels of workplace transmission and overall numbers of infections. Similar impacts were predicted for both once weekly testing with a high sensitivity method (LAMP or point-of-care PCR) and twice weekly testing with lower sensitivity lateral flow device (LFD) tests with workplace-acquired cases reduced by approximately 70% and total workforce cases by around 25%. Crucially both modelled scenarios assumed implementations where testing was undertaken on-site, before entry, and under supervision, and where A and B list contacts of positive cases were traced and isolated. It seems likely that self-administered LFD testing at home would be less impactful as compliance with the testing protocol would be lower.

The available data did not allow an assessment of how contact patterns during 2021 may have differed from ‘usual’, i.e., pre- or post-pandemic, patterns. The numbers of close contacts identified through company contact tracing during 2021 was substantially lower than the numbers reported through an online research survey in July and August 2022. Although some of this difference might reflect methodological differences underpinning the collection of these data rather than a genuine difference in contact behaviours, it seems credible that some degree of reduction in the number or duration of contacts occurred through re-organisation of work activities or through personal behaviour changes. Depending upon the extent of any change in contact patterns achieved, this may have been a major factor in reducing transmission within the power station.

A strength of the analysis is that the agent-based model includes much of the real-world complexity affecting workplace transmission including the within-host viral kinetics and its effects on infectiousness, contact patterns, timing of testing and isolation. Furthermore, the availability of an extensive and detailed database of company test data helped to configure the model and provided assurance that the model predictions were generally consistent with the actual levels and patterns of infections that occurred at the two power stations during 2021. This consistency between the predicted and observed patterns of power station infections provides support for the findings from the counterfactual modelling about the impact of the various mitigations.

The model has many parameters known with varying levels of certainty. Uncertainty in the model outputs was not quantified nor has a comprehensive sensitivity analysis of the impact of parameter values on the model output for the power station workforces been carried out. Therefore, the quantitative outputs for the counterfactual scenarios should be regarded as indicative. However, given that the majority of model parameters and assumptions also apply to the baseline simulations, which displayed considerable concordance with the available information on patterns of infection, confidence in the relative impacts of the mitigations revealed by the counterfactual modelling is judged to be moderate.

The number of confirmed COVID-19 infections in the company testing data will inevitably be an underestimate of the true number of cases. In particular, asymptomatic cases that were not A list or B list contacts of known cases would not have been identified (during the two periods in question there was no widespread screening testing of the workforce). The level of under-reporting may have been greater during September to November 2021 as, according to the company contact tracing narratives, the number of B list contacts per index case identified during this period approximately 45% lower than in the earlier period. Since it is unlikely that the actual frequency of workers sharing the same airspace decreased during this period (given changing attitudes and approaches more generally in the light of the road map and the vaccination programme), this reduction probably represents genuine B list contacts not being classified as such, and as a consequence, not being tested.

The local community incidence of infection in working aged adults was used to seed cases into the simulated workforce. The community incidence was adjusted for under-reporting, to strip-out the contribution of work, and for the presumed pre-emptive isolation at home of the proportion that would have known they were social or household contacts of cases. However, the power station workforce might have experienced a different risk of infection than the wider local community due to behavioural or socio-demographic differences.

A variety of mitigations were not explicitly modelled including social distancing, a prohibition/reduction in meetings, the use of thermal cameras, and increased cleaning and hand sanitation. However, the effects of the first two of these mitigations ought to be reflected in the numbers of A list contacts recorded in internal contact tracing narratives and so are implicit in the contact networks that were developed for use with the model. Thermal cameras may have facilitated the detection of some asymptomatic cases but perhaps more likely may have detected symptomatic cases to be identified and isolated earlier. The simulations assume half of the 95% of symptomatic cases that isolate do so from the outset of the day of symptom onset, i.e., before entering the power station and having contacts with co-workers. The use of thermal cameras, if effective, would support this early identification and isolation.

Short proximity (<2m) contacts lasting fewer than 15 minutes, meaning they would not have qualified as A list contacts, were not explicitly modelled. These contacts, which inevitably must have occurred, represent an additional route by which workplace transmission might have occurred. A significant proportion of these contacts can be assumed to have occurred between pairs of workers who were B list contacts, i.e., those that had medium proximity contact but without more than 15 minutes of short proximity contact. The contribution of these short duration short proximity contacts to transmission will therefore be captured via the transmission rate parameter for medium proximity contacts (β_{medium}), which was calibrated (alongside β_{short}) to achieve the observed secondary attack rates in A and B list contacts. The sensitivity study undertaken the potential impact of contact not captured within the A and B list definitions increased the predicted level of workplace transmission considerably but only had a modest impact upon the predicted total workforce cases. However, the numbers of confirmed cases at the two power stations were consistent with both the baseline and sensitivity scenarios, and so the sensitivity study does not provide a strong basis for preferring a different set of model assumptions about levels of contact.

Testing of A and B list contacts served two purposes, first, it allowed contact tracing for positive contacts to be undertaken and their contacts isolated. This was investigated in exploratory simulations where the testing of A and B list contacts was explicitly modelled (not presented). However, since a majority (70%) of positive contacts would become symptomatic – which, under the model representation, would precipitate contact tracing anyhow – the overall impact of explicitly modelling the testing of contacts on transmission was minimal. Second, testing of B list contacts permitted early release from isolation following two negative tests. Early release of uninfected workers would not affect the dynamics of transmission but would affect levels of workforce absence. As levels of workforce absence were outside the scope of the modelling this process was not included in the simulations.

Routine screening testing during January to March 2021 was not included in the baseline simulations. Based upon the generating company's testing records only limited numbers of screening tests were performed: 1464 tests across both stations over three months with three positive results. Based upon the power station footfall records for this period this amounts to around 1.5 tests per on-site worker over the three-month period. The omission of these screening tests is expected to have very marginally increased the simulated numbers of cases for this period. However, according to the testing records, the frequency of screening tests was not uniform across plant facing and operational job categories (349 in maintenance, 813 in contractors) and hence the impact of screening testing in reducing transmission within these targeted job groups may have been more substantial. The ABM does not have capability to model different frequencies of screening testing in different groups of workers and so the impact of this limited scale testing was not investigated.

The two transmission rate parameters that, in combination with other model parameters, determine the probability of transmission during short and medium proximity contacts were calibrated to the secondary attack rate (SAR) in A list and B list contact tests extracted from the company testing database. In order to increase the sample size and obtain more robust estimates of the SARs all A and B list contacts tested at the two stations during 2021 were included (47 and 238 workers respectively). However, during 2021 there were significant changes that would have affected the risk of transmission for these contacts. Principally these were immunological, e.g., from vaccination and increasing levels infection acquired immunity, and viral, e.g., differences in transmissibility between the Alpha, Delta and Omicron variants, but also potentially behavioural, for instance longer duration close contacts or lower compliance with requirements to wear face coverings. Hence the calibration of the January to March 2021 transmission rate parameters, which relate to period when the Alpha variant was dominant and workforce vaccination was very low, to the test positivity for the whole of 2021 is inherently deficient. Nevertheless, on the basis of the limited contact testing data for this period (16 A list contact tests undertaken January to March 2021) a pragmatic decision was taken to use data from the whole of 2021. Although this will have inevitably created considerable potential for misspecification of the transmission rate paratemeters, this is unlikely to have a large impact on the conclusions in relation to the primary aim of the analysis, namely using counterfactual modelling to investigate the *relative* impact of various mitigation measures.

The analysis did not distinguish between the different types of vaccines nor consider immunity acquired from first doses. The principal vaccines administered to adults in the UK during 2021 were BNT162b2 (manufactured by Pfizer) and ChAdoX1 (manufactured by AstraZeneca). Various studies have reported vaccine effectiveness for various periods after administration of one and two doses of individual vaccines against the Alpha and Delta variants. Most studies estimated slightly higher effectiveness for BNT162b2 than ChAdoX1. An overall effectiveness against infection of 0.75 for the doubly vaccinated is judged to be appropriate (and is consistent with the assumptions used by some SPI-M modelling groups during 2021 [10]). With regard to first doses, which conferred substantially less immunity than two doses, a small number of mainly older workers would have received their first dose towards the end of the January to March period. The small additional level of immunity this would have conveyed to the workforce as a whole was judged to be inconsequential in terms of overall levels of transmission.

Counterfactual modelling highlighted the importance of identifying as many symptomatic cases as possible and isolating them and their contacts as quickly as possible. During periods when sites were not considered by the company to be at increased risk, the definition of COVID-19 symptoms in national guidance was adopted (i.e., high temperature, a new continuous cough, or a loss/change to sense of smell/taste). However, during periods when sites were considered to be at increased risk, the symptom criteria were broadened, and a rapid-turnaround onsite testing programme was implemented to facilitate a more cautious approach to the identification of potential cases. Individuals with one symptom from a list considered most likely to be associated with COVID-19 (the 'red flag' list) or three symptoms from a list that may be associated with the disease (the 'orange flag' list) were defined as 'RISCC' (i.e., **R**eached **I**ndividual **S**ymptom **C**riteria for **C**OVID-19). Whilst the ABM distinguishes between asymptomatic, pre-symptomatic and symptomatic individuals it does model specific symptom types. Nevertheless, the broader symptom definition may be regarded as implicit in the high level of compliance and rapid isolation that was assumed for symptomatic cases (95%).

5.7 Conclusions

The modelling exercise focussed upon January to March 2021 – a period with stringent mitigations, very low levels of workforce vaccination and with the Alpha variant dominant - and September to November 2021 – a period with reduced mitigations, high levels of workforce vaccination and with the Delta variant dominant.

The agent-based model successfully reproduced the observed patterns of cases during the two periods. Total confirmed (test positive) cases at both stations during the January to March 2021 period fell within the model 90% prediction intervals. Total confirmed cases at HYB during September-November 2021 were also within the prediction interval, however cases at HYA for September to November 2021 were slightly lower than predicted. As the test-confirmed number of cases almost certainly understates the true number of workforce infections to some degree, it is likely that the true number of infections at HYA lies within the model prediction interval.

On average the predicted temporal pattern of infections mirrors that in the local community, which are the source of seed infections into the workforce. This is a consequence of the model predicting an average of around one or fewer workplace acquired cases per introduction. However, there was considerable stochastic variation between simulations around this average behaviour, especially over short time periods of the order of a week.

Workplace acquired cases were predicted to represent a minority of the total cases (20% and 36% in January to March 2021 and September-November 2021 respectively).

Adjusting for under-reporting of community infections in the Lancaster local authority area, modelling suggests rates of infection in power station staff were slightly lower (simulated incident rate ratio 0.80) than in the wider community during January to March 2021 and similar to the local community (simulated incident rate ratio 0.98) during September to November 2021. These findings are however sensitive to assumptions around under-reporting of local community infections.

Counterfactual modelling suggested that contract tracing and isolation and remote working contributed meaningfully to reducing transmission. The mandatory use of face coverings at all times inside during January to March 2021 had an even more substantial effect – had they not been used during this period the model predicts the total number of cases would be expected to have been 58% higher, with the expected number of workplace-acquired cases at each station increasing from 6 to 25.

Limited screening testing was carried out during the two modelled periods and has not been included in the baseline modelling for the two periods. Counterfactual modelling suggests that twice weekly screening testing using lateral flow devices combined with isolation of the contacts of positive cases might have reduced total workforce cases during September to November 2021 by 24% and workplace acquired cases by 68%. A similar reduction in transmission might be achieved through lower frequency (once weekly) testing using a higher sensitivity test method such as LAMP or point-of-care PCR (‘RANDOX’) as deployed by the company during outage periods).

5.8 Section 5 References

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Appendix 1: Supplementary tables from Section 2

Table S1: Fully adjusted odds ratios and 95% confidence intervals from separate logistic regression models for each test reason

Exposure	Category	Final model[a] (n=70,686)	Symptoms[b] (n=2,772[c])	Close contacts[b] (n=3175)	Other contacts[b] (n=2,599[d])	Routine screening[b] (n=61,764[e])
Job category	Energy operations	0.91 (0.70, 1.20)	0.94 (0.59, 1.50)	0.69 (0.42, 1.13)	0.34 (0.14, 0.87)	1.87 (1.06, 3.31)
	Engineering	0.90 (0.70, 1.17)	1.08 (0.69, 1.70)	0.79 (0.48, 1.28)	0.27 (0.10, 0.73)	1.12 (0.65, 1.93)
	External	1.05 (0.82, 1.36)	1.20 (0.77, 1.88)	1.55 (0.96, 2.51)	0.36 (0.14, 0.93)	0.93 (0.55, 1.59)
	HSE & security	1.12 (0.78, 1.62)	0.77 (0.40, 1.49)	1.07 (0.56, 2.05)	0.79 (0.28, 2.20)	1.54 (0.73, 3.24)
	Nuclear & scientific	0.96 (0.68, 1.35)	0.76 (0.43, 1.34)	1.09 (0.56, 2.12)	0.10 (0.01, 0.83)	1.78 (0.92, 3.45)
	Office-based	1.00 (baseline)	1.00 (baseline)	1.00 (baseline)	1.00 (baseline)	1.00 (baseline)
	Project management	1.00 (0.66, 1.51)	0.67 (0.33, 1.35)	1.16 (0.51, 2.64)	0.62 (0.17, 2.26)	1.75 (0.80, 3.83)
Sex	Female	0.71 (0.58, 0.86)	0.50 (0.35, 0.72)	0.83 (0.57, 1.22)	0.86 (0.40, 1.87)	0.96 (0.65, 1.41)
Job site	Head Office	0.70 (0.48, 1.03)	0.53 (0.23, 1.20)	0.58 (0.25, 1.36)	0.13 (0.00, 3.69)	0.60 (0.32, 1.14)
	Power station 1	0.58 (0.43, 0.77)	0.27 (0.13, 0.56)	0.25 (0.15, 0.43)	0.18 (0.03, 1.25)	2.05 (1.17, 3.59)
	Power station 2	0.38 (0.29, 0.49)	0.18 (0.10, 0.34)	0.19 (0.11, 0.33)	0.11 (0.02, 0.65)	1.15 (0.71, 1.86)
	Power station 3	0.90 (0.67, 1.20)	0.24 (0.12, 0.46)	0.86 (0.50, 1.48)	0.11 (0.02, 0.71)	1.48 (0.85, 2.58)
	Power station 4	0.42 (0.32, 0.55)	0.13 (0.07, 0.25)	0.19 (0.11, 0.33)	0.13 (0.02, 0.78)	1.39 (0.86, 2.24)
	Power station 5	0.97 (0.70, 1.33)	0.41 (0.19, 0.89)	0.51 (0.27, 0.97)	0.10 (0.01, 0.78)	2.93 (1.72, 4.98)
	Power station 6	0.22 (0.16, 0.29)	0.12 (0.06, 0.24)	0.20 (0.12, 0.34)	0.04 (0.01, 0.28)	0.21 (0.12, 0.38)
	Power station 7	1.00 (baseline)	1.00 (baseline)	1.00 (baseline)	1.00 (baseline)	1.00 (baseline)
	Power station 8	2.05 (1.52, 2.77)	1.17 (0.50, 2.75)	3.90 (1.96, 7.74)	0.84 (0.03, 27.46)	2.09 (1.24, 3.53)
	Other	0.31 (0.21, 0.44)	0.13 (0.06, 0.28)	0.18 (0.10, 0.34)	0.00 (0.00, 0.05)	0.94 (0.44, 2.01)
Vaccination status	Per vaccination[f]	0.97 (0.88, 1.06)	0.89 (0.76, 1.06)	0.86 (0.72, 1.02)	0.80 (0.52, 1.22)	0.89 (0.75, 1.05)
Vulnerability status	Vulnerable	0.78 (0.63, 0.96)	0.87 (0.56, 1.35)	1.43 (0.99, 2.05)	0.57 (0.24, 1.34)	0.87 (0.56, 1.35)
Outage	During outage	1.35 (1.12, 1.63)	0.54 (0.39, 0.74)	5.15 (3.44, 7.71)	4.10 (1.41, 11.94)	0.54 (0.39, 0.74)
Site risk rating	0/1 (lowest risk)	1.00 (baseline)	1.00 (baseline)	1.00 (baseline)	1.00 (baseline)	1.00 (baseline)
	2	0.64 (0.50, 0.82)	0.37 (0.23, 0.62)	1.15 (0.76, 1.74)	1.36 (0.40, 4.65)	0.37 (0.23, 0.62)
	3	1.30 (1.00, 1.69)	1.05 (0.62, 1.78)	2.10 (1.36, 3.23)	4.05 (1.26, 13.02)	1.05 (0.62, 1.78)
	4	1.60 (1.11, 2.31)	0.51 (0.24, 1.10)	2.74 (1.44, 5.22)	5.18 (1.11, 24.15)	0.51 (0.24, 1.08)

[a] adjusted for all variables in the table plus test date, test type, age and test reason; [b] adjusted for all variables in the table plus test date, test type, and age; [c] one observation omitted; [d] 64 observations omitted; [e] 269 observations omitted; [f] up to fully vaccinated (2 or more vaccinations);

Table S2: Frequency of number of tests per person in each time period in the model

Number of tests per person	Q1-3 2020	Q4 2020	Q1 2021	Q2 2021	Q3 2021	Q4 2021	Q1 2022	Q2-3 2022	Overall
1	220 (84%)	911 (59%)	2,228 (37%)	1,504 (24%)	1,641 (41%)	1,401 (63%)	1,500 (92%)	557 (100%)	2,551 (24%)
2	39 (15%)	492 (32%)	940 (15%)	833 (13%)	671 (17%)	420 (19%)	129 (8%)	1 (0%)	1,403 (13%)
3	2 (1%)	79 (5%)	498 (8%)	591 (9%)	409 (10%)	169 (8%)	8 (0%)		932 (9%)
4		39 (3%)	321 (5%)	502 (8%)	348 (9%)	95 (4%)	1 (0%)		707 (7%)
5		7 (0%)	298 (5%)	546 (9%)	307 (8%)	51 (2%)			528 (5%)
6		4 (0%)	371 (6%)	667 (11%)	284 (7%)	36 (2%)			473 (4%)
7		2 (0%)	370 (6%)	826 (13%)	191 (5%)	23 (1%)			408 (4%)
8		1 (0%)	294 (5%)	497 (8%)	88 (2%)	12 (1%)			349 (3%)
9			232 (4%)	142 (2%)	31 (1%)	4 (0%)			345 (3%)
10		1 (0%)	202 (3%)	59 (1%)	10 (0%)	3 (0%)			336 (3%)
11			211 (3%)	63 (1%)	4 (0%)	1 (0%)			311 (3%)
12			86 (1%)	42 (1%)	2 (0%)				312 (3%)
13			26 (0%)	19 (0%)	2 (0%)				314 (3%)
14			7 (0%)	12 (0%)	1 (0%)				314 (3%)
15			5 (0%)	4 (0%)					317 (3%)
16				1 (0%)	1 (0%)				292 (3%)
17									233 (2%)
18									192 (2%)
19				1 (0%)					134 (1%)
20+									317 (3%)

Appendix 2: Contact survey questionnaire

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Appendix 3: Detailed analysis of contact survey

The data are not considered highly sensitive and so simple small number suppression has been applied to tables. For categories where the number of participants is less than five, the number of participants and the percentage are displayed as *.

		Number	%
Time period of completion	Period 1 (22/07-31/07)	158	74.88
	Period 2 (01/08-11/08)	53	25.12
Age group	<30	27	12.80
	30-44	72	34.12
	45-54	55	26.07
	55+	50	23.70
	Prefer not to say	7	3.32
Gender	Male	134	63.51
	Female	68	32.23
	Other/Prefer not to say	9	4.27
Site	Site 1	108	51.18
	Site 2	101	47.87
	Both	*	*
	Other	*	*
Work pattern	Days	190	90.05
	Shifts	21	9.95
Main place of work [a]	Office	179	84.83
	Plant	60	28.44
	Outdoors	6	2.84
Employed by the company	No	57	27.01
	Yes	151	71.56
	Missing	*	*
Job (for those employed by company)	Chemistry	6	2.84
	Engineers	31	14.69
	Environmental Safety Engineer	*	*
	Environmental safety technician	8	3.79
	Finance and Supply chain	12	5.69
	Fuel route – engineering / planning	5	2.37
	Human resources	*	*
	Independent assurance	*	*
	Maintenance (DART/ TAG)	8	3.79
	Nuclear safety group	5	2.37
	Operate technician	5	2.37
	Operations	13	6.16
	Outage	5	2.37
	Performance improvement and training	20	9.48
	Prefer not to say	5	2.37
	Quality Management	*	*
	Safety & Quality	*	*

	Security	*	*
	Station leaders / executive	*	*
	Work management	8	3.79
	process oversight	*	*
	NA [b]	57	27.01
	Missing	7	3.32
Managerial responsibilities	No supervisory or managerial responsibility	119	56.40
	Manager	13	6.16
	Supervisor (of plant or people)	63	29.86
	Prefer not to say	9	4.27
	Missing	7	3.32
Employment type	Full time employee	185	87.68
	Part time employee	17	8.06
	Other	*	*
	Missing	7	3.32
Workplace measures in the last week [c]	Site COVID hubs	37	17.54
	Hand sanitising stations	111	52.61
	Thermographic cameras	17	8.06
	Social distancing	28	13.27
	One-way systems	11	5.21
	Enhanced cleaning regimes	21	9.95
	Travel/car sharing restrictions – at work	8	3.79
	Travel/car sharing restrictions – to/from work	9	4.27
	Footfall/capacity restrictions	11	5.21
	Mess room arrangements	11	5.21
	Canteen restrictions	9	4.27
	Staggered start/finish times	7	3.32
	Operational work bubbles	6	2.84
	Mask supply	42	19.91
	Encouraging and tracking vaccination status	54	25.59
	HVAC complete air extraction	*	*
	Increasing ventilation through open doors/windows where possible	37	17.54
	IT enabled meetings (Skype)	80	37.91
	Pandemic response plan (already in place)	59	27.96
	Track and trace arrangements	28	13.27
	Work from home	73	34.60
	Covid testing, e.g., lateral flow tests	47	22.27
	Other measures	*	*
Physical or close contact with co-workers in the last week	<15 mins	58	27.49
	15-60 mins	56	26.54
	2 hrs	35	16.59
	3 hrs	10	4.74

	4 hrs	17	8.06
	5 hrs	*	*
	6 hrs	8	3.79
	7 hrs	9	4.27
	8+ hrs	13	6.16
	Missing	*	*
Contact part of pre-defined operations work bubble	None	95	45.02
	A little	17	8.06
	Around half	*	*
	More than half	7	3.32
	Most or all	28	13.27
	Don't know	18	8.53
	Not applicable	35	16.59
	Missing	7	3.32
Daily contacts with colleagues in your own team, at work	Median (min-max)	3 (0-60)	
	Missing	7	
Daily contacts with colleagues outside your own team, at work	Median (min-max)	2 (0-50)	
	Missing	7	
Share living accommodation with colleagues	No	192	91.00
	Yes	16	7.58
	Prefer not to say	*	*
	Missing	*	*
Number of colleagues sharing living accommodation	Median (min-max)	1 (0-8)	
	Missing	196	
Method travel to work	Alone by private car, van, bicycle, walking or motorcycle	183	86.73
	Work car/van (alone)	9	4.27
	Private car/van (travel with others)	13	6.16
	Work car/van (travel with others)	*	*
	Missing	*	*
Close contact with colleagues while travelling for work	Median (min-max)	1 (0-3)	
	Missing	191	
Use face covering when <2 m from colleagues	Never	182	86.26
	Occasionally	15	7.11
	About half the time	*	*
	Most/all of the time	8	3.79
	Missing	*	*
Use face covering	Never	178	84.36
	Occasionally	15	7.11
	About half the time or more	6	2.84

generally on site	Missing	12	5.69
Told to shield during pandemic	No	197	93.36
	Yes	11	5.21
	Prefer not to say	*	*
	Missing	*	*
Vaccination status	No - refused	8	3.79
	Yes - one dose	*	*
	Yes - two doses	32	15.17
	Yes - >2 doses	164	77.73
	Prefer not to say	*	*
	Missing	*	*
Family vulnerable to Covid-19	No	121	57.35
	Yes	87	41.23
	Prefer not to say	*	*
	Missing	*	*
Likely to catch Covid-19	Not at all likely	7	3.32
	Not very likely	21	9.95
	Neither likely nor unlikely	43	20.38
	Somewhat likely	88	41.71
	Very likely	31	14.69
	Don't know	17	8.06
	Prefer not to say	*	*
	Missing	*	*
Had Covid-19	No	38	18.01
	Yes	154	72.99
	Unsure	16	7.58
	Missing	*	*

* small number suppression applied
[a] Not mutually exclusive: 28 (13.27%) reported two main work areas, and <5 (<2.37%) reported all three.
[b] NA, not employed by company
[c] Not mutually exclusive: The median number of measures reported was 2 and ranged from zero to 22 (all) measures. 51 (24.17%) reported no measures in the last week.

Appendix 4: Negative binomial regression of numbers of contacts self-reported through an online survey of power station workers

There were 211 participants in total. 202 (95.7%) had completed both questions on work contacts (within their team and outside of their team). For people who had answered one of the contact questions and not the other (n=4), the missing response was assumed to be zero and so there were 206 (97.6%) participants available for analysis.

The total number of work contacts had a mean of 10.1 and a variance that was substantially larger at 145.5. This suggests over-dispersion in the data and so the Poisson model would not be appropriate; therefore, the data were analysed using the negative binomial model. Throughout, the alpha parameters of the negative binomial regression models were greater than zero, confirming the presence of over-dispersion and the choice of negative binomial regression model. Coefficients from the negative binomial regression model have been exponentiated to provide contact rate ratios (CRRs) – e.g., a CRR of 1.20 would mean the contact rate in that group was 1.20 times (or 20% greater than) the contact rate in the reference group.

Results are in Table 1 for the main variables of interest (site, employment, work pattern, main place of work, and job), and other variables collected in the questionnaire. The table presents both unadjusted and adjusted CRRs; CRRs have been adjusted for site and time-period of survey completion as possible design effects, and also adjusted for age since this was found to be a potential confounder (i.e., associated with contact rate in the unadjusted analysis, and associated with some of the main variables of interest). Note that, throughout, there tend to be wide confidence intervals and so there is large uncertainty associated with the estimated CRRs. Therefore, some CRRs may be large – e.g., a CRR=2 representing a doubling of the contact rate – but still may not be statistically significant.

Some of the work variables were associated, and so a multivariable model was used to adjust for multiple work-related variables at the same time. Age, site and time-period of completion were included *a priori*. The work-related variables of employed by the company, work pattern, main area of work, managerial responsibilities and employment type were considered for inclusion in the model. Variables were chosen using a forward stepwise procedure with p-value for inclusion set at $p<0.05$ and p-value for exclusion at $p>0.10$. Table 2 shows the resulting multivariable mode (model 1). Job role was only asked to employees of the company and so, to further explore job role, the same multivariable model was fitted to employee-only data but this time including job role.

All analyses were conducted in Stata statistical software (StataCorp. 2021. Stata Statistical Software: Release 17. College Station, TX: StataCorp LLC). The data are not considered highly sensitive and so simple small number suppression has been applied to tables. For categories where the number of participants is less than five, the number of participants and the median/minimum/maximum number of work contacts are displayed as *. No suppression is applied to model outputs.

To summarise the results for the main work-related variables of interest:

- Number of contacts was not statistically significantly associated with site or employment (i.e., employed by company or a contractor) (Table 1).
- Working shifts (compared to days) and having managerial/supervisory responsibility was associated with higher contact rates (Table 1 and Table 2)
- Working mainly on plant was statistically significantly associated with higher contact rates in the unadjusted analysis (Table 1) but adjustment for other variables, particularly other work-related variables, removed this association (Table 1 and NS in multivariable model). This suggests the initial association between working on a plant and contact rate was due differences in other work-related factors.
- For employees, there were statistically significant differences in contact rates between jobs, particularly when other work-related factors such as working shifts and managerial/supervisory responsibility were taken into account (Table 2). Using engineers as the reference group (since this was the group with the most people): environmental safety technicians, people working in maintenance (DART/TAG), people working in the nuclear safety group and those who responded ‘prefer not to say’ had higher contacts rates than engineers.

For the other variables:

- Age was statistically significantly associated with number of contacts, with those aged 55+ having higher contact rates than those aged <30 (Table 2 , model 1). However, this was not statistically significant when looking at employees only (Table 2 model 2).

- People with family vulnerable to Covid-19 had higher contact rates than those without (Table 1).

Within team and outside team contacts

The median number of contacts within a participant's team was 3 (range 0-60), and the median number of contacts outside their team was 2 (range 0-50). A Wilcoxon signed-rank test suggested this difference was of borderline statistical significance (p=0.056). Figure 1 shows a scatterplot of the contacts within a team and contacts outside the team; there was moderate correlation between these two values (Spearman's rho = 0.57)

The adjusted analysis presented in Table 1 was repeated separately for contacts within the team, and contacts outside the team. For simplicity, the analysis was restricted to the work-related variables of interest. Table 3 shows the results for contacts within team, and Table 5 shows the results for contacts outside the team. Care should be taken when comparing results across the two tables due to the large confidence intervals – e.g., a factor can be statistically significant for one and not the other, even if the coefficients themselves are not statistically significantly different. The best example of this is employment by the company. This variable is significantly associated with contacts within the team (p=0.049, Table 3) but not contacts outside the team (p=0.540, Table 5). However, when you test the CRRs across the two models, you find that the CRRs are not statistically significantly different (1.39 vs 1.15, p=0.270).

Table 4 and Table 6 show the multivariable models for contacts within team and contacts outside team respectively.

- To summarise the results for contacts within the team (Table 3 and Table 4 Number of contacts within team was not statistically significantly associated with site or employment type.

- Working shifts (compared to days) and having managerial/supervisory responsibility was associated with higher contact rates.

- Employment (i.e., employed by company or a contractor) and working mainly on plant was statistically significantly associated with higher contact rates in the minimally adjusted analysis (Table 3), but adjustment for other work-related variables removed these associations (NS in multivariable model). This suggests the initial association between working on a plant and contact rate was probably due differences in other work-related factors.

- For employees, there were statistically significant differences in contact rates between jobs. When adjusting for work-related factors and using engineers as the reference group (since this was the group with the most people): environmental safety technicians and those who responded ‘prefer not to say’ had higher contacts rates than engineers (Table 4).

To summarise the results for contacts <u>outside</u> the team (Table 5 and Table 6):

- Number of contacts outside team was not statistically significantly associated with site, whether they were employed by the company, working pattern or main area of work.
- Having managerial/supervisory responsibility was associated with higher contact rates.
- Working part time rather than full time was associated with contact rates in the minimally adjusted analysis (Table 5), but not when adjusted for other work-related variables (NS in multivariable model).
- For employees, there were statistically significant differences between jobs, particularly when adjusted for managerial responsibilities. When adjusted for work-related factors (i.e., managerial responsibilities) and using engineers as the reference group (since this was the group with the most people): people in the nuclear safety group and those who responded ‘prefer not to say’ had higher contacts rates than engineers (Table 6).

Table 1 Total number of work contacts in a day and contact rate ratios (CRRs) by questionnaire variables

		Participants	Number of work contacts		Unadjusted				Adjusted for age, site and time period of completion			
			Median	Min, Max	CRR	(95%CI)	CRR p-value	Variable p-value [a]	CRR	(95%CI)	CRR p-value	Variable p-value [a]
Total		206	7	0, 90								
Main variables of interest												
Site	Site 1	104	6.5	0, 60	1.00	Ref		0.347	1.00	Ref		0.609
	Site 2	100	7	0, 90	1.28	(0.95-1.73)	0.100		1.23	(0.87-1.73)	0.242	
	Both	*	*	*	0.67	(0.08-6.04)	0.724		0.56	(0.07-4.77)	0.595	
	Other	*	*	*	0.56	(0.06-5.18)	0.611		0.82	(0.09-7.27)	0.857	
Employed by the company	No	56	6	0, 60	1.00	Ref		NA	1.00	Ref		NA
	Yes	146	7	0, 90	1.22	(0.87-1.71)	0.250		1.28	(0.90-1.81)	0.173	
	Missing	*	*	*								
Work pattern	Days	186	6	0, 66	1.00	Ref		NA	1.00	Ref		NA
	Shifts	20	12	0, 90	1.86	(1.14-3.02)	0.013		1.80	(1.12-2.91)	0.016	
Main place of work - office	Not reported	30	10	0, 32	1.00	Ref			1.00	Ref		
	Yes	176	6	0, 90	0.78	(0.52-1.19)	0.251		0.84	(0.55-1.27)	0.404	
Main place of work - plant	Not reported	149	6	0, 66	1.00	Ref			1.00	Ref		
	Yes	57	9	0, 90	1.43	(1.03-1.99)	0.032		1.37	(0.99-1.91)	0.057	
Main place of work - Outdoors	Not reported	202	7	0, 90	1.00	Ref			1.00	Ref		
	Yes	*	*	*	0.76	(0.25-2.28)	0.629		0.94	(0.32-2.79)	0.910	
Job (for those employed by company)	Chemistry	6	8	0, 20	1.06	(0.44-2.54)	0.893	0.173	1.27	(0.53-3.08)	0.591	0.285
	Engineers	31	6	0, 29	1.00	Ref			1.00	Ref		
	Environmental Safety Engineer	*	*	*	0.37	(0.04-3.27)	0.370		0.88	(0.10-7.81)	0.911	

	Participants	Number of work contacts		Unadjusted				Adjusted for age, site and time period of completion			
		Median	Min, Max	CRR	(95%CI)	CRR p-value	Variable p-value [a]	CRR	(95%CI)	CRR p-value	Variable p-value [a]
Environmental safety technician	7	18	1, 32	1.82	(0.82-4.06)	0.143		1.42	(0.62-3.24)	0.410	
Finance and Supply chain	12	3.5	0, 51	1.32	(0.68-2.55)	0.413		1.10	(0.57-2.13)	0.772	
Fuel route – engineering / planning	5	3	0, 23	0.76	(0.29-1.99)	0.575		0.71	(0.27-1.83)	0.478	
Human resources	*	*	*	0.74	(0.22-2.46)	0.618		0.56	(0.17-1.82)	0.334	
Independent assurance	*	*	*	1.47	(0.21-10.4)	0.699		2.04	(0.30-13.9)	0.468	
Maintenance (DART/ TAG)	8	8.5	0, 66	2.36	(1.11-5.02)	0.026		2.06	(0.96-4.43)	0.064	
Nuclear safety group	5	10	4, 35	1.62	(0.64-4.08)	0.309		1.76	(0.67-4.63)	0.254	
Operate technician	5	9	6, 13	1.15	(0.45-2.94)	0.768		1.29	(0.50-3.30)	0.595	
Operations	13	10	0, 90	2.32	(1.23-4.36)	0.009		2.07	(1.11-3.86)	0.022	
Outage	5	3	3, 5	0.44	(0.16-1.21)	0.111		0.40	(0.15-1.08)	0.071	
Performance improvement and training	20	6	0, 40	1.02	(0.58-1.79)	0.936		1.02	(0.57-1.83)	0.938	
Prefer not to say	*	*	*	3.55	(0.90-14.0)	0.070		3.91	(1.02-15.0)	0.047	

		Participants	Number of work contacts		Unadjusted				Adjusted for age, site and time period of completion			
			Median	**Min, Max**	**CRR**	**(95%CI)**	**CRR p-value**	**Variable p-value [a]**	**CRR**	**(95%CI)**	**CRR p-value**	**Variable p-value [a]**
	Quality Management	*	*	*	1.23	(0.30-5.05)	0.778		1.02	(0.25-4.13)	0.979	
	Safety & Quality	*	*	*	1.72	(0.25-12.0)	0.586		1.60	(0.25-10.4)	0.623	
	Security	*	*	*	1.63	(0.51-5.21)	0.407		1.20	(0.38-3.74)	0.758	
	Station leaders / executive	*	*	*	0.83	(0.29-2.37)	0.724		1.06	(0.33-3.46)	0.922	
	Work management	8	8	1, 16	0.95	(0.44-2.07)	0.897		0.96	(0.44-2.10)	0.912	
	process oversight	*	*	*								
	NA [b]	56	6	0, 60								
	Missing	7	10	0, 25								
Other variables												
Time period of completion	Period 1 (22/07-31/07)	154	7.5	0, 90	1.00	Ref		NA	1.00	Ref		
	Period 2 (01/08-11/08)	52	6	0, 60	0.76	(0.54-1.08)	0.122		0.88	(0.58-1.33)	0.544	
Age group	<30	27	5	0, 20	1.00	Ref		0.012	1.00	Ref		0.011
	30-44	71	9	0, 66	1.86	(1.16-3.00)	0.011		1.82	(1.12-2.97)	0.016	
	45-54	54	5	0, 50	1.19	(0.72-1.96)	0.493		1.18	(0.71-1.96)	0.529	

		Participants	Number of work contacts		Unadjusted				Adjusted for age, site and time period of completion			
			Median	Min, Max	CRR	(95%CI)	CRR p-value	Variable p-value [a]	CRR	(95%CI)	CRR p-value	Variable p-value [a]
	55+	50	8	0, 90	2.02	(1.22-3.33)	0.006		2.04	(1.23-3.36)	0.005	
	Prefer not to say	*	*	*	1.47	(0.48-4.50)	0.501		1.48	(0.48-4.51)	0.492	
Gender	Male	132	8	0, 90	1.00	Ref		0.355	1.00	Ref		0.666
	Female	68	6	0, 60	0.80	(0.58-1.10)	0.165		0.88	(0.64-1.21)	0.434	
	Other/Prefer not to say	6	9	4, 12	0.78	(0.32-1.91)	0.587		0.73	(0.22-2.46)	0.614	
Managerial responsibilities	No supervisory or managerial responsibility	117	5	0, 60	1.00	Ref		0.001	1.00	Ref		0.007
	Manager	13	10	1, 51	2.28	(1.26-4.13)	0.007		2.09	(1.13-3.86)	0.019	
	Supervisor (of plant or people)	63	10	0, 90	1.76	(1.28-2.43)	0.001		1.63	(1.18-2.27)	0.003	
	Prefer not to say	6	9.5	1, 16	1.26	(0.53-2.99)	0.606		1.61	(0.68-3.85)	0.280	
	Missing	7	10	0, 25								
Employment type	Full time employee	181	7	0, 90	1.00	Ref		0.150	1.00	Ref		0.074
	Part time employee	16	5	1, 32	0.62	(0.35-1.09)	0.094		0.55	(0.32-0.97)	0.040	
	Other	*	*	*	0.43	(0.09-2.12)	0.299		0.43	(0.09-2.05)	0.289	
	Missing	7	10	0, 25								

		Participants	Number of work contacts		Unadjusted				Adjusted for age, site and time period of completion			
			Median	Min, Max	CRR	(95%CI)	CRR p-value	Variable p-value [a]	CRR	(95%CI)	CRR p-value	Variable p-value [a]
Workplace measures - Site COVID hubs	Not reported	169	7	0, 90	1.00	Ref			1.00	Ref		
	Yes	37	8	0, 66	1.09	(0.74-1.61)	0.648		1.03	(0.70-1.52)	0.881	
Workplace measures - Hand sanitising stations	Not reported	96	7	0, 90	1.00	Ref			1.00	Ref		
	Yes	110	6.5	0, 60	0.89	(0.66-1.20)	0.450		0.89	(0.66-1.20)	0.440	
Workplace measures - Thermographic cameras	Not reported	189	7	0, 90	1.00	Ref			1.00	Ref		
	Yes	17	8	0, 24	0.84	(0.49-1.45)	0.528		0.76	(0.44-1.30)	0.318	
Workplace measures - Social distancing	Not reported	178	7	0, 90	1.00	Ref			1.00	Ref		
	Yes	28	7.5	0, 24	0.72	(0.47-1.12)	0.144		0.67	(0.43-1.04)	0.074	
Workplace measures - One way systems	Not reported	195	6	0, 90	1.00	Ref			1.00	Ref		
	Yes	11	9	0, 24	0.94	(0.48-1.83)	0.861		0.88	(0.46-1.68)	0.705	
Workplace measures - Enhanced cleaning regimes	Not reported	185	7	0, 90	1.00	Ref			1.00	Ref		
	Yes	21	6	0, 40	0.82	(0.50-1.35)	0.445		0.87	(0.53-1.43)	0.594	
Workplace measures - Travel/car sharing	Not reported	198	7	0, 90	1.00	Ref			1.00	Ref		
	Yes	8	9.5	0, 24	0.86	(0.40-1.87)	0.707		0.76	(0.36-1.61)	0.468	

		Participants	Number of work contacts		Unadjusted				Adjusted for age, site and time period of completion			
			Median	Min, Max	CRR	(95%CI)	CRR p-value	Variable p-value [a]	CRR	(95%CI)	CRR p-value	Variable p-value [a]
restrictions – at work												
Workplace measures - Travel/car sharing restrictions – to/from work	Not reported	197	7	0, 90	1.00	Ref			1.00	Ref		
	Yes	9	9	0, 24	0.86	(0.42-1.80)	0.696		0.83	(0.41-1.70)	0.613	
Workplace measures - Footfall/capacity restrictions	Not reported	195	7	0, 90	1.00	Ref			1.00	Ref		
	Yes	11	9	0, 24	0.91	(0.47-1.78)	0.791		0.88	(0.46-1.67)	0.687	
Workplace measures - Mess room arrangements	Not reported	195	6	0, 90	1.00	Ref			1.00	Ref		
	Yes	11	10	1, 24	1.05	(0.54-2.03)	0.892		0.96	(0.50-1.83)	0.902	
Workplace measures - Canteen restrictions	Not reported	197	7	0, 66	1.00	Ref			1.00	Ref		
	Yes	9	12	0, 90	2.02	(1.00-4.10)	0.051		1.68	(0.83-3.40)	0.148	
Workplace measures - Staggered start/finish times	Not reported	199	7	0, 90	1.00	Red			1.00	Ref		
	Yes	7	12	1, 24	1.21	(0.54-2.74)	0.646		1.11	(0.50-2.46)	0.792	
	Not reported	200	7	0, 90	1.00	Ref			1.00	Ref		

		Participants	Number of work contacts		Unadjusted				Adjusted for age, site and time period of completion			
			Median	Min, Max	CRR	(95%CI)	CRR p-value	Variable p-value [a]	CRR	(95%CI)	CRR p-value	Variable p-value [a]
Workplace measures - Operational work bubbles	Yes	6	11	1, 24	1.16	(0.48-2.80)	0.740		1.01	(0.43-2.38)	0.975	
Workplace measures - Mask supply	Not reported	164	7.5	0, 90	1.00	Ref			1.00	Ref		
	Yes	42	6	0, 66	0.93	(0.64-1.34)	0.688		0.88	(0.60-1.27)	0.485	
Workplace measures - Encouraging and tracking vaccination status	Not reported	152	7	0, 90	1.00	Ref			1.00	Ref		
	Yes	54	6	0, 66	1.03	(0.74-1.45)	0.855		1.00	(0.72-1.40)	0.993	
Workplace measures - HVAC complete air extraction	Not reported	202	7	0, 90	1.00	Ref			1.00	Ref		
	Yes	*	*	*	1.04	(0.35-3.06)	0.942		0.90	(0.31-2.58)	0.847	
Workplace measures - Increasing ventilation through open doors/windows where possible	Not reported	169	7	0, 90	1.00	Ref			1.00	Ref		
	Yes	37	9	0, 40	0.87	(0.59-1.29)	0.497		0.80	(0.54-1.17)	0.243	
Workplace measures - IT	Not reported	126	7	0, 90	1.00	Ref			1.00	Ref		
	Yes	80	6.5	0, 66	0.97	(0.72-1.32)	0.858		0.87	(0.64-1.18)	0.363	

		Participants	Number of work contacts		Unadjusted				Adjusted for age, site and time period of completion			
			Median	Min, Max	CRR	(95%CI)	CRR p-value	Variable p-value [a]	CRR	(95%CI)	CRR p-value	Variable p-value [a]
enabled meetings (Skype)												
Workplace measures - Pandemic response plan (already in place)	Not reported	147	7	0, 90	1.00	Ref			1.00	Ref		
	Yes	59	6	0, 66	1.11	(0.80-1.54)	0.543		0.96	(0.69-1.34)	0.820	
Workplace measures - Track and trace arrangements	Not reported	178	6.5	0, 66	1.00	Ref			1.00	Ref		
	Yes	28	8.5	0, 90	1.49	(0.97-2.28)	0.069		1.19	(0.77-1.84)	0.424	
Workplace measures - Work from home	Not reported	133	8	0, 90	1.00	Ref			1.00	Ref		
	Yes	73	6	0, 66	0.84	(0.61-1.15)	0.270		0.77	(0.55-1.08)	0.125	
Workplace measures - Covid testing, e.g., lateral flow tests	Not reported	159	7	0, 90	1.00	Ref			1.00	Ref		
	Yes	47	6	0, 66	1.08	(0.76-1.54)	0.674		1.14	(0.79-1.63)	0.484	
Workplace measures - Other measures	Not reported	205	7	0, 90	1.00	Ref			1.00	Ref		
	Yes	*	*	*	2.49	(0.31-20.1)	0.390		2.48	(0.33-18.8)	0.381	
	Never	179	7	0, 90	1.00	Ref		0.290	1.00	Ref		0.130

		Participants	Number of work contacts		Unadjusted				Adjusted for age, site and time period of completion			
			Median	Min, Max	CRR	(95%CI)	CRR p-value	Variable p-value [a]	CRR	(95%CI)	CRR p-value	Variable p-value [a]
Use face covering when <2 m from colleagues	Occasionally	15	8	0, 26	0.89	(0.50-1.57)	0.689		0.79	(0.44-1.42)	0.433	
	About half the time	*	10	*	0.80	(0.23-2.74)	0.716		0.96	(0.28-3.34)	0.952	
	Most/all of the time	8	2	0, 12	0.47	(0.21-1.03)	0.059		0.40	(0.19-0.88)	0.023	
	Missing	*	*	*								
Use face covering generally on site	Never	176	6	0, 90	1.00	Ref		0.173	1.00	Ref		0.205
	Occasionally	14	11	0, 40	1.47	(0.82-2.66)	0.199		1.34	(0.75-2.37)	0.319	
	About half the time or more	6	3	0, 13	0.54	(0.21-1.36)	0.193		0.52	(0.21-1.29)	0.156	
	Missing	10	11	1, 22								
Told to shield during pandemic	No	196	7	0, 90	1.00	Ref			1.00	Ref		
	Yes	10	5.5	0, 12	0.61	(0.30-1.24)	0.174		0.81	(0.40-1.64)	0.558	
Vaccination status	No - refused	8	8.5	4, 24	1.00	Ref		0.405	1.00	Ref		0.257
	Yes - one dose	*	*	*	0.52	(0.05-5.36)	0.582		0.63	(0.07-6.13)	0.694	
	Yes - two doses	32	5	0, 40	0.78	(0.34-1.82)	0.568		0.62	(0.27-1.42)	0.256	
	Yes - >2 doses	162	7	0, 90	1.12	(0.52-2.41)	0.780		0.95	(0.45-2.03)	0.899	
	Prefer not to say	*	*	*	0.59	(0.14-2.56)	0.480		0.51	(0.12-2.20)	0.369	
	No	120	7	0, 60	1.00	Ref			1.00	Ref		

		Participants	Number of work contacts		Unadjusted				Adjusted for age, site and time period of completion			
			Median	Min, Max	CRR	(95%CI)	CRR p-value	Variable p-value [a]	CRR	(95%CI)	CRR p-value	Variable p-value [a]
Family vulnerable to Covid-19	Yes	86	7	0, 90	1.44	(1.07-1.95)	0.015		1.41	(1.04-1.91)	0.029	
Likely to catch Covid-19	Not at all likely	7	8	0, 29	1.00	Ref		0.896	1.00	Ref		0.774
	Not very likely	20	6.5	0, 30	0.89	(0.35-2.25)	0.800		0.86	(0.35-2.15)	0.750	
	Neither likely nor unlikely	42	5.5	0, 66	0.85	(0.36-2.02)	0.710		0.82	(0.35-1.91)	0.648	
	Somewhat likely	88	6.5	0, 90	0.89	(0.39-2.05)	0.787		0.81	(0.36-1.82)	0.604	
	Very likely	30	10	0, 50	1.17	(0.48-2.85)	0.725		1.16	(0.48-2.81)	0.735	
	Don't know	17	3	0, 51	0.79	(0.30-2.04)	0.621		0.73	(0.28-1.89)	0.516	
	Prefer not to say	*	*	*	0.86	(0.16-4.76)	0.866		1.04	(0.20-5.51)	0.962	
Had Covid-19	No	37	7	0, 35	1.00	Ref		0.439	1.00	Ref		0.624
	Yes	152	6.5	0, 90	1.24	(0.84-1.84)	0.273		1.21	(0.82-1.80)	0.333	
	Unsure	16	9.5	0, 40	1.44	(0.76-2.70)	0.260		1.19	(0.64-2.22)	0.588	
	Missing	*	*	*								

NA, not applicable; CRR, contact rate ratio estimated using separate negative binomial regression models; 95%CI, 95% confidence interval; Ref, reference category for variable.

[a] Joint Wald test for categorical variables with more than two categories. NA for variables with just two categories.

[b] NA, not employed by company

* small number suppression applied

Table 2 Multivariable negative binomial models for the total number of contacts reported by 1) all workers and 2) employees only

		1) All workers (N=199 [a])				2) Employees only (N=142 [a])			
		CRR	**(95%CI)**	**CRR p-value**	**Variable p-value [b]**	**CRR**	**(95%CI)**	**CRR p-value**	**Variable p-value [b]**
Age group	<30	1.00	Ref		0.035	1.00	Ref		0.420
	30-44	1.39	(0.85-2.26)	0.188		1.08	(0.60-1.97)	0.792	
	45-54	0.94	(0.57-1.55)	0.796		0.91	(0.48-1.71)	0.773	
	55+	1.73	(1.05-2.85)	0.032		1.38	(0.71-2.68)	0.342	
	Prefer not to say	1.15	(0.39-3.42)	0.798		0.58	(0.17-1.99)	0.383	
Time period of completion	Period 1 (22/07-31/07)	1.00	Ref			1.00	Ref		
	Period 2 (01/08-11/08)	0.97	(0.65-1.46)	0.898		0.77	(0.48-1.25)	0.294	
Site	Site 1	1.00	Ref		0.555	1.00	Ref		0.783
	Site 2	1.24	(0.88-1.75)	0.216		1.23	(0.83-1.83)	0.302	
	Both	0.85	(0.11-6.67)	0.879		1.21	(0.20-7.32)	0.832	
	Other	0.48	(0.05-4.23)	0.508		0.92	(0.12-7.01)	0.937	
Work pattern	Days	1.00	Ref			1.00	Ref		
	Shifts	1.79	(1.12-2.88)	0.016		2.92	(1.37-6.23)	0.005	
Managerial responsibilities	No supervisory or managerial responsibility	1.00	Ref		0.008	1.00	Ref		<0.001
	Manager	2.25	(1.23-4.13)	0.009		4.35	(2.16-8.78)	<0.001	
	Supervisor (of plant or people)	1.55	(1.12-2.14)	0.008		1.97	(1.37-2.83)	<0.001	
	Prefer not to say	1.45	(0.61-3.45)	0.398		1.61	(0.66-3.92)	0.292	
Job (for those employed by company)	Chemistry					1.61	(0.71-3.63)	0.252	0.011
	Engineers					1.00	Ref		
	Environmental Safety Engineer					0.85	(0.12-6.25)	0.874	
	Environmental safety technician					2.25	(1.06-4.77)	0.034	
	Finance and Supply chain					0.81	(0.44-1.50)	0.496	
	Fuel route – engineering / planning					0.40	(0.16-1.01)	0.053	
	Human resources					0.94	(0.32-2.78)	0.917	

	1) All workers (N=199 [a])				2) Employees only (N=142 [a])			
	CRR	**(95%CI)**	**CRR p-value**	**Variable p-value [b]**	**CRR**	**(95%CI)**	**CRR p-value**	**Variable p-value [b]**
Independent assurance					1.59	(0.29-8.84)	0.595	
Maintenance (DART/ TAG)					2.17	(1.09-4.30)	0.027	
Nuclear safety group					2.66	(1.12-6.34)	0.027	
Operate technician					0.66	(0.22-1.97)	0.457	
Operations					0.85	(0.37-1.94)	0.703	
Outage					0.47	(0.18-1.20)	0.115	
Performance improvement and training					1.10	(0.64-1.87)	0.738	
Prefer not to say					6.16	(1.84-20.6)	0.003	
Quality Management					1.09	(0.31-3.86)	0.892	
Safety & Quality					1.39	(0.26-7.35)	0.701	
Security					0.84	(0.30-2.40)	0.749	
Station leaders / executive					0.39	(0.11-1.36)	0.138	
Work management					1.22	(0.59-2.49)	0.592	

NA, not applicable; CRR, contact rate ratio estimated using a separate negative binomial regression models for all workers and employees, including all variables listed as independent variables; 95%CI, 95% confidence interval; Ref, reference category for variable.

[a] numbers differ from those presented in **Table 1** due to missing data.

[b] Joint Wald test for categorical variables with more than two categories. NA for other variables with just two categories.

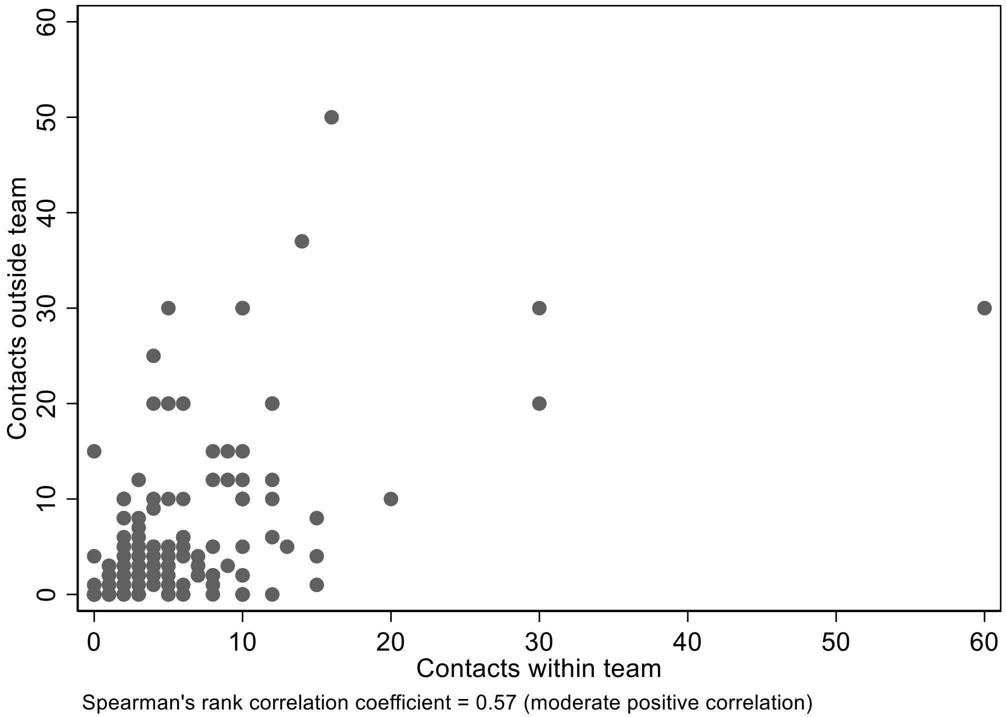

Figure 1 Scatterplot of the number of contacts within a participant's team and the number outside their team

Table 3 Number of work contacts <u>within</u> the participant's team in a day and adjusted contact rate ratios (CRRs) for questionnaire variables of interest

		Participants	Number of work contacts within team		Adjusted for age, site and time period of completion			
			Median	Min, Max	CRR	(95%CI)	CRR p-value	Variable p-value [a]
Total		206	3	0, 60				
Main variables of interest								
Site	Site 1	104	3	0, 30	1.00	Ref		0.654
	Site 2	100	4	0, 60	1.20	(0.87-1.66)	0.267	
	Both	*	*	*	0.65	(0.08-5.14)	0.681	
	Other	*	*	*	1.41	(0.20-9.99)	0.729	
Employed by the company	No	56	3	0, 30	1.00	Ref		
	Yes	147	4	0, 60	1.39	(1.00-1.94)	0.049	
	Missing	*	*	*				
Work pattern	Days	186	3	0, 30	1.00	Ref		
	Shifts	20	7.5	0, 60	2.04	(1.33-3.12)	0.001	
Main place of work - office	Not reported	30	6	0, 15	1.00	Ref		
	Yes	176	3	0, 60	0.72	(0.49-1.06)	0.100	
Main place of work - plant	Not reported	149	3	0, 30	1.00	Ref		
	Yes	57	5	0, 60	1.61	(1.19-2.18)	0.002	
Main place of work -	Not reported	202	3	0, 60	1.00	Ref		
	Yes	*	*	*	0.80	(0.28-2.26)	0.669	

		Participants	Number of work contacts within team		Adjusted for age, site and time period of completion			
			Median	Min, Max	CRR	(95%CI)	CRR p-value	Variable p-value [a]
Outdoors								
Job (for those employed by company)	Chemistry	6	4.5	0, 10	1.18	(0.54-2.60)	0.674	0.007
	Engineers	31	3	0, 12	1.00	Ref		
	Environmental Safety Engineer	*	*	*	0.92	(0.12-7.05)	0.939	
	Environmental safety technician	7	12	1, 15	2.15	(1.07-4.31)	0.031	
	Finance and Supply chain	12	2	0, 14	0.85	(0.47-1.54)	0.599	
	Fuel route – engineering / planning	5	3	0, 8	0.73	(0.30-1.76)	0.483	

	Participants	Number of work contacts within team		Adjusted for age, site and time period of completion			
		Median	Min, Max	CRR	(95%CI)	CRR p-value	Variable p-value [a]
Human resources	*	*	*	0.44	(0.13-1.42)	0.169	
Independent assurance	*	*	*	0.71	(0.10-5.29)	0.739	
Maintenance (DART/ TAG)	8	4	0, 16	1.46	(0.75-2.83)	0.265	
Nuclear safety group	5	5	2, 6	1.15	(0.49-2.70)	0.743	
Operate technician	5	6	3, 8	1.74	(0.78-3.89)	0.177	
Operations	13	7	0, 60	2.48	(1.46-4.21)	0.001	
Outage	5	2	1, 2	0.39	(0.15-1.02)	0.056	
Performance improvement and training	20	3.5	0, 13	1.20	(0.72-1.99)	0.479	

		Participants	Number of work contacts within team		Adjusted for age, site and time period of completion			
			Median	Min, Max	CRR	(95%CI)	CRR p-value	Variable p-value [a]
	Prefer not to say	*	*	*	4.55	(1.48-14.0)	0.008	
	Quality Management	*	*	*	1.30	(0.38-4.41)	0.679	
	Safety & Quality	*	*	*	0.84	(0.15-4.72)	0.840	
	Security	*	*	*	1.08	(0.40-2.91)	0.879	
	Station leaders / executive	*	*	*	1.63	(0.60-4.45)	0.341	
	Work management	8	4.5	1, 15	1.47	(0.75-2.87)	0.260	
	process oversight	*	*	*				
	NA [b]	56	3	0, 30				
	Missing	7	3	0, 10				
Other variables								
Managerial	No supervisory or	117	3	0, 30	1.00	Ref		0.034

		Participants	Number of work contacts within team		Adjusted for age, site and time period of completion			
			Median	Min, Max	CRR	(95%CI)	CRR p-value	Variable p-value [a]
responsibilities	managerial responsibility							
	Manager	13	5	1, 14	1.47	(0.83-2.61)	0.186	
	Supervisor (of plant or people)	63	4	0, 60	1.54	(1.14-2.08)	0.005	
	Prefer not to say	6	5	1, 8	1.44	(0.64-3.23)	0.375	
	Missing	7	3	0, 10				
Employment type	Full time employee	181	4	0, 60	1.00	Ref		0.110
	Part time employee	16	2.5	1, 12	0.60	(0.35-1.03)	0.064	
	Other	*	*	*	0.44	(0.10-2.01)	0.289	
	Missing	7	3	0, 10				

NA, not applicable; CRR, contact rate ratio estimated using separate negative binomial regression models; 95%CI, 95% confidence interval; Ref, reference category for variable.

[a] Joint Wald test for categorical variables with more than two categories. NA for variables with just two categories.

[b] NA, not employed by company

* small number suppression applied.

Table 4 Multivariable negative binomial models for the total number of contacts within the participant's team, reported by 1) all workers and 2) employees only

		1) All workers (N=199 [a])				2) Employees only (N=142 [a])			
		CRR	**(95%CI)**	**CRR p-value**	**Variable p-value [b]**	**CRR**	**(95%CI)**	**CRR p-value**	**Variable p-value [b]**
Age group	<30	1.00	Ref		0.103	1.00	Ref		0.463
	30-44	1.16	(0.74-1.82)	0.525		0.90	(0.53-1.54)	0.709	
	45-54	1.00	(0.63-1.60)	0.992		0.91	(0.51-1.62)	0.755	
	55+	1.62	(1.02-2.57)	0.043		1.15	(0.64-2.07)	0.642	
	Prefer not to say	1.14	(0.42-3.12)	0.793		0.45	(0.14-1.41)	0.171	
Time period of completion	Period 1 (22/07-31/07)	1.00	Ref			1.00	Ref		
	Period 2 (01/08-11/08)	0.97	(0.66-1.40)	0.852		0.81	(0.52-1.24)	0.323	
Site	Site 1	1.00	Ref		0.871	1.00	Ref		0.759
	Site 2	1.14	(0.83-1.57)	0.416		1.22	(0.85-1.75)	0.279	
	Both	0.88	(0.12-6.27)	0.894		1.20	(0.22-6.67)	0.833	
	Other	1.08	(0.16-7.33)	0.937		1.04	(0.18-5.87)	0.967	
Work pattern	Days	1.00	Ref			1.00	Ref		
	Shifts	1.96	(1.28-2.99)	0.002		2.76	(1.34-5.684)	0.006	
Managerial responsibilities	No supervisory or managerial responsibility	1.00	Ref		0.055	1.00	Ref		0.001
	Manager	1.62	(0.93-2.83)	0.091		2.54	(1.35-4.79)	0.004	
	Supervisor (of plant or people)	1.45	(1.08-1.95)	0.014		1.72	(1.24-2.37)	0.001	
	Prefer not to say	1.22	(0.55-2.71)	0.629		1.24	(0.56-2.74)	0.600	
Job (for those employed by company)	Chemistry					1.45	(0.69-3.06)	0.329	0.001
	Engineers					1.00	Ref		
	Environmental Safety Engineer					0.90	(0.13-6.11)	0.913	
	Environmental safety technician					2.78	(1.46-5.29)	0.002	
	Finance and Supply chain					0.76	(0.43-1.36)	0.359	
	Fuel route – engineering / planning					0.48	(0.20-1.15)	0.100	

	1) All workers (N=199 [a])				2) Employees only (N=142 [a])			
	CRR	**(95%CI)**	**CRR p-value**	**Variable p-value [b]**	**CRR**	**(95%CI)**	**CRR p-value**	**Variable p-value [b]**
Human resources					0.60	(0.19-1.84)	0.368	
Independent assurance					0.58	(0.09-3.87)	0.574	
Maintenance (DART/ TAG)					1.58	(0.85-2.93)	0.147	
Nuclear safety group					1.63	(0.73-3.64)	0.230	
Operate technician					0.86	(0.31-2.39)	0.773	
Operations					1.03	(0.48-2.23)	0.939	
Outage					0.44	(0.17-1.12)	0.086	
Performance improvement and training					1.33	(0.83-2.15)	0.240	
Prefer not to say					7.12	(2.50-20.3)	<0.001	
Quality Management					1.28	(0.41-3.99)	0.666	
Safety & Quality					0.76	(0.15-3.76)	0.735	
Security					0.68	(0.24-1.89)	0.456	
Station leaders / executive					0.93	(0.31-2.79)	0.903	
Work management					1.78	(0.95-3.33)	0.072	

NA, not applicable; CRR, contact rate ratio estimated using a separate negative binomial regression models for all workers and employees, including all variables listed as independent variables; 95%CI, 95% confidence interval; Ref, reference category for variable.

[a] numbers differ from those presented in **Table 1** due to missing data.

[b] Joint Wald test for categorical variables with more than two categories. NA for variables with just two categories.

Table 5 Number of work contacts <u>outside</u> the participant's team in a day and adjusted contact rate ratios (CRRs) for questionnaire variables of interest

		Participants	Number of work contacts outside team		Adjusted for age, site and time period of completion			
			Median	Min, Max	CRR	(95%CI)	CRR p-value	Variable p-value [a]
Total		206	2	0, 50				
Main variables of interest								
Site	Site 1	104	2	0, 30	1.00	Ref		0.741
	Site 2	100	2	0, 50	1.23	(0.80-1.91)	0.350	
	Both	*	*	*	0.48	(0.03-7.63)	0.606	
	Other	*	*	*	NA			
Employed by the company	No	56	2.5	0, 30	1.00	Ref		
	Yes	147	2	0, 50	1.15	(0.73-1.80)	0.540	
	Missing	*	*	*				
Work pattern	Days	186	2	0, 50	1.00	Ref		
	Shifts	20	5.5	0, 30	1.66	(0.88-3.12)	0.116	
Main place of work - office	Not reported	30	5	0, 20	1.00	Ref		
	Yes	176	2	0, 50	0.98	(0.57-1.69)	0.949	
Main place of work - plant	Not reported	149	2	0, 50	1.00	Ref		
	Yes	57	4	0, 30	1.21	(0.79-1.83)	0.379	
Main place of work - Outdoors	Not reported	202	2	0, 50	1.00	Ref		
	Yes	*	*	*	1.07	(0.27-4.29)	0.924	
Job (for those employed by company)	Chemistry	6	3.5	0, 10	1.44	(0.46-4.48)	0.530	0.290
	Engineers	31	2	0, 25	1.00	Ref		
	Environmental Safety Engineer	*	*	*	0.88	(0.04-18.8)	0.937	
	Environmental safety technician	7	4	0, 20	0.81	(0.27-2.39)	0.699	
	Finance and Supply chain	12	1.5	0, 37	1.33	(0.57-3.10)	0.506	
	Fuel route – engineering / planning	5	0	0, 15	0.62	(0.18-2.09)	0.439	
	Human resources	*	*	*	0.66	(0.15-2.88)	0.577	

		Participants	Number of work contacts outside team		Adjusted for age, site and time period of completion			
			Median	Min, Max	CRR	(95%CI)	CRR p-value	Variable p-value [a]
	Independent assurance	*	*	*	3.64	(0.33-39.8)	0.290	
	Maintenance (DART/ TAG)	8	2	0, 50	2.67	(1.00-7.09)	0.049	
	Nuclear safety group	5	6	0, 30	2.59	(0.73-9.13)	0.140	
	Operate technician	5	4	1, 6	0.74	(0.21-2.60)	0.639	
	Operations	13	5	0, 30	1.82	(0.82-4.02)	0.140	
	Outage	5	2	1, 3	0.44	(0.12-1.61)	0.216	
	Performance improvement and training	20	2	0, 30	0.83	(0.38-1.79)	0.632	
	Prefer not to say	*	*	*	3.59	(0.65-19.7)	0.141	
	Quality Management	*	*	*	0.79	(0.13-4.70)	0.798	
	Safety & Quality	*	*	*	2.73	(0.27-28.0)	0.398	
	Security	*	*	*	1.33	(0.31-5.77)	0.703	
	Station leaders / executive	*	*	*	0.63	(0.11-3.43)	0.591	
	Work management	8	2	0, 5	0.47	(0.16-1.39)	0.170	
	process oversight	*	*	*				
	NA [b]	56	2.5	0, 30				
	Missing	7	3	0, 20				
Other variables								
Managerial responsibilities	No supervisory or managerial responsibility	117	2	0, 30	1.00	Ref		0.016
	Manager	13	5	0, 37	2.67	(1.24-5.77)	0.012	
	Supervisor (of plant or people)	63	4	0, 50	1.69	(1.11-2.59)	0.015	
	Prefer not to say	6	4.5	0, 10	1.85	(0.61-5.61)	0.280	
	Missing	7	3	0, 20				
Employment type	Full time employee	181	2	0, 50	1.00	Ref		0.105
	Part time employee	16	1.5	0, 20	0.49	(0.24-0.99)	0.048	
	Other	*	*	*	0.42	(0.05-3.21)	0.400	
	Missing	7	3	0, 20				

NA, not applicable; CRR, contact rate ratio estimated using separate negative binomial regression models; 95%CI, 95% confidence interval; Ref, reference category for variable.
[a] Joint Wald test for categorical variables with more than two categories. NA for other variables.
[b] NA, not employed by company
* small number suppression applied.

Table 6 Multivariable negative binomial models for the total number of contacts outside the participant's team, reported by 1) all workers and 2) employees only

		1) **All workers (N=199 [a])**				2) **Employees only (N=142 [a])**			
		CRR	**(95%CI)**	**CRR p-value**	**Variable p-value [a]**	**CRR**	**(95%CI)**	**CRR p-value**	**Variable p-value [a]**
Age group	<30	1.00	Ref		0.028	1.00	Ref		0.343
	30-44	1.73	(0.92-3.25)	0.091		1.83	(0.82-4.08)	0.140	
	45-54	0.89	(0.46-1.73)	0.737		1.25	(0.54-2.88)	0.601	
	55+	1.89	(0.99-3.63)	0.055		2.20	(0.89-5.43)	0.088	
	Prefer not to say	1.49	(0.37-5.99)	0.571		1.70	(0.37-7.80)	0.492	
Time period of completion	Period 1 (22/07-31/07)	1.00	Ref			1.00	Ref		
	Period 2 (01/08-11/08)	0.88	(0.52-1.49)	0.627		0.51	(0.27-0.98)	0.044	
Site	Site 1	1.00	Ref		0.728	1.00	Ref		0.999
	Site 2	1.28	(0.82-2.00)	0.274		0.99	(0.59-1.67)	0.978	
	Both	0.74	(0.05-10.7)	0.827		0.82	(0.08-8.88)	0.873	
	Other	NA				NA			
Managerial responsibilities	No supervisory or managerial responsibility	1.00	Ref		0.016	1.00	Ref		0.001
	Manager	2.67	(1.24-5.77)	0.012		5.77	(2.29-14.5)	<0.001	
	Supervisor (of plant or people)	1.69	(1.11-2.59)	0.015		2.09	(1.28-3.41)	0.003	
	Prefer not to say	1.85	(0.61-5.61)	0.280		1.40	(0.45-4.41)	0.563	
Job (for those employed by company)	Chemistry					1.85	(0.62-5.54)	0.272	0.044
	Engineers					1.00	Ref		
	Environmental Safety Engineer					0.98	(0.05-17.8)	0.988	
	Environmental safety technician					1.27	(0.45-3.56)	0.647	
	Finance and Supply chain					0.75	(0.33-1.70)	0.486	

	Fuel route – engineering / planning	0.56	(0.18-1.75)	0.318
	Human resources	0.97	(0.24-3.89)	0.967
	Independent assurance	2.56	(0.28-23.3)	0.404
	Maintenance (DART/ TAG)	2.50	(1.00-6.26)	0.051
	Nuclear safety group	3.58	(1.11-11.6)	0.033
	Operate technician	1.07	(0.33-3.51)	0.905
	Operations	1.75	(0.81-3.74)	0.152
	Outage	0.40	(0.11-1.43)	0.159
	Performance improvement and training	0.71	(0.33-1.50)	0.369
	Prefer not to say	4.67	(0.97-22.5)	0.055
	Quality Management	0.76	(0.14-3.97)	0.741
	Safety & Quality	1.94	(0.23-16.6)	0.546
	Security	1.24	(0.32-4.76)	0.753
	Station leaders / executive	0.15	(0.02-0.93)	0.041
	Work management	0.55	(0.19-1.55)	0.258

NA, not applicable; CRR, contact rate ratio estimated using a separate negative binomial regression models for all workers and employees, including all variables listed as independent variables; 95%CI, 95% confidence interval; Ref, reference category for variable.

[a] numbers differ from those presented in **Table 1** due to missing data.

[b] Joint Wald test for categorical variables with more than two categories. NA for other variables.

Appendix 5: Supplementary analyses and figures from Section 4

The analysis of the instantaneous growth rate for the whole population does not show substantially different results compared to using the adult population only, as illustrated below (Figure 4.11 and 4.12). In the pre-vaccination period, the smoothed curves for the community reported cases at the three geographical scale seem in better agreement than in Figure 4.6, and the relative difference between the peak in the power plant and in the community (large scale) is even more evident in Figure 4.12.

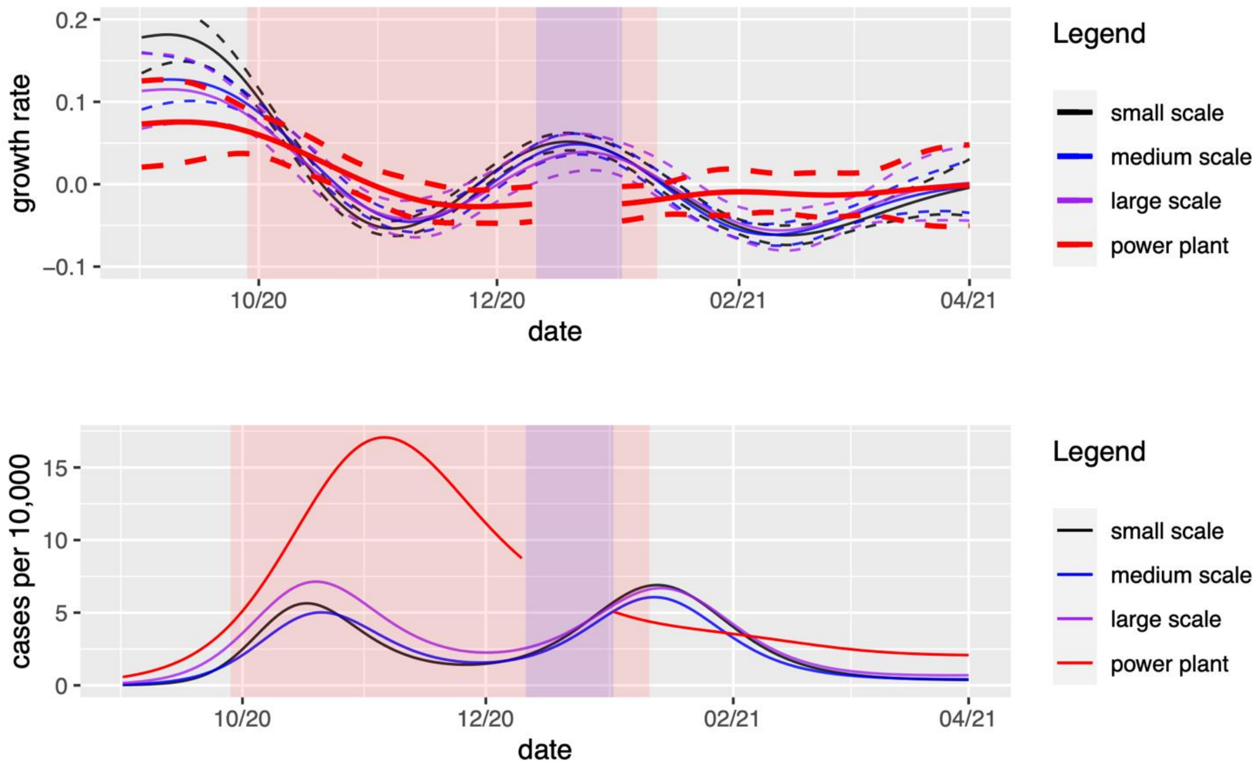

Figure 4.11: Estimated growth rate and smoothed incidence curve, pre-vaccination period (from 01/09/2020 to 31/03/2021), for the whole population. Instantaneous growth rate estimated via GAM with day-of-the-week effect, for the power plant (red) and the local community at three geographical scales (small/medium/large community). Continuous lines represent the mean estimate, dashed lines the 95% confidence intervals.

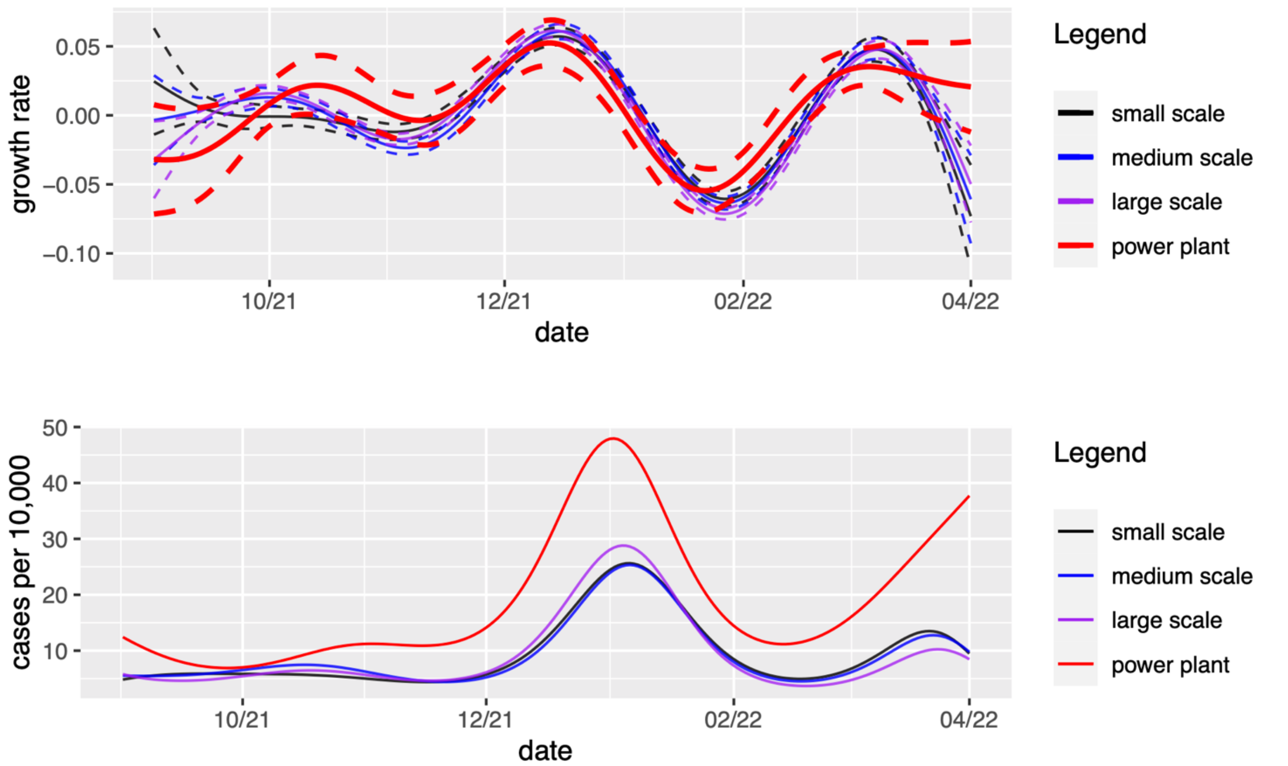

Figure 4.12: Estimated growth rate and smoothed incidence curve, post-vaccination period (from 01/09/2021 to 31/03/2022), for the whole population. Instantaneous growth rate estimated via GAM with day-of-the-week effect, for the power plant (red) and the local community at three geographical scales (small/medium/large community). Continuous lines represent the mean estimate, dashed lines the 95% confidence intervals.

Finally, the ABM simulations of workplace infections and reported cases strongly depend on the assumed community under-reporting factor: Table 4.5 shows that, assuming a lower under-reporting factor, both the modelled infections and detected cases are substantially lower than what observed in Table 4.2 and what reported in the database.

Table 4.5: Same as Table 4.2, with different hypotheses: introductions are modelled assuming a community under-reporting factor of 1, and no delay between symptoms and diagnosis and tracing of contacts. For the investigated parameter range, the model returns a substantially lower number of reported cases as the realised.

	Workplace reproduction number														
Fraction of detected cases	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
0.1	-95% (+20)	-94% (+42)	-93% (+73)	-93% (+102)	-92% (+138)	-91% (+185)	-89% (+230)	-88% (+297)	-87% (+362)	-85% (+423)	-83% (+518)	-82% (+581)	-79% (+658)	-78% (+718)	-77% (+788)
0.2	-89% (+18)	-88% (+40)	-87% (+62)	-85% (+91)	-84% (+124)	-82% (+168)	-80% (+203)	-77% (+259)	-75% (+309)	-72% (+380)	-69% (+434)	-67% (+499)	-62% (+586)	-58% (+649)	-56% (+708)
0.3	-83% (+17)	-82% (+35)	-80% (+56)	-79% (+79)	-76% (+109)	-74% (+141)	-71% (+183)	-68% (+225)	-65% (+272)	-61% (+315)	-56% (+384)	-52% (+433)	-48% (+500)	-42% (+571)	-38% (+629)
0.4	-78% (+15)	-76% (+32)	-74% (+52)	-71% (+75)	-69% (+97)	-67% (+126)	-63% (+158)	-60% (+189)	-57% (+224)	-52% (+271)	-47% (+322)	-43% (+364)	-37% (+419)	-32% (+478)	-26% (+533)
0.5	-72% (+13)	-70% (+27)	-68% (+47)	-66% (+63)	-63% (+87)	-60% (+103)	-57% (+133)	-53% (+163)	-49% (+193)	-46% (+225)	-41% (+267)	-36% (+304)	-30% (+352)	-24% (+397)	-18% (+449)
0.6	-66% (+12)	-65% (+24)	-62% (+40)	-60% (+53)	-57% (+77)	-54% (+94)	-52% (+112)	-48% (+132)	-45% (+158)	-40% (+184)	-35% (+218)	-30% (+251)	-26% (+279)	-21% (+317)	-16% (+350)
0.7	-61% (+10)	-59% (+22)	-57% (+35)	-54% (+47)	-52% (+62)	-50% (+75)	-46% (+95)	-43% (+108)	-40% (+130)	-37% (+150)	-32% (+176)	-29% (+189)	-24% (+220)	-19% (+251)	-14% (+280)
0.8	-56% (+9)	-54% (+19)	-52% (+28)	-49% (+40)	-47% (+51)	-45% (+62)	-42% (+76)	-39% (+91)	-37% (+105)	-34% (+116)	-30% (+136)	-27% (+152)	-24% (+167)	-19% (+197)	-16% (+209)
0.9	-51% (+7)	-49% (+16)	-46% (+23)	-45% (+31)	-43% (+43)	-41% (+51)	-39% (+60)	-36% (+74)	-34% (+81)	-32% (+91)	-28% (+106)	-26% (+118)	-23% (+128)	-20% (+142)	-17% (+160)
1	-45% (+5)	-43% (+14)	-42% (+19)	-41% (+25)	-39% (+31)	-37% (+39)	-36% (+46)	-34% (+52)	-31% (+65)	-30% (+68)	-28% (+80)	-25% (+88)	-23% (+97)	-21% (+106)	-20% (+112)

The PROTECT COVID-19 National Core Study on transmission and environment is a UK-wide research programme improving our understanding of how SARS-CoV-2 (the virus that causes COVID-19) is transmitted from person to person, and how this varies in different settings and environments. This improved understanding is enabling more effective measures to reduce transmission – saving lives and getting society back towards 'normal'.

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