NERA
ECONOMIC CONSULTING

Infection Resilient Environments Social Cost Benefit Analysis

Royal Academy of Engineering

June 2022

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Executive Summary

NERA Economic Consulting ("NERA", "we") were commissioned by the Royal Academy of Engineering (RAEng) to develop a social cost benefit analysis (SCBA) for infection resilience across building environments in the UK. Our work was carried out under the terms of our contract with RAEng dated 23 December 2021.

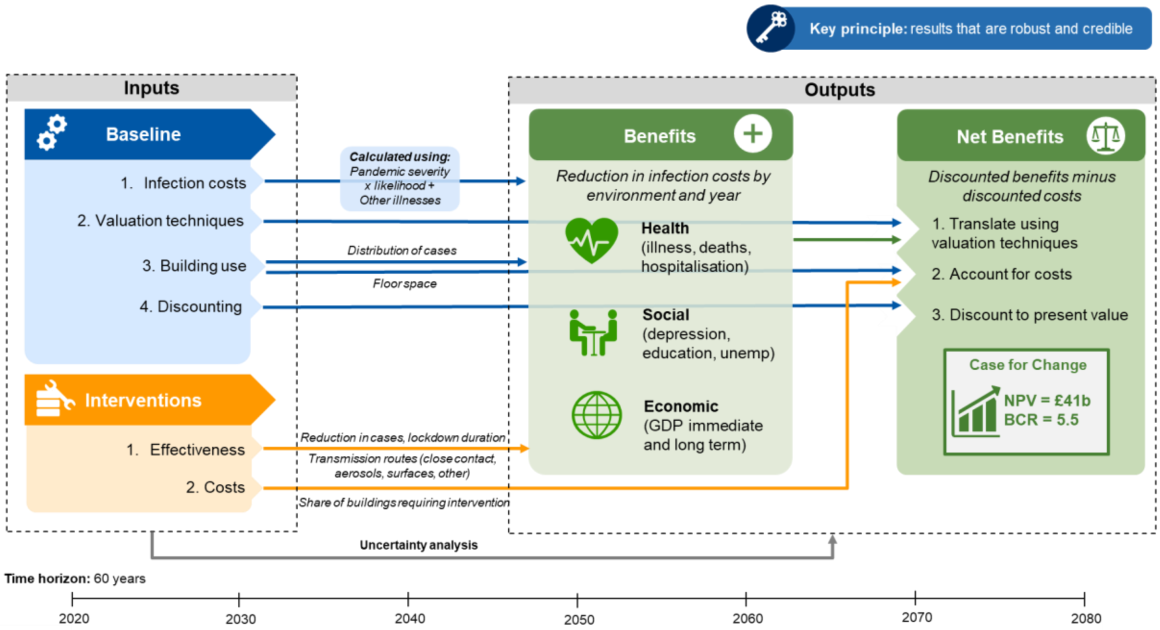
Our objectives were to:

- Consider the widest possible range of social and economic costs from infection, thereby enabling a holistic analysis of infection resilience (minimizing disease transmission).
- Appraise the potential impact of a range of interventions for UK building environments, i.e. ways in which building environments could be improved to reduce the transmission of known endemic and pandemic diseases.
- Do the above in a robust and transparent way that can be developed further in the future, and that takes into account the inherently high level of uncertainty in the analysis.

As part of our work, we:

- Held regular meetings with the RAEng "working group" comprised of Dr. Alexandra Smyth, Jennifer Ward-George, Shema Bhujel, and Dr. Nick Starkey.
- Held meetings with members of an expert steering group (comprised of Frank Mills, Edith Blennerhassett, Hywel Davies, and Prof. Marcella Ucci).
- Held bilateral meetings with experts in ventilation and infection transmission (Prof. Catherine Noakes, Prof. Andrew Curran, Dr. Yiqun Chen, and Dr. Martie Van Tongeren), and costing building construction (Colin Goodwin).
- Carried out a literature review into (1) the impacts of influenza-type pandemics and seasonal influenza, (2) valuation approaches that could be used to monetise these impacts, (3) the effectiveness of ventilation, and (4) the costs of ventilation.
- Developed a flexible approach and modelling tool (see Figure 1) that allows us to estimate the net present value of improving ventilation in commercial, industrial, local, and residential buildings at an aggregate level. The methodology is aligned with guidance set-out in the Green Book (HMT, 2020) and our modelling assumptions are based on what seems to us to be the best available information on infection costs, effectiveness, and implementation costs for the UK.
- Developed a transmission model to estimate (at a high level and in simple terms) the distribution of infections over different environments, based on the four major factors that determine transmission: frequency, duration, density, and risk.
- Developed a cost model to estimate the installation, operation, and maintenance costs per square meter of various types of ventilation.
- Received reviews on an earlier draft of the report from experts in ventilation and infection transmission (Prof. Catherine Noakes and Prof. Andrew Curran) and an expert in economics and cost benefit analysis (Prof. Anthony Venables).

Figure 1: Approach overview



Source: NERA illustration.

Our key findings are that:

- The total societal costs of infection (health, social, and economic) are large and wide reaching. We estimate that the annual discounted expected cost of influenza type infection (pandemic and seasonal) in the UK is about £23 billion (or 1% of GDP in 2020) over a 60-year period, with influenza-type pandemics accounting for 64% of these costs. We also estimate that the total undiscounted societal costs of a severe influenza-type pandemic in 2020 would be about £1.3 trillion (or 60% GDP). This is the first study, to our knowledge, to perform a comprehensive evaluation of health, social, and economic costs of pandemic and seasonal influenza. Our key assumption is that disease incidence, behaviour, and the share of environments that require improved interventions remain largely similar in the future. We therefore account for recent advances in technology such as vaccination availability and efficacy, but we do not account for potential future (unknown) advances in technology and significant behavioural changes.
- We find that influenza-type pandemic costs are distributed as follows: 27% health (e.g., severe illness, long-term illness, and death), 26% social (e.g., depression and lost education), and 48% economic (e.g., healthcare costs and reduction in GDP) while seasonal influenza is 58%, 10%, and 31%, respectively. We expect that the economic costs of pandemics that we estimate are relatively high compared to the health costs because government actions to prevent the spread of pandemics resulted in fewer deaths than would have occurred without these restrictions, but potentially larger economic impacts.
- Most infection costs originate in local buildings such as schools, hospitals, and local community buildings (56%), with residential and commercial buildings accounting for a smaller share (20% and 17%, respectively). Our analysis suggests that industrial buildings, other buildings, and transport account for a small share of transmission (4%, 1%, and 1%, respectively). This corroborates recent findings based on COVID-19 as experts believe that a large share of transmission occurred in schools, hospitals, and homes, as these largely

remained occupied during the pandemic, while there are likely to be fewer cases in commercial buildings, that largely remained closed or very under-utilised, and public transport, as trip durations are short.

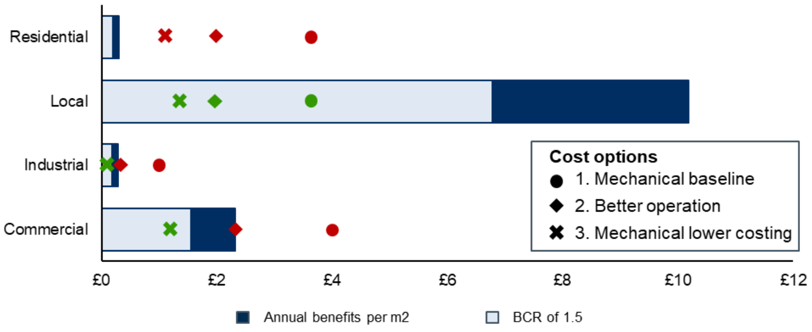
- The total potential benefits that could be unlocked by ensuring buildings are fully infection resilient are £1.3 trillion (£ 2020) over a 60-year period.
- The focus of the cost-benefit analysis is on ventilation because the intervention can be clearly defined, there are credible estimates on effectiveness, and requires major long-term investment in buildings to implement. Ventilation has the greatest effect on transmission through aerosols over distances larger than 1-2m. Ventilation measures may have some effects on close range and surface transmission routes, but this is far less certain. We have not estimated the effectiveness of other interventions such as testing, masks, distancing, surface cleaning, or vaccines, although these measures are also likely to play an important role in reducing infection transmission.
- Implementing improved ventilation (≥10 l/s/p) from poor ventilation (≤2 l/s/p) is expected to reduce long range aerosol transmission by about 50%. Improving ventilation and ensuring good air quality is also expected to improve productivity by around 1-4 %, although there is considerable uncertainty in these estimates at a wider scale.
- The total potential annual benefits from an infection resilience lens of implementing improved ventilation (≥10 l/s/p) in all buildings that require improvements (assumed to be 50% in the baseline) is about £3 billion per year or £174 billion over a 60-year period. This is 13% of the total potential benefits and depends on the likelihood and severity of influenza-type infection (pandemic and seasonal), effectiveness of ventilation in reducing transmission, the share of aerosol cases, the share of buildings requiring improvements, and the speed with which ventilation can be implemented.

Interpreting average annual benefit and cost estimates. The *average benefit or cost from improving ventilation in all floor space over all buildings within a building type per year over a 60-year period*. Lifetime average benefits and costs can be calculated by multiplying the annualised benefit by 60 years. We note that average benefits and costs mask considerable heterogeneity within building types and does not imply that ventilation would not be effective in some buildings or in some areas within the building. It also does not imply that it should be implemented in all areas within a building. Our estimates are likely to represent a lower bound for benefits as most buildings will not require improved ventilation in 100% of the building, while estimates may be an upper bound for costs, as it may not be required to install ventilation in all areas of a building. Hence, we stress that the net present value and the estimated benefit cost ratios are averages, represent what it would mean to improve ventilation in all buildings of a certain type, and may be conservative.

- The average annual lifetime discounted benefits over a 60-year period per square meter of floor space by building type from an infection resilience lens is: £2.3 (commercial), £0.3 (industrial), £10.2 (local), and £0.3 (residential). This implies that the benefits per square meter are highest in local buildings and lowest in residential buildings and suggests that the approach to ventilation should vary by building type. These results suggest that we should prioritise low-cost interventions such as opening windows in residential and industrial buildings, while more expensive mechanical ventilation may be suitable for local and commercial buildings.

- These estimates do not account for potential wider benefits of ventilation beyond infection resilience, which include reduced prevalence of sick building syndrome, lower rates of asthma, lower exposure to air pollutants and improvements in productivity. We provide a rough quantitative estimate for the impact on productivity. Using a conservative estimate of the impact of ventilation and the scope of labour productivity indicates that the discounted benefits per square meter may in fact be significantly higher for commercial (£6.5) and local (£13.6) buildings, although there is considerable uncertainty in these figures. Therefore, we focus on the benefits through an infection lens in our main analysis, however it seems plausible that the total benefits of ventilation may be significantly larger if the wider benefits are fully accounted for.
- In order to unlock the potential benefits from ventilation through an infection resilient lens, with benefits one and a half times as high as costs, the cost profile per square meter would need to be less than: £1.5 (commercial), £0.2 (industrial), £6.8 (local), and £0.2 (residential). Our current estimates for mechanical ventilation range between £1.2 – £4.0 for commercial buildings, £0.2 – £1.0 for industrial buildings, £1.6 – £3.8 for local buildings, and £1.1 – £3.8 for residential buildings. This implies that, from an infection resilience perspective, mechanical ventilation is not viable in residential buildings at a wider scale and suggests that costs need to be reduced further for the largescale implementation of mechanical ventilation to make sense in residential buildings. There will, however, of course be specific situations where it will make sense (e.g., very densely occupied factories and/or certain types of high density accommodation).

Figure 2: Potential benefits that can be unlocked from improved ventilation through an infection resilience lens at various cost levels



Benefits (£ 2020)			
Annual		Lifetime (bn)	
Per m2	Total (bn)	Total	NPV
£0.3	£0.6	£40	-£109
£10.2	£1.7	£100	£84
£0.3	£0.1	£6	£2
£2.3	£0.5	£30	£14

Notes: Annual lifetime discounted benefits and costs in £ 2020. Lifetime benefits are the sum of annual infection resilient benefits over 60 years. Benefits do not include wider benefits of ventilation such as though improved productivity. Costs include installation, operation, and maintenance. Green indicates a benefit-cost ratio (BCR) of at least 1.5, indicating benefits are at least 1.5 times higher than costs (BCR > 1.5) while red indicates the BCR is below 1.5. Mechanical combined with natural ventilation has similar results as the lower costing scenario. The NPV (net present value) column is for the lowest cost option 3.

- There are numerous different ways to unlock these benefits. Figure 2 illustrates the range of cost estimates we consider and the potential benefits that could be unlocked by building types. We considered four main options:

  1. Installing mechanical ventilation in all buildings that require improvements. Based on our baseline cost estimates from SPONS (2022), this is only cost effective from an infection resilience perspective in local buildings (NPV of £63 billion and BCR of 2.7).

2. Ensuring mechanical ventilation is operated properly in buildings that already have ventilation installed (behavioural solution) is more cost effective (NPV of £41 billion and BCR of 5.5 in local buildings), but the costs only just equal benefits for commercial buildings and are still too high to warrant improving ventilation in all industrial and residential buildings. This is because operating mechanical ventilation (even with heat recovery) increases the cost of heating buildings compared to the situation of no ventilation (although it may be cost saving compared to natural ventilation).
3. Cheaper mechanical ventilation could unlock significantly more benefits. When considering our lower bound cost estimates for installation from Hawkins (2011) and operation of mechanical ventilation, the net present value becomes positive for commercial (£14 billion), industrial (£2 billion), and local (£84 billion) buildings, with corresponding BCRs of 1.9, 1.6, and 6.3, respectively.
4. Cheaper mechanical ventilation combined with natural ventilation may also reduce operating costs further. However, this appears to only have a small impact on cost effectiveness as overall operating costs are expected to decline by about 6%.

- There is a wide range of uncertainty, although the BCR in local buildings remains high given the alternative assumptions. In this report we include a range of sensitivity tests and robustness checks. But just as importantly, we have provided RAEng with a flexible modelling tool which will allow them, and potentially others, to explore the impact of a wide range of assumptions or interventions as society's understanding of key issues (such as transmission, infection impacts, and the costs of various interventions) develops over time. It would for example be fairly easy to run the model with air cleaning interventions, such as HEPA filters, instead of ventilation, assuming that it delivers benefits comparable to improving ventilation, as it just requires replacing the installation, operation, and maintenance costs for ventilation with appropriate costs for air cleaning devices.
- Our approach focuses on average effects which masks considerable heterogeneity in impacts and risk factors within aggregate building types. So just as our analysis suggests that the best approach to ventilation (and by extension likely also other forms of intervention like surface cleaning and distancing) will vary by building type, so it will vary by different context within these building types. For example, we would expect the case for mechanical ventilation to be stronger in areas of factories that are densely packed (such as in changing rooms and refreshment areas) than in industrial properties on the whole.

1. Introduction

NERA Economic Consulting ("NERA", "we") were commissioned by the Royal Academy of Engineering (RAEng) to develop a social cost benefit analysis (SCBA) for infection resilience across environments in the UK. Our work was carried out under the terms of our contract with RAEng dated 23 December 2021. We received input from various expert stakeholders but the work in this report is our own.

1.1. Objectives

Our objectives were to:

- Consider the widest possible range of social and economic costs from infection, thereby estimating a holistic impact of infection resilience.
- Evaluate a range of interventions for UK environments on transmission of known endemic and pandemic diseases.
- Do the above in a robust and transparent way that can be developed further in the future, and that takes into account the inherently high level of uncertainty in the analysis.

1.2. Scope

In order to ensure maximum credibility of the SCBA, we focussed on:

- *Buildings* in the UK (we exclude transport).
- *Clearly defined interventions* that can be implemented in buildings with credible evidence of effectiveness (we focus on ventilation, excluding distancing and surfaces). Other behavioural interventions such as testing, masks, and surface cleaning were not in scope.
- *A timeframe* that captures the likelihood of another major pandemic while managing the difficulties in making predictions and assumptions over the very long-term (we consider a 60-year time horizon).
- *Preventable and transmittable diseases* that are most likely to impact UK residents in the timeframe (we focus on influenza type pandemics and common respiratory illnesses).
- *Infection impacts that can be quantified* (we focus on major health, social, and economic impacts that have been quantified in earlier literature).

1.3. Approach

We developed a social cost benefit analysis (SCBA) methodology that accounts for wider social and economic impacts of infection and can evaluate a range of possible interventions to improve infection resilience within buildings. This involved defining a suitable baseline, collecting evidence on the effectiveness and costs of interventions to improve infection resilience, and building a model which incorporates these two aspects and allows us to estimate the expected net present value of the interventions. The analysis also incorporates a wide degree of uncertainty in order to capture the inherent uncertainty of infection outcomes.

1.4. Structure of report

The rest of this report is structured as follows:

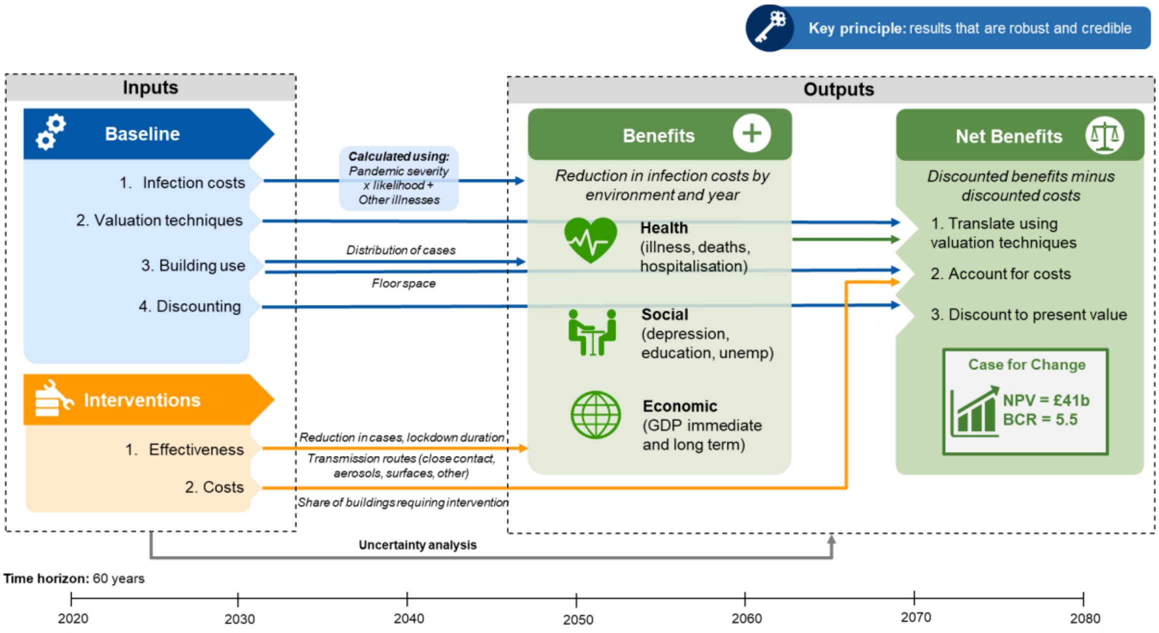
- In Section 2 we develop our SCBA methodology and outline our valuation techniques.
- Section 3 defines the baseline infection risk, severity, transmission, and other demographic and economic characteristics of the UK.
- Section 4 outlines the effectiveness and costs of implementing ventilation.
- Section 5 presents our results of the expected infection costs, the benefits and costs of ventilation, and the uncertainty analysis.
- Section 6 concludes.

2. Methodology

2.1. Overview

We develop a social cost benefit analysis (SCBA) methodology following guidance set-out in the Green Book (HMT, 2020). Our approach can account for a wide range of social and economic impacts of infection and can evaluate a range of possible interventions to improve infection resilience within buildings. Figure 3 presents a high-level overview of the approach. Key inputs are baseline assumptions on infection impacts, valuation techniques, building use, and other variables, as well as assumptions on the effectiveness and costs of interventions to improve infection resilience. The major outputs are the expected benefits of the intervention which incorporates the baseline and intervention assumptions and the expected net present value (NPV) of societal benefits. These NPVs are calculated using valuation techniques and discount rates. The methodology also incorporates a wide degree of uncertainty in order to capture the inherent uncertainty in the analysis and is modelled over a long time horizon to account for the durability of buildings and frequency of severe pandemics.

Figure 3: Approach overview



Note: NPV and BCR results refer to local buildings based on improved operation of mechanical ventilation (see Results Section 5.3.2). *Source:* NERA illustration.

We assume that in the absence of the interventions we consider, key determinants including disease incidence, behaviour of people and governments, as well as the share of environments with poor quality interventions (e.g., insufficient ventilation) will remain similar in the future as they have been in the past. Therefore, we define the baseline or counterfactual scenario (what the world will look like in the absence of intervention) as the *'do nothing'* case and that the world will remain largely similar in terms of infection outcomes and human behaviour.

In order to define the baseline, we first collect an extensive list of health, social, and economic impacts of infection. These impacts are then translated into monetary terms using valuation approaches that are standard in the literature. We also collect other important demographic, economic, and environmental metrics such as population size, GDP, and building floorspace.

The costs of infection are then allocated among environments based on the expected distribution of cases which are estimated by developing a transmission model.

Next, we collect and summarise the effectiveness and costs of interventions based on the latest scientific and industry evidence. We consider the effectiveness of an intervention as its ability to reduce the likelihood of transmission and therefore reduce the number of cases. We then develop a cost model to estimate the installation, operation, and maintenance costs based on industry recognised sources.

Finally, we build a model that links interventions to infection costs as well as demographic, economic, and environmental characteristics to calculate the present value of benefits and costs. We consider two major mechanisms: reduced transmission and reduced likelihood and duration of government lockdowns. We frame our analysis in a relatively long timeframe or "appraisal period" (60-years), given the relatively long economic life of physical infrastructure as well as the frequency with which major pandemics tend to occur. Benefits and costs are discounted to 2020 £ to ensure comparability. Finally, we test the model uncertainty by inputting a range of lower and upper bound assumptions.

2.2. Defining the baseline

For the baseline, we assume that disease incidence, behaviour, and the share of environments that require improved interventions remain largely similar in the future. More specifically as our model is primarily based on historical evidence, we make the following assumptions:

- No change in pre-pandemic levels of interventions (share of buildings requiring improved ventilation remains the same).
- Influenza-type pandemics and illnesses are transmitted in the future in a similar way to how they are transmitted now (the main transmission routes of influenza are aerosols and droplets during close or direct contact with infected people, aerosols that remain suspended in the air, and via surfaces).
- Behavioural response to pandemics will be similar (people will visit the same environments with the same frequency and duration, and experience the same impacts e.g., severe depression).
- Government response to severe pandemics will be similar (healthcare support, economic support and restrictions).

This is often called the 'do nothing' case. We consider this as the relevant counterfactual for two main reasons:

1. We are interested in the *overall impact* (including private investments) that interventions can have rather than specific impacts over which the government has control.
2. There is a large degree of uncertainty surrounding current levels of interventions, infection risk, and transmission in different environments, and how governments would respond to a future pandemic. The analysis of how these things might change in the future is outside the scope of our work.

In order to define the baseline, we first estimate the health, social, and economic costs of infection. This involves performing a literature review of the direct and indirect impacts of influenza-type pandemics and other seasonal influenza, developing a model to estimate the total societal impacts of illness in the future, translating these impacts into monetary terms, validating the impacts with expert stakeholders, and evaluating which assumptions we are unable to capture.

We categorise the literature review into three main sections: infection incidence; utilisation and quality of environments; and other assumptions.

We first consider which infections are most likely to severely impact society over the next century. Based on our literature review, we identify influenza type infections as the major known pandemic risk in developed countries and therefore focus on influenza type viruses in our analysis more generally. We then examine the likelihood and severity of influenza-like pandemics. We find that the literature studying the severity of influenza-type pandemics tends to focus on a rather narrow view of infection impacts (loss of life and income losses), so we expand the impacts considered to also include illness and societal impacts of disease. As these impacts have only been documented in more recent times, this section focuses more heavily on the impacts of COVID-19, with a view to generalising these results to future pandemics. Finally, we discuss the key transmission routes through which influenza virus is transmitted between people and set out the rationale for our quantitative assumptions on transmission routes.

We then define the environments that we are considering when examining infection resilience and explain how we determine our assumptions on the floorspace, quality of interventions, utilisation, and the distribution of infection over environments. We consider four major building types: commercial, industrial, local, and residential, which together account for 98% of floor space and align with the planning land use classes. We collect floorspace data aligning the building type definitions as closely to the planning land use classes as possible.

We then consider the quality of interventions over different buildings. As there is no data available on the share of buildings requiring interventions (such as ventilation), we make several high-level assumptions and validate these with experts. Information on the distribution of infection over building types is also not available, so we develop a model to estimate the distribution of transmission over environments based on the main determining factors in the literature: frequency, duration, density, risk. Frequency accounts for how often people visit a specific environment, duration accounts for how long people remain in the environment, density accounts for how close people are from one another, and risk accounts for the behavioural or environmental aspects such as whether people are singing or exercising or whether buildings are well ventilated.

In the final section of the baseline, we define assumptions for the demographic, economic, and healthcare trends that are required to estimate the societal costs of infections in the future. These include population size, age distribution, economic conditions, and healthcare capacity.

2.3. Defining the intervention

We consider how interventions to reduce the transmission of illness reduce the number of cases and the duration of lockdowns. Table 1 presents a list of potential interventions that are expected to improve infection resilience. As stated in our scope, we identify clearly defined interventions that cannot be immediately implemented in buildings with credible evidence of effectiveness and costs. Therefore, we focus on ventilation, and exclude air cleaning, surfaces, distancing, and other interventions such as plumbing and drainage.

Table 1: List of potential interventions

Ventilation	Air cleaning	Distancing	Surfaces	Other
Natural/passive system (trickle vents, open windows, fans)	HEPA filters (high efficiency/performance filtration system)	Building design	Material choice and coating	Plumbing & drainage maintenance
Mechanical ventilation system (including personalized systems)	UV germicidal irradiation to inactivate pathogen in the air	Occupancy limits*	No touch technologies	PAPA drainage system
		Appoint-ments*	Regular deep-cleaning*	Looped or daisy chain pipework
			Hand sanitisers*	Free masks*

Note: * Represents interventions that are more short-term.
Source: RAEng (2021).

We focus on ventilation as a major long-term intervention to improve infection resilient environments for the following reasons:

- The intervention can be clearly defined: implementing a ‘good enough ventilation system’ defined as 10 l/s/p (HM Government, 2010).[1]
- We can obtain credible estimates of the effectiveness in buildings on pandemic and seasonal influenza.
- Large opportunity for change as many existing buildings do not maintain ventilation standards over the building lifetime.
- Other interventions are difficult to define, analyse, and quantify in buildings or are more suitable as short-term interventions such as occupancy reductions and advanced surface cleaning.[2]

Ventilation is also associated with other wider benefits including reducing sick building syndrome symptoms, respiratory allergies, and asthma as well as increasing productivity and perceived air quality. Meanwhile, ventilation may also increase wider societal costs including thermal discomfort (Fisk, 2004). Although it is outside the scope of this report to quantify these wider impacts, we perform an additional (rough) analysis, where we approximate the potential improvements due to improved productivity.

Figure 4 presents an overview of the key inputs required to examine the impact of improved ventilation. First, we perform a literature review to determine the expected effectiveness of different forms of ventilation in reducing the share of cases due to airborne transmission. Next, we calculate the installation, operation, and maintenance costs of different forms of ventilation based on industry cost guidance. We consider mechanical and natural ventilation, although the

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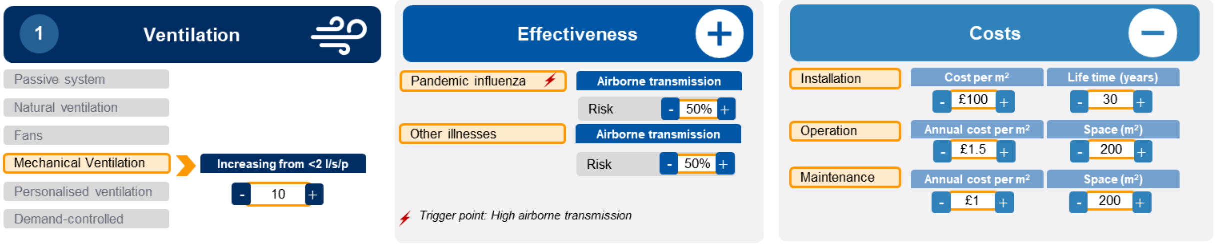
[1] This is the case for most buildings. There are some spaces, such as hospitals, where higher ventilation rates may be desirable.

[2] For example, distancing has had a massive impact on retailing but firms that were able to continue operations online have done relatively well. Those that have remained as “bricks rather than clicks” have suffered. Similarly, distancing has had a massive impact on office working. While it is unclear at this point whether this has improved or reduced productivity, it has had a large adverse impact on cafés and restaurants located near offices.

literature review and cost estimates focus on mechanical ventilation (the most expensive type of ventilation) due to the availability of reliable information. Nevertheless, we also aim to present some approximations for the benefits and costs of natural ventilation as a more cost-effective alternative.

Figure 4: Overview of intervention inputs



Notes: Effectiveness refers to the ability of the intervention to improve infection resilience of an environment (reduction in infection). Social and economic impacts are captured through reduction in pandemic costs.

2.3.1. Benefit calculation infection resilience

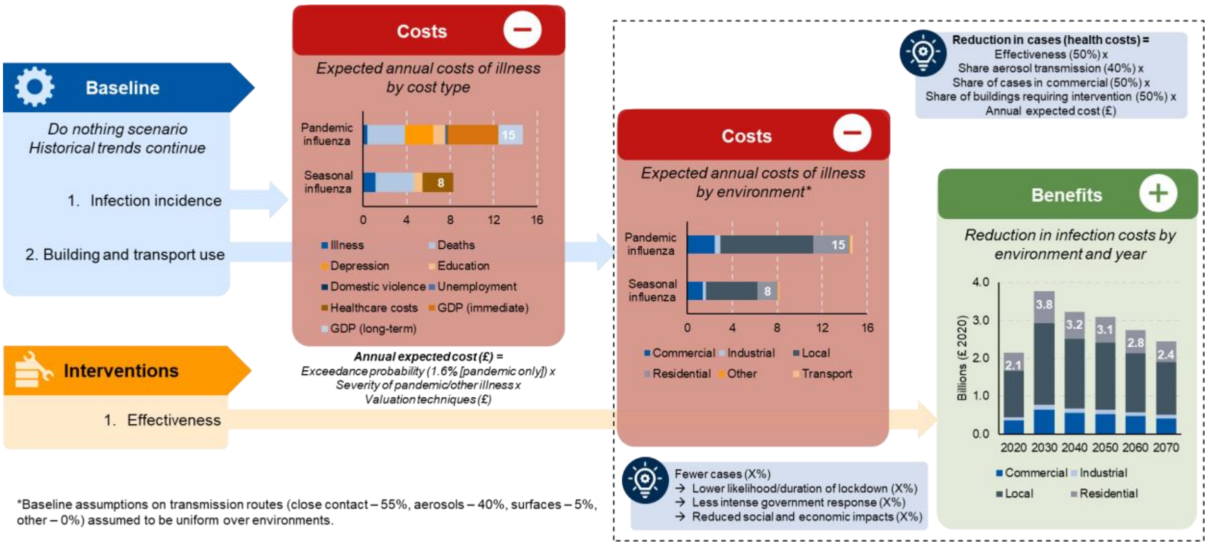
We then calculate the benefits as the reduction in infection costs due to (1) fewer cases and (2) a reduction in the duration and intensity of lockdowns. The share of health outcomes (e.g., severe illness and death) are assumed to be linearly related to the share of cases that occur in each environment.

The share of social and economic impacts (e.g., depression and GDP which are driven mainly by the likelihood, duration, and nature of lockdowns) are assumed to be linearly related to the share of cases that occur in each environment.

Figure 5 illustrates the steps required to calculate the benefits. Based on infection incidence assumptions, we calculate the expected total annual costs of infection (influenza-type pandemics as well as seasonal influenza) in any given year. We then assume that these costs are distributed over environments given the share of infections transmitted in each environment. Finally, we estimate the benefit as the reduction in cases due to the effectiveness of the intervention and thereby the reduction in infection costs. This has two important implications:

1. The share of health outcomes (e.g., severe illness and death) are assumed to be linearly related to the share of cases that occur in each environment.
2. The share of social and economic impacts (e.g., depression and GDP which are driven mainly by the likelihood, duration, and nature of lockdowns) are assumed to be linearly related to the share of cases that occur in each environment.

Figure 5: Calculating benefits from improved ventilation



*Baseline assumptions on transmission routes (close contact – 55%, aerosols – 40%, surfaces – 5%, other – 0%) assumed to be uniform over environments.

Source: NERA illustration.

For the avoidance of doubt, we recognise that these are simplified assumptions, but it is inherently difficult to distribute or allocate infection costs (e.g., deaths, depression, and GDP) to different environments in anything like a precise way. We do, however, believe the position to be reasonable because the share of cases captures:

- The initial environments where transmission occurs and which causes increased prevalence (and therefore transmission) of influenza throughout the country. Cases are strongly associated with negative health outcomes (e.g., hospitalisations) that have led to capacity constraints in the healthcare system and therefore to government decisions to impose lockdowns.

- The increase in likelihood and duration of lockdowns in a probabilistic way. It seems reasonable to assume that more cases result in a higher likelihood because of an increase in hospitalisations and a reduction in healthcare capacity. More cases are also likely to be related to longer lockdowns as it takes longer for the prevalence of the virus to subside.

- Impacts in a clear and transparent way. More complex assumptions such as non-linear thresholds based on available healthcare capacity are difficult to understand and implement due to the complex nature of discrete jumps in impacts. The evidence case to support more complex assumptions is also thin.

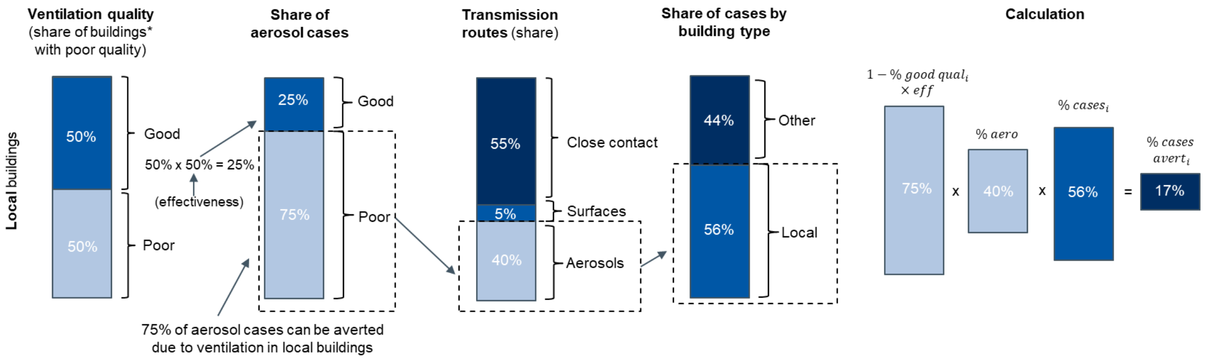
We therefore apply our effectiveness assumption as an estimate of the percentage reduction in cases and thereby the reduction in infection impacts.

In order to calculate the benefits from fewer infections, we first need to calculate the share of cases that can be averted in each environment (see Figure 6). This depends on the share of buildings with good quality ventilation, the effectiveness of ventilation, the share of cases due to aerosols (which is the form of transmission most addressed by ventilation), and the share of cases by environment:

$$\%\, cases\, avert_i = ((1 - \%\, good\, qual_i) \times eff) \times \%\, aero \times \%\, cases_i \qquad (1)$$

where i represents the building type. The share of buildings with good quality ventilation ($\% \, good \, qual_i$) and highly effective ventilation (eff) are important, because in such environments not much many cases can be averted. By contrast, the gains are large in environments where either ventilation is inherently poor or ineffective. The share of cases by aerosols ($\% \, aero$) and the share of cases transmitted within building types ($\% \, cases_i$) are also important because this determines the total share of cases that can be averted.

Figure 6: Illustrative share of cases averted calculation



Source: NERA illustration.

We then multiply the share of cases averted by the expected health, social, or economic impact ($E[impact_j]$), the effectiveness of ventilation (eff), and the share of buildings where ventilation is installed ($\% \, install_i$). Therefore, the expected benefit for building type i and impact j, can be calculated as:

$$E[benefit_{ij}] = E[impact_j] \times \% \, cases \, avert_i \times eff \times \% \, install_i \qquad (2)$$

As an illustrative example, the expected impact of death in an average year in 2030 is $E[impact_{death}] = 6{,}542$, therefore the expected reduction in deaths from installing ventilation in *all local buildings* in 2030 is 549 (6,542 × 17% × 50% × 100%).

It is important to note that we make two important assumptions, that (1) the effectiveness is the same for all buildings and (2) the share of aerosol cases is the same for all building types. As for (1), our literature review does not suggest that the effectiveness of ventilation differs over building types. Meanwhile, for (2), we decided it was best to make this assumption because reliable data on the share of aerosol cases by building type and the share of buildings requiring improved ventilation was unavailable at the time of this study, but highlight that with better data, this could be modified.

2.3.2. Benefit calculation productivity

In order to quantify the impact of ventilation on productivity in the workplace, we require a measure of labour productivity over different building types. Labour productivity is often measured using wages or nominal output per hour (OECD, 2021; ECB, 2020).[3] Each measure has its advantages and disadvantages. In 2020, wages per hour were about 60% lower than

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[3] We find that nominal output per hour and average hourly earnings show very similar trends over the 2000-2020 period.

output per hour. Wages only equal marginal labour productivity under restrictive assumptions of a perfectly competitive labour market and therefore are likely to represent a lower bound of labour productivity. Meanwhile, output is obtained by factors other than labour (capital, and land), therefore nominal output per hour is likely to represent an upper bound of labour productivity. The overestimate from using output per hour is likely to be larger in retail sectors, where material and capital costs represent a larger share of overall output, and lower in services sectors where labour is a major component. As we are interested in estimating an order of magnitude impact on productivity, we take the conservative approach and use annual wages as our measure of labour productivity.

Another concern with measuring the effect of ventilation on labour productivity is that the most productive firms and professions in terms of wages, such as professional services, select into better quality (well ventilated) buildings. This is because, unlike infection costs which are external, productivity gains are private. Therefore, employers have an incentive to install good quality ventilation under the assumption that benefits outweigh the costs and that employers are aware of the benefits. Hence, average labour productivity is likely to be an overestimate for the buildings that currently lack good quality ventilation. As we lack data on the distribution of wages within sectors and do not know which firms have good quality ventilation to begin with, we make the simplifying assumption that wages follow a uniform distribution and that the most productive firms already have good quality ventilation. Therefore, we multiply average wages by the share of buildings that require improved ventilation to get the average wages of the least productive buildings, where ventilation is likely to be poor.

To estimate the wider impact of ventilation on productivity we can then multiply our measure of labour productivity per building type ($productivity_i$) by the effectiveness of ventilation in improving productivity ($\%\Delta productivity$), and the share of buildings where ventilation is installed ($\%install_i$). Therefore, the expected benefit of the intervention on productivity for building type i can be calculated as:

$$E[benefit_i] = productivity_i \times \%\ \Delta productivity\ \times \%install_i \tag{3}$$

2.3.3. Cost calculation

There are important temporal aspects to our analysis. For example, the costs of installing a ventilation system to all building types could be assumed to occur immediately (in what would amount to an extremely rapid intervention) or it could be assumed to occur over a few years or decades. Likewise, the benefits from the installed ventilation system will be gained throughout the lifetime of the ventilation system. The key issue related to the time frame concerns the differential timing of intervention costs and intervention benefits. We therefore make the following assumptions to provide a cost calculation relevant to the long (60 year) appraisal period (illustrated in Figure 7):

1. The cost of installation is a one-off fixed cost and there are no borrowing costs.[4]
2. The intervention will be completed over a decade (i.e., the installation of ventilation system to all buildings within a building type category will be spread over 10 years).

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[4] The Green Book (HMT, 2020) stipulates that the “cost of borrowing is not included as a decision variable on whether to go ahead with an individual project or not”.

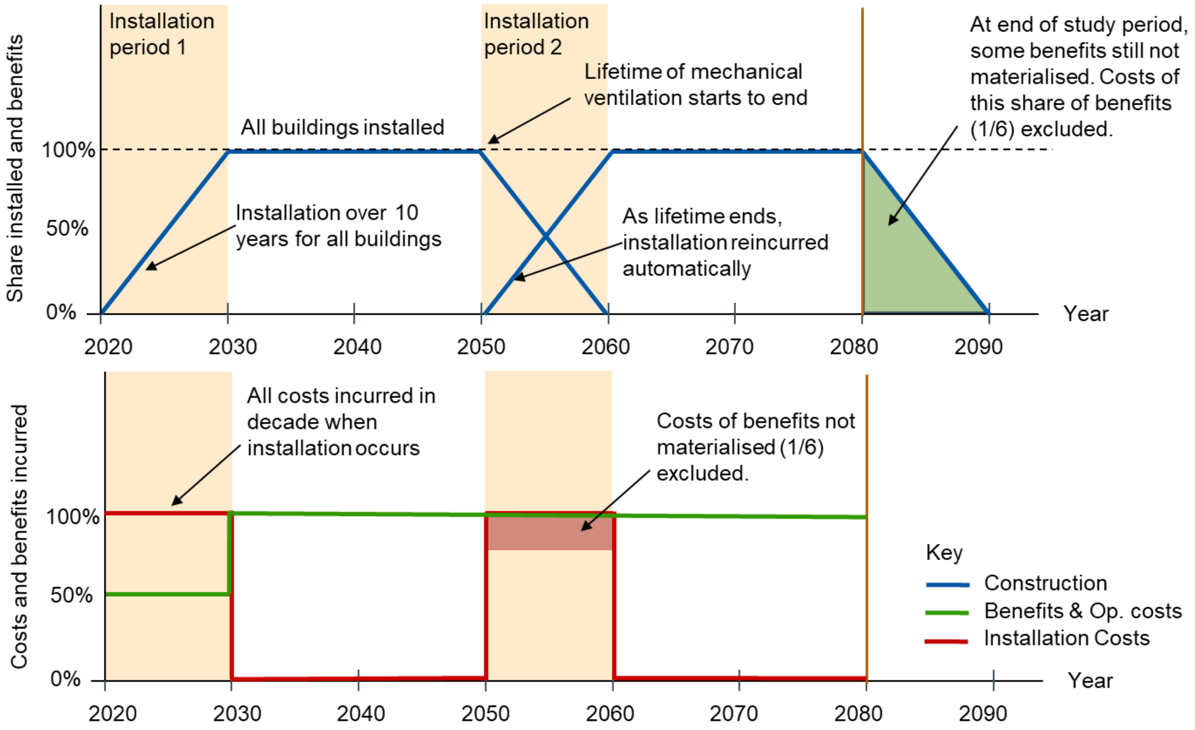
3. The lifetime of a mechanical ventilation system is assumed to be 30 years (CIBSE, 2014). The residual value of the ventilation system is zero.

4. The installation will be repeated every 30-years (spread over 10 years for all buildings) in order to maintain 10 l/s/p of ventilation throughout the appraisal period.

5. Benefits as well as operation and maintenance costs are incurred from the moment that ventilation systems are installed.

6. The costs for benefits not incurred within the 60-year appraisal period are excluded from the cost calculation.

Figure 7: Installation, costs incurred, and benefit distribution over time

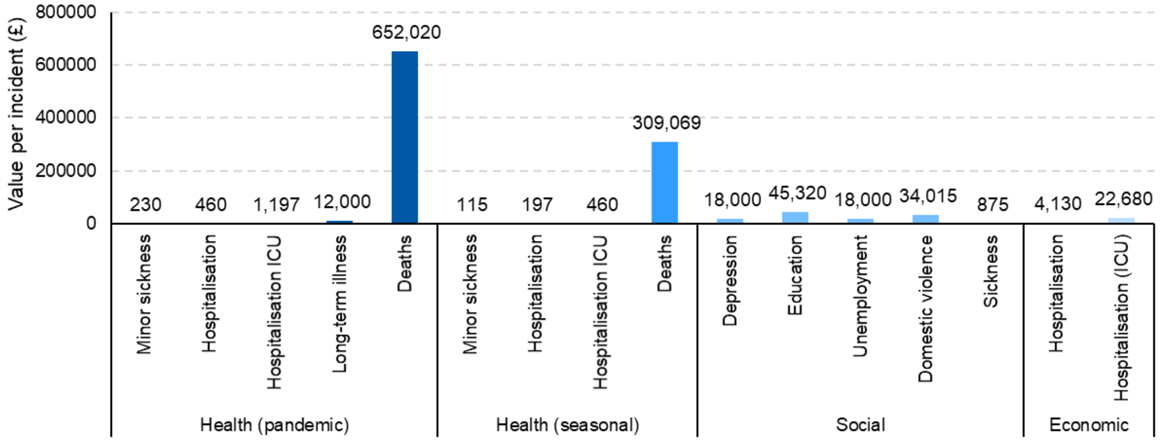


Source: NERA Illustration.

2.4. Valuation techniques

We draw on various approaches to assign monetary values to health, social, and economic infection impacts. We align these methods with the Green Book (HMT, 2020), using the latest valuation approaches. The full list of assumptions is documented in Annex A.1: Model assumptions and Annex A.2: Valuation techniques.

Figure 8: Overview valuation assumptions per incident (£ 2020)



Notes: Pandemic and seasonal influenza valuations differ slightly due to differences in severity. See Appendix A for calculations and sources.

Health outcomes. Primarily estimated based on health-related quality of life (HRQOL) measures, Quality Adjusted Life Years (QALYs), and the duration for which people are facing these negative health outcomes. We collect HRQOL estimates and duration of illness based on a literature review and calculate the reduction in health outcomes as:

$$Value = (1 - \mathrm{HRQOL_i}) \times QALY \times Duration_{years} \tag{4}$$

where i is the type of illness being considered. That said, we assume that one QALY equals £60,000 (HMT, 2020) and apply the following health related assumptions (see sources in Appendix):

- Cases: HRQOL is 0.8 and duration 10 days.
- Severe illness: HRQOL is 0.6 and duration is 7 days.
- Hospitalisation: HRQOL is 0.6 and duration is 7 days.
- Hospitalisation (severe): HRQOL is 0.48 and duration is 14 days.
- Long-term illness: HRQOL is 0.8 and duration is 1 year.
- Death: Average age of death is 75 and life expectancy is 11 years.

Social outcomes. We focus on four areas with well documented and applied approaches to valuation: mental health, loss in education, unemployment, and domestic violence. To translate these impacts into monetary figures, we use HRQOL measures, lifetime returns to education, and life satisfaction approaches. We use the following assumptions (see sources in Appendix):

- Depression: Difference in HRQOL is 0.3 and duration is 1 year.
- Education: Discounted average lifetime earnings are £515,000 and the private return to education is 8.8% for each year of education. |These impacts are likely underestimates because they exclude the social returns from education.
- Unemployment: Loss in life satisfaction is £18,000 and duration is 1 year.

- Domestic violence: Economic and social cost of domestic violence per victim is £34,000.

Economic outcomes. Disease also impacts economic outcomes via changes in behaviour and government restrictions. A major impact of lockdowns has been direct economic losses via firm closures that have particularly impacted services sectors with intensive human contact. Additional losses include health costs due to increased hospitalisations. We use the following valuation assumptions for health outcomes (see sources in Appendix):

- Hospitalisation: Cost of hospital bed is £590 per night and duration is 7 days.
- Hospitalisation (severe): Cost of ICU hospital bed is £1,620 per night and duration is 14 days.

We do not require valuation approaches to quantify costs via direct changes in overall economic activity (GDP) and long-term scarring as these metrics are already in monetary terms.

Distributional concerns. Pandemics (and illness more generally) have also been shown to have differential impacts along dimensions of gender, race and ethnicity, and social deprivation (The British Academy, 2021). It is challenging to account for distributional impacts in an aggregate cost benefit analysis, however it can be done by separating impacts by groups (e.g., gender or income) in order to determine whether some groups are impacted more than others. It is also possible to assign priority or marginal utility of income weightings to aggregate these impacts, but the results from re-weighting should always be presented alongside the results without weighting (HMT, 2020). Although we do not pursue this approach in this study due to scoping constraints, we discuss one potential approach to capture the distributional concerns arising due to lost schooling in the baseline section.

Non-quantified impacts. We were unable to include several infection impacts into our model framework because there are currently no existing approaches to assign monetary values or due to a lack of robust evidence on the impacts. Below we list out several of the most important impacts that are missing (note this is not an exhaustive list):

- Deferred health treatments (health). During the pandemic surgeries or even more routine health checks were postponed. This could lead to higher costs to the NHS due to an increase in severity of symptoms.
- Trust in governments and media (social). Trust in the government, news organisations and politicians decreased significantly during the pandemic (Reuters, 2021).
- Social contact for children (social). We focus on the impact of lockdown on learning and subsequent future earnings. However, we do not factor in the lost social contact between children and the positive externalities resulting from social contact.
- Cost of COVID deaths to family and friends (social). In assigning a monetary value of death we investigate the life expectancy at the average age of death due to the illness. We then multiply this by the value of a quality adjusted life year. This, however, does not consider the potential negative externalities of death on other individuals e.g., friends or family. We are yet to come across any literature that examines or rigorously quantifies this negative externality.
- Forced isolation and missing social contact (social). We do not directly assess the social impact of forced isolation and missing social contact for adults partly because this is hard

to measure but also because these impacts are likely to have significant overlaps with the impact of depression (which we do measure). Therefore, we do not directly measure this impact to avoid double counting.

For completeness, there are also a number of potentially positive or ambiguous impacts that we have not analysed but could be in future work, such as how pandemics can accelerate technological change (e.g., through remote working) and affect the spatial location of businesses and people and, in turn, the strength of agglomeration effects.

2.5. Uncertainty

Measures to improve infection resilience and forecasts are inherently uncertain. In order to identify how variations in underlying assumptions affect our SCBA analysis, we consider how our baseline results change for the following six main areas of uncertainty:

1. Influenza-like pandemic likelihood.
2. Expected infection costs.
3. Share of aerosol transmission.
4. Effectiveness of ventilation.
5. Case distribution over environments.
6. Share of buildings requiring improved ventilation.

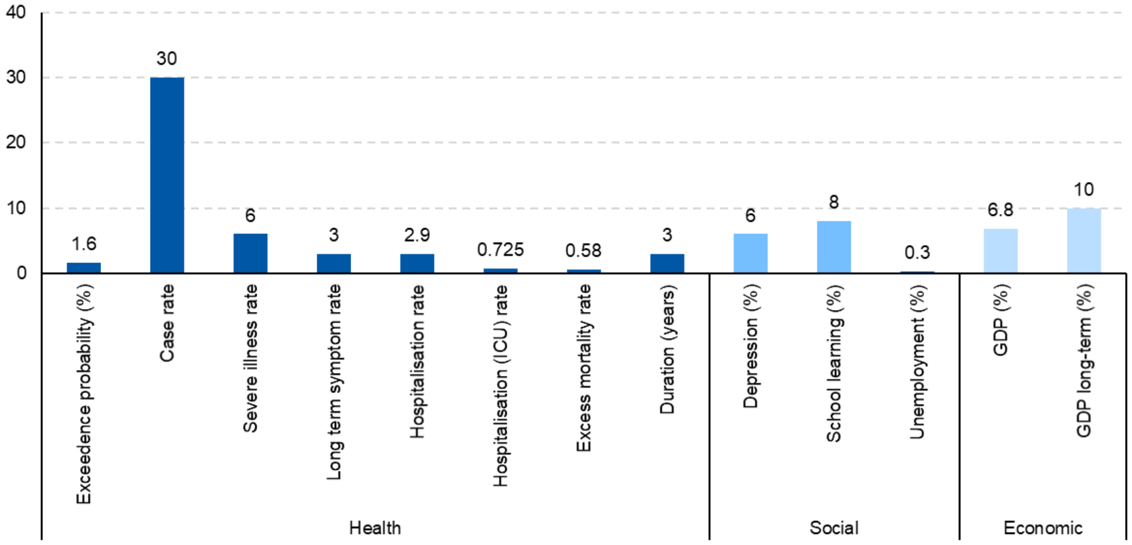
In the next section we describe our key findings from the literature which guide our assumptions on what suitable lower and upper bound assumptions might be. We refer to the lower bound as assumptions that are likely to reduce our estimated NPVs and BCRs, while upper bound assumptions are expected to increase these estimates.

3. Baseline

In the following section, we define our baseline assumptions for infection incidence and transmission (Section 3.1). Section 3.2 outlines our building type classification and how we estimate the distribution of cases over building types. Lastly, other demographic and economic characteristics that play an important role in estimating the impact of infection costs are defined in Section 3.3. The full list of assumptions is documented in Annex A.1: Model assumptions.

3.1. Infection incidence

Figure 9: Overview of key infection assumptions for influenza-type pandemics



Note: Rates are per 100 population (converted from standard per 10,000 pop) for illustrative purposes. Effects are averages over pandemic duration. For example, a case rate of 30 per 100 implies that 30% of the population will become infected by the disease over the course of the pandemic whereas a depression rate of 6% implies a 6% increase in depression for each year.

3.1.1. Pandemics

Influenza-type pandemics. What distinguishes influenza pandemics from other potential pandemics are very high attack (or case) rates (>30%), rapid transmission, increasing occurrence, and unpreparedness of our environments to mitigate airborne transmission (Kilbourne, 2004; Piret & Boivin, 2021). Influenza pandemics therefore have a high potential for widespread disruption to our societies and economies. As a result, the vast majority of literature estimating the expected pandemic costs focuses on influenza-type pandemics (McKibbin & Sidorenkho, 2006; Keogh-Brown & Barnett, 2011; Fan, Jamison & Summers, 2018). We follow this line of literature and focus on influenza-type pandemics more generally, including other forms of respiratory viruses with similar transmission routes, most notably coronaviruses.

Likelihood. Predicting the occurrence of a pandemic event is inherently uncertain (Lindahl & Grace, 2015). Several studies have attempted to model pandemic likelihood using exceedance probabilities. An exceedance probability is defined as the annual probability of a pandemic having a severity exceeding a certain threshold (generally in terms of standard mortality units or SMUs).[5]

Based on historical pandemics, Fan, Jamison & Summers (2018) estimate the overall annual exceedance risk of any influenza-type pandemic as 3.6%. Pandemics are separated into moderately severe (<10 SMU) and severe (>10 SMU). Moderately severe pandemics cause relatively small costs with an average SMU of 2.5 and exceedance probability of 2%, therefore, we focus on severe pandemics which have an average severity of 58 SMUs and an exceedance probability of 1.6%. This implies that a severe pandemic is expected to occur (on average) every 63 years (1/0.016). Several other studies find a range of estimates for exceedance probabilities of severe pandemics ranging from 0.5% for pandemics of a severity similar to the Spanish Flu (Madhav et al., 2018), to 3.3% for 'COVID type' pandemics (Metabiota, 2021).

Evidence also suggests that the likelihood of pandemics is increasing. This is due to increased global travel and integration, urbanisation, changes in land use, and greater exploitation of the natural environment (Jones et al., 2008). While the literature is not clear on whether this increased risk is captured in the exceedance probability estimates, we note that the above-mentioned likelihoods may be increasing over time.

To summarise, in our baseline model we assume an exceedance probability of 1.6% and severity of 58 SMUs and use the range of 0.5% to 3.3% in the uncertainty analysis. This range of estimates aims to capture the increased future likelihood while also recognising the inherent uncertainty involved in estimating pandemic likelihood.

Duration. The duration of a pandemic influences the overall impact and severity. In our analysis, we annualise the average impacts of disease (although impacts may vary from year to year, we take the average) and multiply these by average pandemic duration to come to a figure for total pandemic costs. Based on earlier literature, it appears that pandemics generally last for between 2-3 years. As we are considering a severe pandemic, we assume a duration of 3 years.

Severity. Several studies have estimated the impact of pandemic severity in terms of mortality and income losses. These estimates are generally converted into estimates representing costs as a share of GDP to demonstrate the magnitude of the issue and aid in comparison. Estimates of the losses due to influenza-type pandemics pre-COVID suggest losses in the order of 0.3% to 20% GDP, while more recent estimates of the COVID pandemic suggest higher figures of around 100% of GDP.

Smith, Keogh-Brown & Barnett (2011) estimate that the impact of pandemic influenza on the labour force due to deaths and absenteeism is expected to reduce total UK GDP by 0.3% to 0.6%. Meanwhile, McKibbin & Sidorenko (2006) estimate income losses of 11% of gross national income (GNI) in the UK. Fan, Jamison & Summers (2018) estimate higher costs of influenza-type pandemic risk due to deaths and incomes losses at around 20% total GDP (0.3% of GDP per annum) in high-income countries, with over 80% of the costs coming from increased mortality. More recent back-of-the-envelope estimates incorporating the societal losses of education and both the immediate and long-term impacts on GDP from shutting down economies suggest higher figures yet of around 100% of GDP (Yeyati & Filippini, 2021).

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[5] Standard mortality unit (SMU) represents a 10^-4 mortality risk, or number of deaths per 10,000 population.

This study aims to present a more comprehensive overview of pandemic impacts, including health, social, and economic impacts. To our knowledge, no such study assessing the comprehensive societal damages of pandemics in the UK (or elsewhere) exists. Therefore, in the following section, we compile a range of the best available estimates of the impacts of pandemics from the literature and compile this into an estimate of expected damages of a future influenza-type pandemic. We note that although several of the studies we draw upon rely on impacts of the current COVID pandemic, our aim is to generalise these results to future influenza-type pandemics more generally using historical precedent as a guide.

Severity – Health. Pandemics impact physical health via mortality as well as morbidity. To align with our exceedance probability, we assume an excess mortality of 58 SMUs (Fan, Jamison & Summers, 2018). This is around twice as high as the current estimates for COVID-19 (27 SMUs)[6] and lower than the estimates for the Spanish flu (110-550 SMUs). This suggests that COVID-19 was a 'moderately severe' pandemic as compared to what we might expect with a 'Spanish Flu' type pandemic, but we should also note that healthcare capacity and capabilities have improved significantly over the past century, potentially mitigating some of the worst case scenarios.

Pandemics also result in higher morbidity as infections cause illness of differing degrees of severity. We assume the attack rate is 30%, which implies that 30% of the population (or 3,000 people per 10,000) will become infected. This is in line earlier literature, as well as estimates of the attack rate from the Spanish flu and COVID-19 (Piret & Boivin, 2021).

We assume that approximately 20% of infections experience severe symptoms. This is slightly higher than the findings from COVID-19 and reflects the fact that we are considering a more severe pandemic in terms of mortality (approximately 13.8% of COVID-19 cases experience severe symptoms while 80% have mild to moderate symptoms (WHO, 2020)). Furthermore, infection causes long-term impacts is common in various diseases (Spinney, 2022). We assume that 10% of cases result in long-term symptoms, which is slightly lower than current estimates for COVID-19 (13.7%) and reflects the current uncertainty over the duration for which long-term symptoms persist.

We assume that for each death, there are approximately five hospitalisations, of which 25% result in ICU hospitalisation. This is also in line with data from COVID-19 where every death was associated with 4 hospitalisations and one in four hospitalisations included an ICU admission (GovUK, 2022; CIHI, 2022).

The average age of death due to the pandemic is important as this determines expected number of years of life lost per death which determines the valuation of a death. We make an informed assumption on the average age of death due to a future pandemic of 75 years old based on historic pandemics and considering advancements in healthcare. We investigate excess mortality across ages for three historic pandemics (Spanish flu, the Asian influenza A pandemic during the 1950's and the Hong Kong influenza A pandemic during the 1960's) as well as the current COVID-19 pandemic. Using this excess mortality data from Luuk et al. (2001), we calculate the average age of death for each pandemic.

We find average ages of death to be 23, 81, 68, and 80 years old for the Spanish flu, Asian influenza, Hong Kong influenza, and COVID-19 pandemics respectively. We take a

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[6] This is calculated as 184,000 deaths (8 March 2022) divided by 67.1 million population times 10,000 (GovUK, 2022).

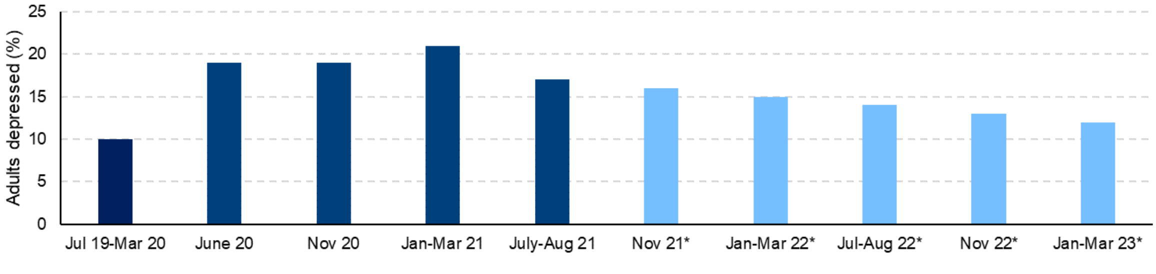
conservative estimate of an average age of death at 75 (the average age over the past four pandemics is 63 which would imply a higher loss of life). This takes into consideration the fact that there have been considerable advancements in medicine, availability of vaccines, and general improvements in health since the previous pandemics. We also note how Spanish flu may be an outlier in terms of all ages being equally affected by the disease.

Severity – Social. Pandemics also cause mental health issues, losses in educational attainment, and an unequal burden on vulnerable groups. There is little to no evidence on the impacts of earlier pandemics on these dimensions of impact. We therefore aim to capture these dimensions of impact to the fullest extent possible by examining the societal impacts of government and behavioural responses to the COVID-19 pandemic, while acknowledging that the social impacts of future pandemics may be somewhat different depending on the extent of government intervention and learning.

Deterioration in mental health can occur due to depression, anxiety, fear, loneliness, forced isolation, and unemployment among other reasons and can result in a significant reduction in quality of life. We capture this impact via the increase in depression and unemployment during the COVID-19 crisis, while noting that this is likely to represent an underestimate of the total impact on mental health (ONS, 2021).

Figure 10 illustrates the share of adults depressed in the pre-pandemic and subsequent periods. National lockdowns resulted in a spike in depression in adults from 10% to 21% in January 2021. The average increase in the share of adults depressed was 9 percentage points higher between June 2020 and August 2021 (the last month data has been collected). Extrapolating the downwards trend as lockdowns were relaxed, would imply that depression increased by 6 percentage points on average over the expected pandemic duration of three years as compared to the baseline. Young adults between the ages of 16-29 were most impacted (increasing for 11% to 29%), suggesting that depression in children is also likely to have increased. We therefore assume that depression increased by 6 percentage points on average in the entire population over the entire duration of the pandemic.

Figure 10: Share of adults moderately or severely depressed



Notes: * Indicates NERA extrapolation of trend towards baseline. *Source:* ONS (2021) and NERA calculations.

Education loss due to home schooling in environments with less supervision, unsuitable conditions, and equipment may also cause a large loss in long-term earnings potential (The World Bank, UNESCO and UNICEF, 2021; IFS, 2021). Overall, we adopt a similar approach as IFS (2021) and estimate that the quality of education declined by 8% on average over the first two years of the COVID-19 pandemic, resulting in students losing an average of around 700,000 years of schooling per year. The reduction in quality of education equals the average annual duration of online teaching over the two years (22%) times the reduction in supervised teaching hours due to online teaching (2/7) times one minus the reduction in learning gap due to government programmes (assume this equals government expenditure divided by required expenditure to reduce gap according to IFS, or 38%).

One of the social impacts of restrictions during the pandemic was the increase in domestic violence. This is because most victims were forced to isolate with their abusers. We measure the increase in domestic violence by investigating the increase in police recorded domestic abuse-related crimes. From May 2019 to May 2020, the ONS finds that police recorded domestic abuse-related crimes increases by approximately 7000. We then multiply this number by three to reflect the duration of the pandemic (3 years). Note that there was an increasing trend in domestic violence before the pandemic so the 7000 might represent an overestimate of police recorded domestic abuse-related crimes. However, most domestic abuse crimes are not reported and therefore our estimate overall could be an underestimate.

The social costs of unemployment include the feeling of alienation and difficulties in re-integrating people back into society. Areas with high unemployment (particularly youth unemployment) tend to have more crime and vandalism. We assess the link between pandemics and infection with unemployment, in order to assess how improving infection resilience might mitigate pandemics and therefore the social costs of unemployment resulting from a pandemic.

During the initial stages of the pandemic, there was a significant increase in unemployment followed by significant government interventions (e.g., furlough). We take the actions of governments as given which means that we assume governments will respond to future pandemics in a similarly strong way (e.g., by introducing furlough schemes). Therefore, we investigate the change in the observed unemployment rate just before the pandemic (February 2020) to unemployment in February 2022 (towards the end of the pandemic). We find unemployment to increase by 0.3% between these two time periods.

Pandemics have also been shown to have differential impacts along dimensions of gender, race and ethnicity, and social deprivation (The British Academy, 2021). Low-income households are more likely to be furloughed/unemployed or to continue travelling to work despite the risk of infection. Low-income households also tend to be less suitable environments for home schooling which can result in poorer educational attainment and more stress for adults (Nazroo et al., 2020). Furthermore, minority groups (e.g., Black African, Bangladeshi) faced higher mortality rates than the white population (Dowd, Ding, Akimova & Mills, 2020). Mothers were 47% more likely than fathers to have lost their jobs or resigned from their jobs and women are more likely to be working in occupations that require frequent contact with people and exposure to disease (Nazroo et al., 2020; ONS, 2021). Some other commentators have also reported how increased remote working during the pandemic in some cases may actually have been beneficial, for example to white collar workers and to women by making it more possible for them to re-enter the workforce (Magennis, Desmond & Hetherington, 2022). Although estimating the distributional impacts over groups is outside the scope of this study, Box 1 demonstrates how distributional weighting can be used to identify which groups faced higher burdens from pandemics in the case of education.

Box 1: Distributional Impacts in Education

Distributional weighting is based on the rationale that one pound to the poor increases social welfare more than one pound does to the rich. This is due to diminishing marginal utility of income i.e., as one gets richer the value of an extra pound of income becomes smaller. Distributional weighting can therefore capture differences in impacts of pandemics or infection simply due to differences in income. However, to undertake distributional weighting one needs to attribute different impacts across different income groups. Below we highlight how this could be done when assessing the impact of lost schooling during lockdowns. This is because the IFS published data on differences in learning quality during lockdown across income groups e.g., differences in average learning times and differences in what schools provide to children. However, attributing different impacts of pandemics across income groups for all pandemic impacts is difficult and outside the scope of this SCBA. We have therefore not made this technique operational in our analysis.

When considering distributional weighting, a specific utility function must be assumed. This utility function inputs income and outputs a level of utility. Often a constant relative risk utility function is taken (Stenman, 2005). This type of utility function implies that an individual's risk premium relative to income, stays constant as income changes. We create distributional weights based on a CRR utility function and estimates of risk aversion parameters in the literature (Layard et al., 2008).

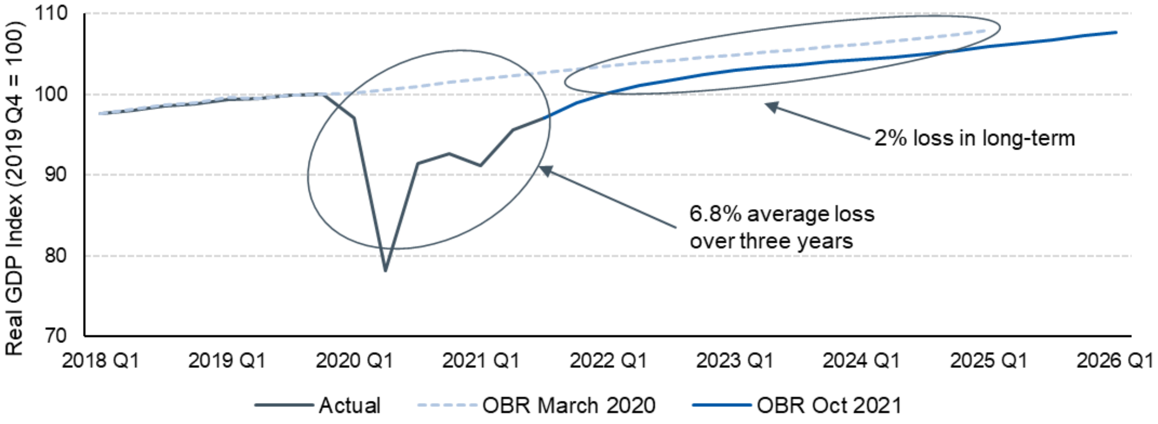
Income Quintile	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**
Income (GBP)	15,000	26,000	37,000	51,000	100,000
Weights	3.23	1.58	1.0	0.66	0.27

Source: NERA Analysis.

We then weight the monetary impacts of education in lockdown across the different income groups by the weighting factor i.e., multiply the monetary impact by 3.23 if the individual's expected lifetime annual earnings are in the lowest quintile.

Severity – Economic. Pandemics can cause economic impacts due to health care costs, direct losses in GDP, and long-term output losses. The increase in hospitalisation and ICU beds causes large costs to the healthcare system. Based on our estimates of the severity of health outcomes, we also estimate the cost in terms of the number of hospital (regular and ICU) bed nights using standard day rates and assumptions on the duration in hospital. More specifically, we assume that the cost of a hospital bed is £590 per day and £1,620 for an ICU bed (Guest et al., (2020)) and that patients remain in hospital for 7 days and 14 days, respectively (Nuffield Trust, 2021; Shryane et al., 2020).

Figure 11: Economic impact of COVID on real GDP in the UK



Source: OBR (2021) and NERA analysis.

The immediate reduction in economic activity due to government lockdowns and restrictions on mobility resulted in a significant decline in GDP. Figure 11 illustrates the realised GDP and the OBR October 2021 projection as compared to the original baseline OBR projection, pre-pandemic (dotted line). We define the difference between the pre-pandemic projection and actual outcome over a three year period as the direct impact of the pandemic on economic activity. On average annual GDP declined by 6.8% relative to the baseline period. We note that this may present a slight overestimate of the impact on GDP due to the occurrence of Brexit in 2021 which is expected to have had a negative impact, however CEPR (2021) also finds that GDP declined by around 6.5% in advanced economies, suggesting that the OBR forecast may have already taken the Brexit impacts into account.

In the longer term, pandemic related scarring on long-run productivity could arise due to labour market hysteresis, impaired skill acquisition, belief scarring, an increase in zombie companies, and policy error (Bartholomew & Diggle, 2021; Fuentes & Moder, 2021). Estimates of long-term scarring in the UK economy from COVID-19 range between -3% and -1%. In the baseline, we follow the OBR (2021) approach and estimate that long-term scarring lasts for 5 years after the end of the pandemic and results in an additional economic loss of 2% per year, resulting in an additional economic loss of around 10% of GDP.

3.1.2. Other illnesses

We also consider other respiratory illnesses that are transmitted along similar routes as influenza-type pandemics. More specifically, we include seasonal influenza and pneumonia (and we exclude other respiratory illnesses such as Asthma and COPD which may face lower symptoms due to better quality air). Seasonal influenza infects approximately 10% to 30% of Europe’s population annually. As with influenza-type pandemics, older people, younger children and those with chronic conditions are generally most impacted and have a higher risk of developing serious complications, including pneumonia, myocarditis and encephalitis, that may result in death (ECDPC, 2022).

Although the exact number of pneumonia cases caused by influenza virus is unclear (bacteria and fungi can also cause pneumonia), a meta-analysis finds that 22% adults and 49% of children diagnosed with pneumonia had evidence of viral infection (Ruuskanen, Lahti, Jennings & Murdoch, 2011). Therefore, we assume that 35% of pneumonia cases, deaths, and hospitalisations can be attributed to respiratory viral infections that are the focus of this study. In England and Wales in 2019, seasonal influenza and pneumonia were responsible for 29,500 deaths, of which 1,200 were attributed to seasonal influenza. Under the assumption that 35% of pneumonia cases are due to respiratory viruses, this implies that the annual death rate from seasonal influenza and pneumonia is around 1.9 per 10,000 population (11,100/59.7 million). Furthermore, we assume that seasonal influenza and pneumonia have an annual attack rate of 20%, with a hospitalisation (ICU) rate of 9 (1.3) per 10,000 inhabitants (Storms et al., 2017; CDC, 2022).

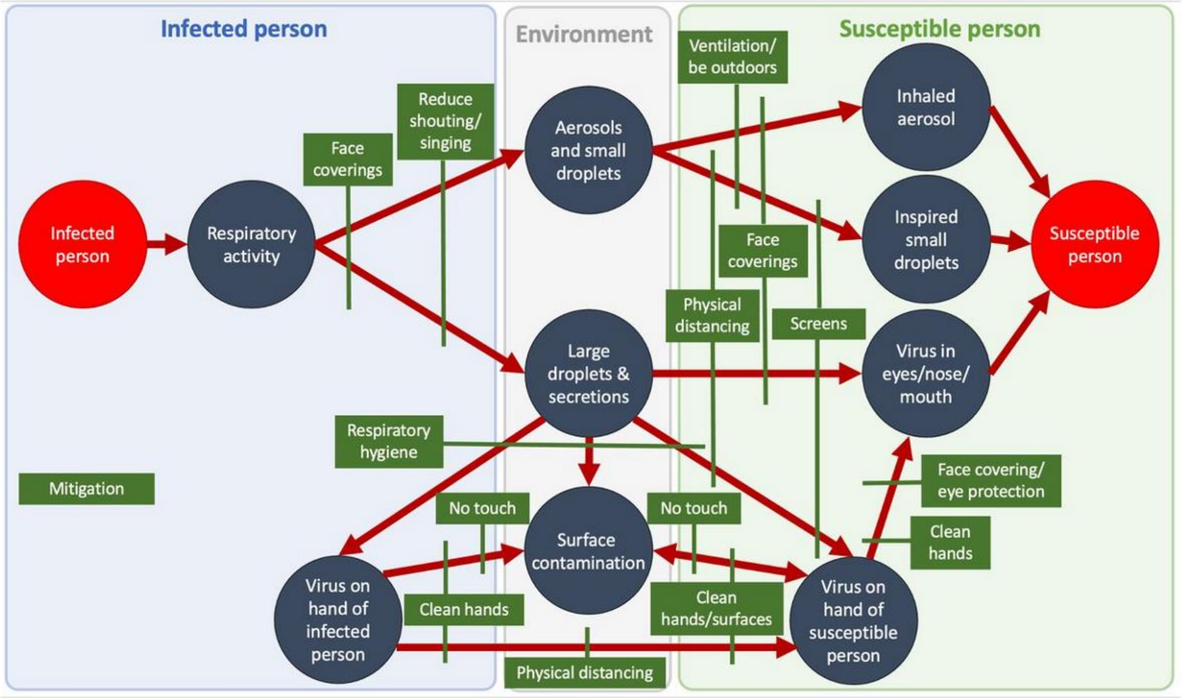
Another significant cost to seasonal respiratory illnesses is the lost days of schooling children experience due to illness. We find school absences due to illness to be 2.6% in 2018/19 (ONS). Given 190 days of schooling per year and that 27% (ONS) of absences were due to minor illness (including flu), this implies around 1 day of sick leave per student per year on average due to seasonal respiratory illnesses. We then convert this figure into an *annual* expected loss of education and multiply this by our previously highlighted value for a year of education.

3.1.3. Influenza transmission

The major transmission routes of influenza viruses are via close contact, aerosols, and surfaces (Killingley & Nguyen-Van-Tam, 2013). Figure 12 illustrates the known pathways through which an infected person can transmit the virus to a susceptible person, and several measures that can be implemented to reduce the risk of transmission. Transmission occurs through respiratory activity in the infected person, including breathing, coughing, and sneezing. Viral particles in the infected person can then be transmitted to a susceptible person via aerosols and small droplets. These aerosols can build up and remain suspended in the air for long durations, potentially travelling over long distances (>2 meters) in specific environmental conditions. Transmission can also occur due to large droplets and secretions that can be directly transmitted via direct/close contact or via contaminated surfaces (SAGE, 2020a).

Although the exact quantitative importance of each transport route (close contact, aerosols, and surfaces) is unknown, it is generally accepted that most transmission occurs due to close contact, followed by aerosols, while the risk of surface transmission is likely to be small (Atkinson & Wein, 2008; Goldman, 2020; Curran, 2022; Noakes, 2022). As quantifying the relative importance of transmission routes is essential for our analysis, we assume that 55% of transmission occurs via close contact, 40% is via aerosols, and 5% is via surfaces in our baseline model.

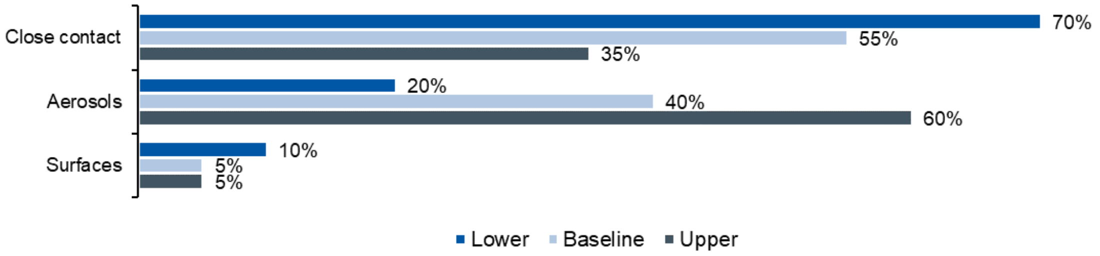
Figure 12: Influenza transmission routes and mitigation measures



Source: Freeman et al. (2021).

Due to the large degree of uncertainty over these assumptions, we test the sensitivity of our findings to a lower bound scenario where aerosols play a smaller role in transmission (20%) and an upper bound scenario where aerosols play a larger role (60%) in transmission. Based on the evidence we have collected; it appears that it is more likely that aerosols play a dominant role in transmission, so we consider the upper bound estimate more realistic than the lower bound (Atkinson & Wein, 2008; Lewis, 2021; Noakes, 2022).

Figure 13: Transmission route assumptions for influenza viruses



Note: Lower and upper bound scenario is for aerosols. *Source:* NERA illustration.

3.2. Behaviour and environments

3.2.1. Building type classification

In order to develop a detailed understanding of the existing floorspace distribution across different building types, we use two datasets: the Non-Domestic Rating (NDR) stock of properties published by the Valuation Office Agency (VOA), and the Energy Performance

Certificates (EPC) for all properties issued by the Department for Levelling Up, Housing and Communities. Primary Description and Special Category (SCat) Codes are assigned to all rateable properties by the VOA and identify the type of property which are grouped under four building types such as retail, office, industry and other.[7] Starting from the building type mapping adopted by the VOA, we define five major building types: commercial (retail and office), industrial, local, residential, and other to align the building type definitions as closely to the planning land use classes as possible.

Table 2: Building type classification

Building type	VOA Sectors	Building planning
Commercial	Retail Offices	Class E except Gym/Fitness, day nurseries
Industrial	General industrial Storage and distribution Other industrial	Class B plus industrial floorspace used for incineration purposes, chemical treatment or landfill or hazardous waste
Local	Learning and non-residential Local community Hospitals Residential institutions	Class F, Class C2A, plus hospitals, Bingo halls, concert halls, Conference and exhibition centres
Residential	All dwellings	Class C3, Class C4
Other	All other types of buildings	Class C1, Class C2, Sui Generis excluding bingo and concert halls plus Residential care homes, Gym/Fitness, day nurseries

Source: Valuation Office Agency and Planning portal.

Table 2 shows the breakdown of our mapping of sectors to various building types following NDR categories in relation to the planning land use classes.[8] As can be seen, the building type adopted in the framework is closely linked to the use class categories.

3.2.2. Floorspace and quality of buildings

For the purpose of estimating floor space across different buildings, we fuse the NDR stock of properties with the EPC floorspace data for all properties. This is because NDR provides floorspace values for properties that are rated by the VOA in England and Wales but not all properties are valued by measuring floorspace. For example, the floor space values for schools, hospitals and libraries are not valued by measuring floor space, so NDR data does not have any floor space statistics on these which are particularly defined as local building type. The EPC data, on the other hand, provides the total floor space in England and Wales for dwellings and non-dwelling (in a less granular building type categories). Floorspace estimation involves the following three steps:

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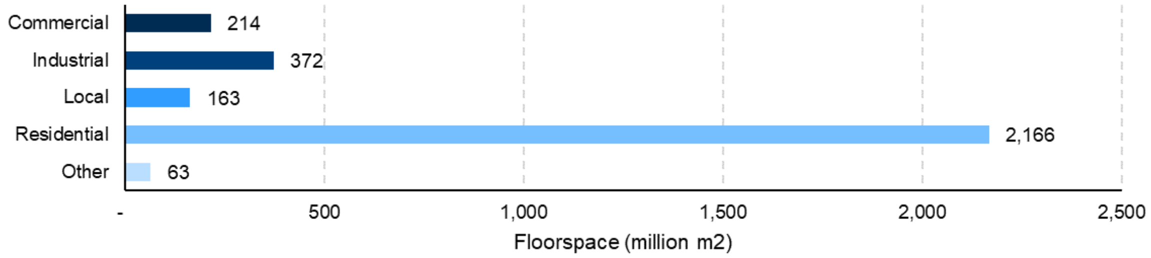
[7] See NDR Stock of properties data description accessible from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1018140/NDR_Stock_of_Properties_including_Business_Floorspace_Metadata

[8] Planning Portal the use class list accessible from https://www.planningportal.co.uk/permission/common-projects/change-of-use/use-classes

1. Extracting the floorspace values for commercial, industrial and other types of building from NDR floor space data.
2. Fusing NDR with EPC total floor area database to obtain the floorspace allocated for local and residential building types.
3. Extrapolating the UK floorspace values from England and Wales by using the ratio of UK population to the sum of England and Wales population.

As shown in Figure 14, residential floor space accounts for the largest area with 2,166 million m^2 (73%), followed by industrial buildings with 372 million m^2 (12%), commercial buildings with 214 million m^2 (7%), local buildings with 163 million m^2 (4%), and other buildings (2%).

Figure 14: Floor space estimates by building type



Source: NERA Analysis of NDR and EPC data.

It is important to determine the current quality of the UK building stock in order to choose the level of intervention and compute its corresponding benefits and costs. This is one of the key model assumptions as this determines the size of building floor space that should be targeted by the intervention and therefore both the benefits and costs. However, there is a large degree of uncertainty surrounding current quality level of buildings in the UK. Based on our discussion with experts, we assume that 50% of all buildings have an ineffective or inadequate ventilation system which could be reinstalled – in order to operate effectively and adequately – at a lower cost than buildings without any effective ventilation (Davies, 2022). Given the uncertainty with the figure, we do not differentiate this by building type. We also develop two uncertainty analyses around this assumption by using 25% and 75%, and consider the implication of buildings with currently adequate ventilation systems installed, but inadequate operation.

We do not find any evidence of differences amongst building types in terms of current quality of ventilation systems. Nevertheless, we design the SBCA framework to be able to account for various assumptions on the current quality of the UK building stock, if better data becomes available.

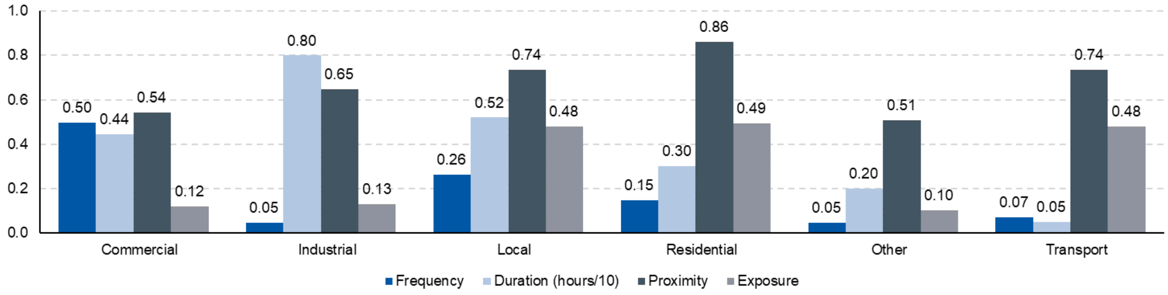
3.2.3. Distribution of infection

Transmission risk is influenced by various factors, including contact patterns, environmental factors, and socio-economic inequalities. Transmission can occur in essentially any setting; however, some environments are at greater risk due to behavioural and environmental factors (SAGE, 2020a). As is the case with transmission routes, the scientific literature it yet to precisely quantify the importance of transmission in different environments. Therefore, to determine the number and distribution of infections that occur in each setting, we need to make assumptions on how people behave and utilise environments in the past (both during pandemics and in inter-pandemic years) and in the future. This is challenging to model precisely as understanding and predicting how people use buildings is inherently uncertain, however it is crucial for our analysis to know approximately how many cases occur in each setting to determine which settings are most at risk and therefore should be prioritised.

To estimate the distribution of infections over different environments, we develop a simple model based on the four major factors that determine transmission: frequency, duration, density, and risk (SAGE, 2020a). How frequently people visit environments is relevant because it determines the likelihood that a susceptible person comes into contact with an infected person. The duration that people spend in a particular environment is also important as the risk of infection increases with the time spent in a risky setting. Density is important as it determines the proximity between people which is a major factor determining risk of close contact transmission. Finally, the riskiness of a setting plays an important role in transmission and is determined by to the types of activities people are performing and the quality of safety measures. For example, settings where people breathe a lot of particles (singing, exercising), are forced to be in close contact (hair dressing), and are poorly ventilated present greater risks.

Our aim is to estimate approximately what share of cases occur in different environments during a pandemic. We therefore collect data on the frequency of trips to different locations in 2020 (the first year of the COVID-19 pandemic) from the National Travel Survey (DfT, 2021). We then use our best judgement to approximate how long people spend in different environments. Lastly, we collect ONS (2020) occupancy risk data on proximity and exposure to determine the relative densities in different settings and the risk of transmission. Although the ONS data is based on a US analysis of these factors using 2019 data and therefore working practices and conditions may be somewhat different from the UK, the data presents a useful indication of the settings in which one is more likely to encounter someone infected with influenza virus. Furthermore, "there is a clear correlation between exposure to disease, and physical proximity to others across all occupations", which gives additional confidence that the data provides a useful indication of the metrics (density and risk) we aim to capture (ONS, 2020).

Figure 15: Transmission model assumptions



Note: Frequency is represented as the share of trips to a specific destination, duration is in hours (divided by 10), proximity and exposure are both represented on a scale between 0 (no crowding or exposure) to 1 (very close or highly exposed). *Source:* NERA Analysis of DfT (2021) and ONS (2020).

Frequency. To calculate the relative frequency with which people visit different environments, we first classify trip purposes from 2020 National Travel Survey into different building types (see Annex for classification). We only consider trips outside the home, so residential applies to visiting friends at home. We also define transport as the share of public transport trips because we assume that the risk of transmission (outside a person's household) is low in private transport. We then calculate the sum of trips per person per year over the classified building types and compute the share of trips by building type. To determine the relative share of commuting trips to commercial, industrial, and local buildings, we assume that 30% of commutes during the lockdown period are to industrial sites and that 30% are to local sites. We believe that this is reasonable, as the share of employment in industrial and local buildings (based on our classification) are both 17% and most workers in these sectors would have been classified as essential, so we essentially assume the relative share of commutes almost doubles for these sectors. Based on the NTS, we find that the trip distribution in 2020 can be summarised as follows: 50% commercial, 5% industrial, 26% local, 15% residential, 5% other, and 7% transport (see Figure 15).[9]

Duration. We approximate duration spent in each environment by applying reasonable hourly estimates for each trip purpose and weighting the estimated duration by the frequency of visits to each setting. For example, shopping is estimated to take 30 minutes, entertainment is 2 hours, and commuting is 8 hours (see Annex for estimated durations per trip purpose). We then take the weighted average hourly duration for each environment which results in the following average durations: 4.5 hours commercial, 8 hours industrial, 5.2 hours local, 3 hours residential, and 0.5 hours transport (see Figure 15, numbers are divided by 10 for illustrative purposes).

Density. We use ONS (2020) data on proximity by occupation to proxy for the density or occupancy of an environment. Proximity to others is measured using survey data about the context in which people work, with a value of 0 to 100. People are asked *"How physically close to other people are you when you perform your current job?"* with following possible answers:

- 0 – I do not work near other people (beyond 100 ft.).
- 25 – I work with others but not closely (for example, private office).
- 50 – Slightly close (for example, shared office).
- 75 – Moderately close (at arm's length).
- 100 – Very close (near touching).

We classify occupations based on the SOC 2010 sectoral classifications into environments and calculate the average proximity score on a scale of 0 to 1, weighted by the share of employment in each environment.[10] Proximity can be summarised as follows: 0.54 commercial, 0.65 industrial, 0.74 local, 0.86 residential, 0.51 other, and 0.74 transport (see Figure 15).

Risk. The ONS (2020) data also contains information on exposure to disease by occupation. People are asked *"How often does your current job require that you be exposed to diseases or infection?"* with following possible answers:

- 0 – Never.

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[9] Numbers may not sum to 100% due to rounding. Transport is not included as a destination and represents the share of public transport trips.

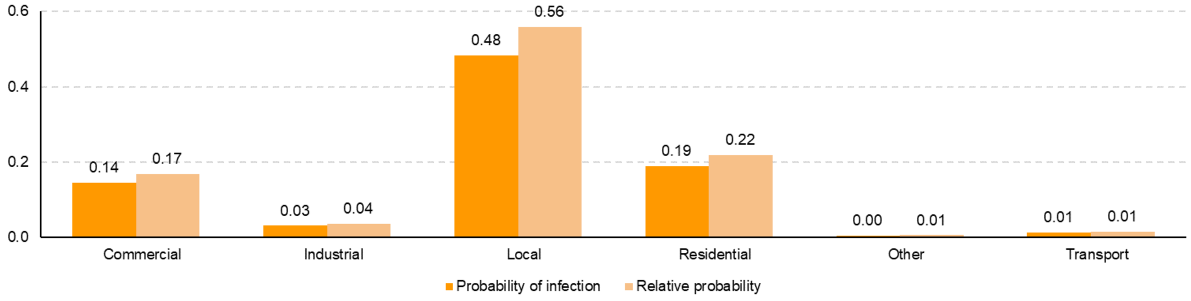
[10] In industrial, local, and residential buildings the range of people in physically close proximity is likely to be more consistent than on public transport or in some commercial buildings (e.g., shops), which may impact the likelihood of coming into contact with an infected person. We do not account for this directly, however it is likely to be correlated to the duration within an environment.

- 25 – Once a year or more but not every month.
- 50 – Once a month or more but not every week.
- 75 – Once a week or more but not every day.
- 100 – Every day.

Using the classified occupations, we calculate the average exposure score on a scale of 0 to 1 weighted by the share of employment in each environment. Exposure can be summarised as follows: 0.12 commercial, 0.13 industrial, 0.48 local, 0.49 residential, 0.10 other, and 0.48 transport (see Figure 15).

The probability of infection in each environment is then calculated as *Frequency x Duration x Density x Risk*. The literature is not clear about whether any specific factor is more important, so we weight each factor equally. We then calculate the relative probability between 0 and 1, which we interpret as the approximate share of cases transmitted in each environment. This can be summarised as follows: 17% commercial, 4% industrial, 56% local, 22% residential, 1% other, and 1% transport (see Figure 16). This seems to be reasonably intuitive most commercial buildings were closed during the first year of the pandemic, so we are likely to see few cases in these environments. In contrast, schools and hospitals (local buildings) are well known to have been major transmission hotspots during the COVID-19 pandemic, so it is reassuring that we see that the highest share of cases are estimated to occur in local buildings (Curran, 2022; Noakes, 2022).

Figure 16: Modelled infection probability by environment

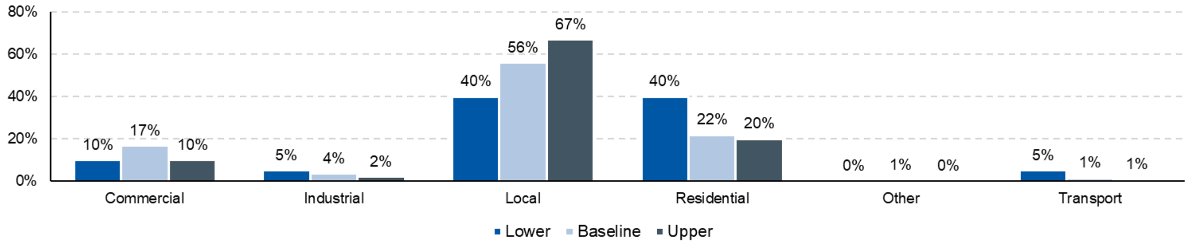


Note: Probability of infection equals Frequency x Duration x Density x Risk. *Source:* NERA Analysis.

To calculate the relative importance of environments where seasonal influenza is transmitted, we re-estimate the model with frequency and weighted hourly duration data using 2019 National Travel Survey data, the year before the pandemic (DfT, 2020). The results are almost identical (only commercial becomes 16% and transport becomes 2%), therefore we assume the same infection distribution for influenza-type pandemics and seasonal influenza.

The model of infection transmission over different environments has a few limitations. It does not capture environmental risk, as the exposure risk metric we use is only likely to capture behavioural risk. The model also only assumes that residential transmission occurs due to visiting friends and family. SAGE (2020a) reports that the secondary attack rate, the risk of another household member being infected if there is an infected person in a household is 18%, on average. Therefore, the share of residential transmission may in fact be higher than 22%. To account for this uncertainty, we consider a lower, baseline, and upper bound estimate of the share of transmission over building types as illustrated in Figure 17.

Figure 17: Share of cases by environment assumptions



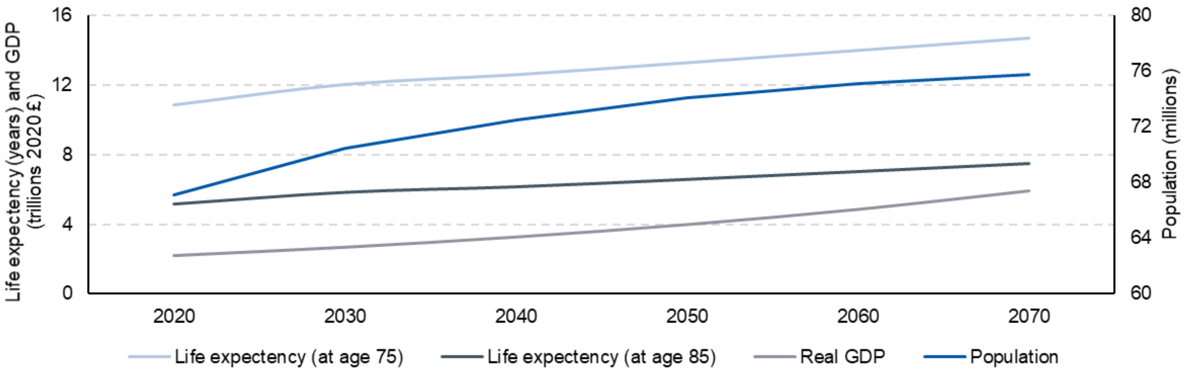
Source: NERA illustration.

3.3. Demographic, economic, and healthcare trends

Demographic, economic, and healthcare changes such as the population size, age distribution, economic conditions, and healthcare capacity have also determined the societal costs of infections in the past and will continue to do so in the future. We therefore integrate forecasts for 2020 to 2080 for population size, life expectancy at a given age, GDP growth, and wages.

Population size estimates for the UK are obtained via PopulationPyramid (2019) which uses the 2019 United Nations World Population Prospects (medium variant), among other sources to forecast population size. We obtain life expectancy data for each age from ONS (2022) life tables. We use a standard long-term expected real GDP growth rate of 2% per year (HMT, 2020) to forecast the real GDP of the UK economy. Finally, we assume that real wages grow at the same rate as real GDP to forecast wages over the period.

Figure 18: Demographic and economic trend assumptions



Source: NERA illustration.

We assume that the remaining baseline assumptions remain constant over the period of study (2020-2080). We recognise that this is a simplification, but it was outside the scope of this project to forecast these metrics, and we were unable to readily obtain estimates for the remaining assumptions up until 2080.

Two assumptions require particular attention. Healthcare capacity is important as it is strongly related to the likelihood of lockdowns and the social and economic impacts we estimate. On the one hand, we believe our assumption seems reasonable as we are not aware of political commitments to increase capacity of the healthcare system which may be under more constraints as the population ages. On the other hand, healthcare capacity may improve due to better quality medication (such as vaccines) which may reduce the burden on the healthcare system and reduce the likelihood of intrusive, large scale lockdowns. Governments may also refine their response to pandemics and impose more targeted and less strict lockdowns, which might reduce the negative impacts of pandemics.

Changes in real annual wages for employment in commercial and local buildings are solely driven by population growth projections and real wage growth. We think this is reasonable as hours worked per person have remained roughly constant since World War II, while the employment to population ratio remained roughly constant since the mid 1990's (McGrattan and Rogerson, 2004). However, we acknowledge the uncertainty in applying an average estimate of wage growth for commercial and local buildings in the same way.

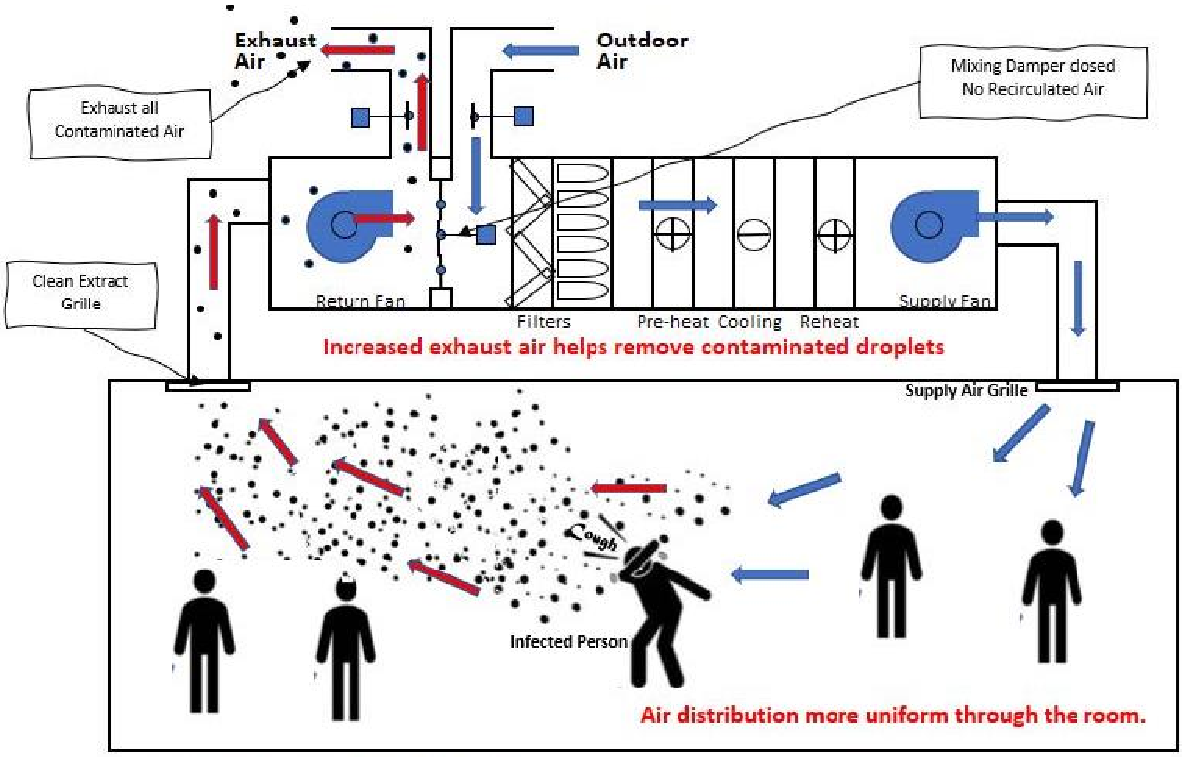
4. Intervention

Various interventions could improve infection resilience in environments (see Section 2.3). We focus on ventilation because it can be clearly defined, has credible estimates, has significant scope for improvement, and requires long-term planning decisions.

In this section, we carry out a literature review into the effectiveness of ventilation in reducing transmission of pandemic and seasonal influenza and develop a cost model to estimate the installation, operation, and maintenance of ventilation systems. Section 4.1 presents an overview of ventilation and how it is expected to reduce airborne transmission. Section 4.2 summarises the literature on the effectiveness of ventilation and Section 4.3 describes our cost estimates and scenarios we consider in the analysis. A full list of assumptions is available in Annex A.1: Model assumptions.

4.1. Overview

Figure 19: How (mechanical) ventilation reduces risk of disease exposure



Notes: The benefit is from increased dilution at a higher ventilation rate rather than the distribution of air. The same concept applies for natural ventilation (e.g., open windows or trickle vents). *Source:* NAADUK (2022).

4.1.1. The importance of ventilation

Respiratory viruses (such as COVID and influenza) can be spread through very small aerosols and droplets released in exhaled breath (see Figure 19). There is evidence to suggest that these aerosols can be carried more than 2m in the air and cause infection if they are inhaled (SAGE 2020b).

Ventilation (or the level of outdoor air supply) dilutes any pollutants produced indoors, including airborne virus particles such as aerosols. This dilution occurs through two channels:

1. Incoming outdoor air mixing with existing indoor air.
2. Incoming outdoor air displacing any indoor polluted air back outdoors.

Furthermore, ventilation can be beneficial in other aspects of human health beyond the spread of respiratory illnesses. There is evidence to suggest that ventilation reduces the prevalence of sick building syndrome, lowers rates of asthma, reduces exposure to other air pollutants and improves productivity (Sundell et al. 2011).

4.1.2. Types of ventilation interventions

Mechanical ventilation. Provides ventilation by using fans to move outside air into and out of rooms. Mechanical ventilation strategies can vary significantly and are dependent on the size of the room/building. For instance, in small spaces and buildings the mechanical ventilation may be in the room (e.g., bathroom extract in a house). However, in larger commercial buildings mechanical ventilation may be more complex where a network of ducts and fans are used to blow clean air into rooms and/or extract the stale potentially polluted air. Mechanical ventilation can reduce heat loss from introducing new air through air recycling and heat recovery systems, however air recycling can re-introduce virus particles and is therefore not recommended for infection prevention.

Natural ventilation. Provides outside air without using any fans and relies on openings in the building. This could be as simple as opening windows or using trickle vents (small vents at the top of a window). The strength of natural ventilation is highly dependent on varying external climatic conditions and is quite difficult to install in properties that are already built, since it is also generally necessary to add openings to several walls (Architreecture, 2022). However, the running costs (operating and maintenance) of natural ventilation are much lower than mechanical ventilation (Architreecture, 2022).

In this study, we focus on mechanical ventilation for four reasons:

1. Natural ventilation is only suitable some of the time. For example, Aviv et al. (2021), find that the weather in London is only suitable for natural ventilation about 30% of the time (most of the time it is too cold). This is likely to hold for the UK more generally.
2. Mechanical ventilation provides more consistent ventilation, provided it is working correctly (SAGE, 2020c). With natural ventilation, the driving factors are user behaviour (occupancy), user control (whether windows/vents are opened), and the environment (wind, temperature, humidity), while mechanical ventilation can be designed more easily to accommodate for these factors. This means that natural ventilation is less able to maintain a stable ventilation rate of 10 l/s/p throughout the day as environmental and occupancy factors vary.
3. The local outdoor air quality is a major challenge to natural ventilation. In many places (particularly in inner cities) outdoor air pollution is high which might in fact make natural ventilation unhealthy (Aviv et al., 2015).
4. Lack of rigorous information on the costs of natural ventilation in different building types. Our key source on costs (SPONS) does not distinguish between the costs of installing natural ventilation in buildings.

4.1.3. Defining ‘good enough’ ventilation

The ventilation rate refers to the volume of outside air that is provided to a room over a period of time. This is commonly measured through litres of outside air per second per person. As highlighted in RAEng (2021), it is difficult to precisely define what good enough ventilation is. This leads to a lack of a “shared sense of what constitutes best practice” with some building owners and operators not being clear on what constitutes ‘good enough’ ventilation strength.

Guidance and regulation recommend a value of 10 l/s/p as a good level of ventilation, particularly in commercial buildings (HM Government, 2010; CIBSE, 2016). The returns to ventilation (in terms of lower cases of illnesses) tend to decrease if ventilation is higher than 10 l/s/p (Fisk, 2000). The evidence suggests that values of ventilation in the range of 1-3 l/s/p result in a significantly increased risk of transmission and have been cited as major factors causing several COVID-19 super-spreading events, for example the Skagit Valley Chorale (Miller et al., 2020). Therefore, we define good enough ventilation, as ventilation that achieves a constant rate of 10 l/s/p.

4.1.4. Determining the impacts from upgrading ventilation systems

Mitigation of disease transmission in indoor spaces is crucial, especially during the winter months where most activities are held in enclosed indoor environments. We attempt to understand the different transmission mechanisms (e.g., close contact, aerosol, surfaces) and how they relate to ventilation of indoor air. Overall, we find that ventilation only impacts aerosol transmission.

We then assess the impact of ventilation by investigating the scientific literature on the extent to which ventilation reduces case rates of the aerosol transmission routes of different types of diseases. We consider COVID-19 and other respiratory illnesses (pneumonia and influenza). We then evaluate the wider impacts of ventilation, namely on workforce productivity.

Analysing COVID-19 provides us with an illustration into how ventilation affects case rates of a major respiratory pandemic. We investigate pneumonia and influenza to gauge the impact of ventilation on seasonal respiratory illnesses. Finally, we generalise the findings to respiratory illnesses more generally to determine our baseline model assumptions for the effectiveness of ventilation in reducing transmission of future influenza-type pandemics and seasonal influenza.

On the cost side of the intervention, we develop a cost model that reflects the installation, operating and maintenance costs per square meter of building space, of implementing mechanical ventilation that achieves the ventilation rate of 10 l/s/p.

4.2. Effectiveness

4.2.1. Influenza-type pandemics

Ideally, we could obtain information on the relationship between ventilation strength and the number of infections using field data from earlier influenza-type pandemics. However, due to a lack of research on pandemics pre-COVID-19, we focus on the literature on the pandemic and the relationship between COVID-19 incidence and ventilation. In theory, every time the ventilation rate is doubled, exposure is halved – therefore going from 2 l/s/p to 10 l/s/p could result in an 80% decrease in transmission (Peng et al., 2022). However, this type of relationship is likely to be overly optimistic in practice due to incomplete mixing of air, transient exposures, and the non-linear dose-response relationship that determines how exposure relates to infection.

Field and experimental studies suggest that systems are expected to reduce aerosol transmission by approximately 50%. Gettings et al. (2020) investigate the relationship between COVID-19 cases and ventilation across schools in Georgia (US) in 2020. Adjusting for county-level COVID-19 incidence, they find that COVID-19 incidence was 48% lower in schools using HEPA filtration units, compared to the no-ventilation baseline. HEPA filtration units were set at the minimum recommended ventilation rate in the US, which is 10 l/s/p according to the ASHRAE standard. The decrease of 48% is mainly from reductions in the aerosol transmission because masks and distancing were mandatory along with surface cleaning interventions, hence close contact and surface transmission were at a minimum.

Theoretical studies also find expected reductions in aerosol transmission of about 50%. According to RHEVA (Federation of European Heating, Ventilation and Air Conditioning Associations), holding variables such as floor area, breathing rate and occupancy time constant in classrooms, the probability of infection decreases by 43% as ventilation rates double from 4 l/s/p to 8 l/s/p. Burridge et al. (2020) find that the R number approximately reduces by 50% across different scenarios (e.g., desk work, talking sedentary, super-spreading events) as ventilation rates improve from 4 to 10 l/s/p. Jones et al. (2021) find that relative exposure risk decreases by 53% as ventilation in classrooms increase from 3.4 l/s/p to 9.2 l/s/p, holding constant factors such as occupants, floor area, room volume. The scope of these findings applies only to long-range airborne aerosol transmission.

To summarise, implementing a ‘good enough ventilation system’ (10 l/s/p) from ‘bad levels’ of ventilation (2 l/s/p) reduces aerosol transmission by approximately 50%. This estimate comes with the caveat that no large-scale field studies have been carried out during a live influenza-type pandemic, therefore the applicability of this estimate in different environments and behavioural conditions cannot be verified. To account for the uncertainty in assessing the effectiveness of ventilation we therefore consider an upper and lower bound estimate of 80% and 30%, respectively.

4.2.2. Seasonal influenza and other respiratory illness

A review of the literature by Seppanen et al. (1999) suggests that a 5 l/s/p increase in building ventilation rates across the building stock (commercial and institutional) decreases the prevalence of upper respiratory and eye symptoms by 35%. Milton et al. (2000) finds a relative risk factor of 1.53 associated with lower ventilation compared to high ventilation, in offices. The authors define high ventilation as 24 l/s/p and low ventilation as 12 l/s/p. A relative risk factor of 1.53 implies that 35% of short-term sick leave was attributable to lower ventilation. Jaakkola and Miettinen (1995) find that likelihood of sick building syndrome in offices decreases by 66% as ventilation rates improve from the low category (below 5 l/s/p) to the middle category (between 15 and 25 l/s/p).

Brundage et al. (1998) assess the impact of high levels of natural ventilation on the incidence of acute respiratory illnesses in army barracks. They found that confirmed cases were 33% higher in newer army barracks with closed windows and lower rates of outdoor air supply, compared to older barracks with more holes in the building and open windows (better natural ventilation). Drinka et al. (1996) investigate an outbreak of influenza across four nursing home buildings with differing levels of ventilation on a single campus. Ventilation levels in one building were approximately double ventilation rates in all the other buildings (in terms of supplied outside air). They find that respiratory illness prevalence was on average 50% lower in the better ventilated building as compared to the other buildings with similar levels of vaccination and nursing care. Finally, Mendel et al. (2013) find that increasing classroom ventilation rates from the California average (4 l/s/p) to the new state standard (7 l/s/p) resulted in a decrease in absence due to illness of 3.4%.

To summarise, we find that implementing a good enough ventilation system (10 l/s/p) from 'poor levels' of ventilation (approximately 2 l/s/p) reduces *overall* cases of seasonal respiratory illnesses by about 30%.[11] To our knowledge, most of the literature does not specify impacts on specific transmission routes such as aerosol. As aerosol cases are likely to account for less than 100% of respiratory illness cases, it seems reasonable to assume that ventilation reduces the share of aerosol cases of seasonal influenza virus by over 30%. For consistency, we therefore assume that ventilation reduces *aerosol cases* by 50% for both pandemic and seasonal influenza.

4.2.3. Productivity

We aim to estimate the impact of improved ventilation on work performance (productivity) by employment sector and building type. Seppanen et al. (2006) conduct a meta-analysis of nine studies related to the impact of ventilation on work performance. These studies are carried out in both field and simulated environments in various countries (United States, Singapore, and Sweden). Weighting each study by the sample size and importance of performance indicators, the authors find that higher ventilation rates are associated with positive but diminishing marginal improvements in productivity (see Figure 20).[12] Within the lower ventilation range of 6.5-10 l/s/p the increase in performance is 2-3.5% per 10 l/s/p additional ventilation. The authors only find statistically significant results for ventilation rates below 17 l/s/p (Figure 20 illustrates the point estimate as well as the 95% confidence interval).

Fisk et al. (2011) also estimate the benefits and costs of providing different amounts of ventilation in US offices. The authors also find a positive but diminishing effect of ventilation on productivity. An increase in ventilation rates from 6.5 to 10 l/s/p results in an increase in average worker performance of 0.76% while an increase from 8 to 15 l/s/p increases performance by 0.91%.

Due to a lack of data, both studies only examine the relationship between work performance and ventilation rates above 6.5 l/s/p. In order to estimate the increase in productivity from poor quality ventilation (2 l/s/p) to good quality ventilation (10 l/s/p) we need to extrapolate the trends found in Seppanen et al. (2006) and Fisk et al. (2011) to include rates below 6.5 l/s/p. In our baseline scenario we assume that the improvement in productivity of 10 l/s/p in the range 2-6.5 l/s/p is the same as observed at 6.5 l/s/p. This implies that improving ventilation from 2

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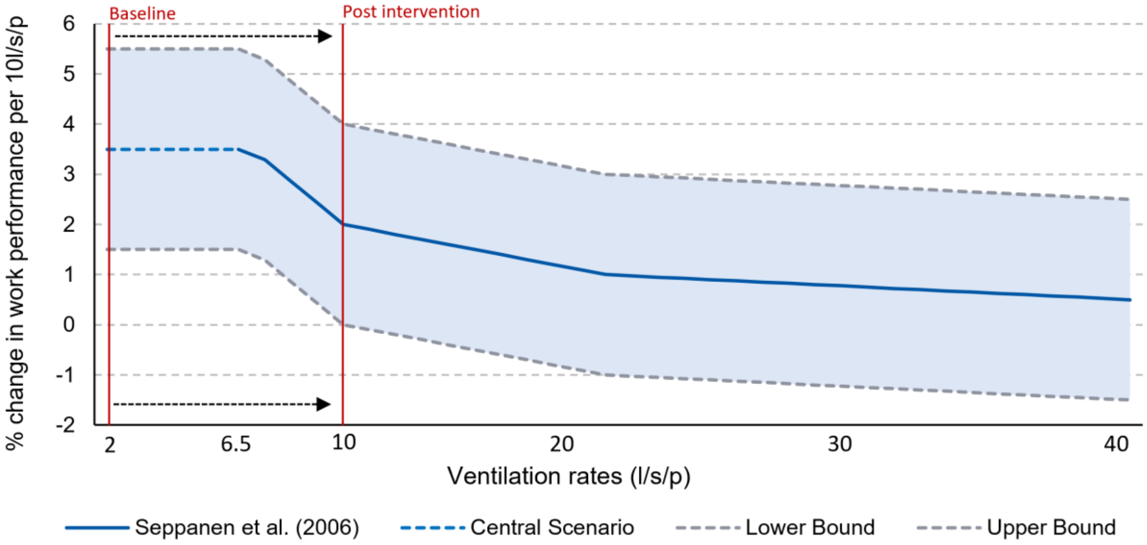
[11] Under the assumption that ventilation has the same effect on influenza-type pandemics as seasonal respiratory illness (50% reduction in aerosol transmission), this would imply that the aerosol transmission route may in fact be 60%. We therefore use an upper bound for aerosol transmission of 60%, although the exact share remains uncertain.

[12] At higher ventilation rates of 10-20 l/s/p the marginal (10 l/s/p) increase in performance becomes 1-2%, while at higher initial ventilation rates, the effect becomes insignificantly different to zero. Performance indicators include: Multiplication (units per hour), Addition (units per hour), Text typing (characters per min), Average handling time, Average talk time, Average wrap up time, Proof reading, Creative thinking, Reaction time test, and a Swedish Performance Evaluation System (SPES).

to 10 l/s/p increases productivity by 2.8% and 1.7% in Seppanen et al. (2006) and Fisk et al. (2011), respectively.[13]

Figure 20: The impact of ventilation on productivity



Note: We extrapolate the impact of ventilation on productivity between 2 and 6.5 l/s/p assuming the point estimate at 6.5 l/s/p from Seppanen et al (2006) applies to lower initial levels of ventilation. The upper and lower bounds used in our analysis are constructed as the 95% confidence interval. Numbers are approximations, based on a visual inspection of Fig 1. *Source:* NERA analysis of Seppanen et al. (2006).

There may be several reasons why this is an over or underestimate of the impact of ventilation on labour productivity. Seppanen et al. (2006) find that the change in performance is higher at lower initial levels of ventilation, therefore our assumption that the impact of ventilation on productivity at 2 l/s/p is the same as at 6.5 l/s/p may underestimate the true impact of ventilation. On the other hand, as these estimates do not come from wide-scale field studies and may only be applicable in certain types of relatively simple office environments, this may in fact overestimate the impact more generally.

To account for this uncertainty, we therefore consider two further scenarios which we obtain by applying the 95% confidence interval of Seppanen et al. (2006) estimates to out central scenario assumption. As a result, we assume a lower bound of 1.4% and an upper bound of 4.2%. The lower bound assumption allows us to reflect the smaller productivity gains found in Fisk et al. (2011) and we use this lower bound in our estimates to present the most conservative estimate of the impact.

As the performance in indicators on which improvements in performance is measured are only applicable to certain office-type jobs, we think it is reasonable to apply our productivity assumption improvement only to commercial and local buildings, where office-type jobs are carried out.

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[13] An increase in ventilation of 10 l/s/p from 2 l/s/p to 12 l/s/p is expected to increase productivity by 3.5%. Therefore, an increase in ventilation of 8 l/s/p (from 2 to 10 l/s/p) is around 2.8% (3.5%*0.8) in Sepannen et al. (2006). An increase in productivity of 0.76% (ventilation increases from 6.5 to 10 l/s/p) divided by 3.5 (change in ventilation rates) times 4.5 (6.5 minus 2 l/s/p) in Fisk et al. (2011) implies an increase in productivity of 1.7%.

4.2.4. Summary

The key takeaways and implications for our modelling approach is as follows. Implementing good enough ventilation (10 l/s/p) from poor levels of ventilation (around 2 l/s/p):

- Reduces *aerosol cases* by about 50% for both influenza-type pandemics and seasonal influenza in the baseline. To capture the uncertainty of this estimate, we assume that ventilation reduces the number of aerosol cases by 30% as a lower bound and 80% as an upper bound.
- Increases productivity in commercial and local buildings by 1.4% (a conservative lower bound estimate) in the baseline.

4.3. Costs

4.3.1. Overview

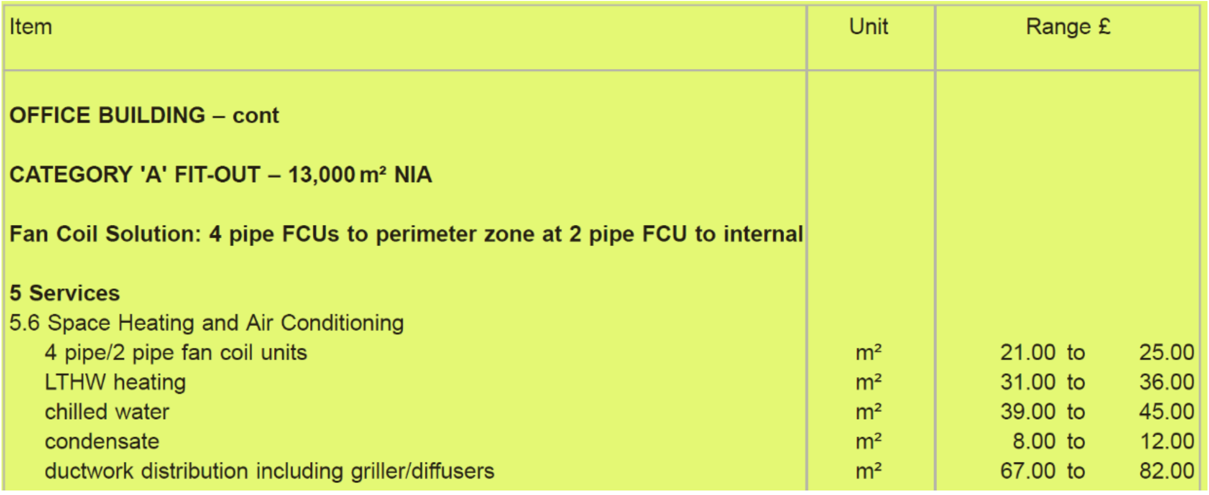
We develop our cost model based on discussions with Colin Goodwin, an expert cost modeller at CIBSE. The major costs of installing mechanical ventilation are split into three categories: installation, operating, and maintenance costs. Installation costs can be thought of as a one-off fixed cost that only needs to be paid if the building has no ventilation system, or if the current ventilation system in the building is at the end of its life cycle. Operating costs refer to the additional cost of electricity used by fans (only applies for mechanical ventilation) and heat loss due to extracting and supplying the indoor space with outside air (applies to all ventilation). Maintenance costs refer to the costs incurred to maintain 10 l/s/p strength of ventilation throughout the lifecycle of the ventilation unit. Both maintenance and operating costs can be thought of as running costs that have to be paid on an annual basis. The Excel file documenting the key assumptions of the cost model (220304 Cost model) is available upon request from RAEng.

4.3.2. Installation costs

Our main source of data is the SPONS industry price book 2022. SPONS has information on the actual incurred commercial installation costs of ventilation and air cleaning in various types of newly built buildings, e.g., offices, shops, schools, and hospitals. As recommended by Colin Goodwin, an industry expert, we assume that new buildings are fit to the recommended ventilation requirement of 10 l/s/p (HM Government, 2010).

Figure 21 shows an example of the costs per square meter breakdown for several ventilation cost elements. We pick out the individual cost elements that are most relevant to ventilation e.g., “4 pipe/2 pipe fan coil units” in Figure 21. Individual cost element choices are highlighted within our cost model. We then match the type of building in SPONS to our previously defined building categories (commercial, industrial, local, and residential). Below is a summary of all the buildings analysed in SPONS and how the buildings correspond to our building type categories.

Figure 21: Extract from SPONS



Item	Unit	Range £	
OFFICE BUILDING – cont			
CATEGORY 'A' FIT-OUT – 13,000 m² NIA			
Fan Coil Solution: 4 pipe FCUs to perimeter zone at 2 pipe FCU to internal			
5 Services			
5.6 Space Heating and Air Conditioning			
4 pipe/2 pipe fan coil units	m²	21.00 to	25.00
LTHW heating	m²	31.00 to	36.00
chilled water	m²	39.00 to	45.00
condensate	m²	8.00 to	12.00
ductwork distribution including griller/diffusers	m²	67.00 to	82.00

Source: SPONS (2022).

Table 3: Building type categorisation

Commercial	Industrial	Local	Residential
Shopping Mall	Distribution Centre	Airport Terminal	Hotel
Supermarket	Data Centre	Performing Arts Centre	Affordable development
Office building		School	Private development
Business park		Sports hall	
Bar		School	
Spa		Gym	

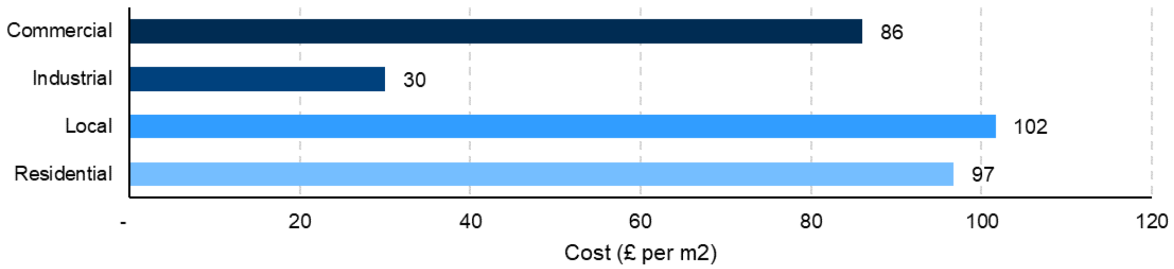
Source: SPONS and NERA Analysis.

For a given building type category, we calculate weighted average ventilation costs. We weight each building cost element by the relative importance of the building element to improving infection resilience. For example, we use a weighting of 100% when the building elements included are directly related to ventilation that improves infection resilience such as "ductwork distribution" in Figure 21. We use a weight of 50% when there are significant heating/cooling costs included or if the ventilation systems are not only used for infection resilience, such as chilled water in Figure 21. We use a weight factor of 25% when there are significant heating/cooling costs plus other factors (e.g., industrial processes which are unlikely to be related to infection resilience). All the weighting factors are provided within the cost model.

Figure 22 illustrates our estimates of installation costs per square meter for each building type. Installation costs for commercial, local, and residential buildings are relatively similar at around £100 per m^2, with costs being significantly lower for industrial buildings (£30 per m^2). These cost estimates appear to be high compared to other sources. Heat, space and light LTD (2016) find installation costs to be closer to £30 per m^2 across all building types. Hawkins (2011) finds costs to vary from £20 to £60 per m^2 for 'ventilation services' across all building types.

We take the estimates from SPONS (2022) as the baseline costs of implementing mechanical ventilation in buildings as these are considered to be the most accurate representation of the costs of implementing ventilation. We then use the costs from Hawkins (2011) as an alternative lower cost of installation.

Figure 22: Installation costs per square meter



Source: NERA Analysis of SPONS (2022).

We find a likely life cycle for a mechanical ventilation system to be approximately 30 years (CIBSE 2014). This is lower than the appraisal period (60 years) and therefore we account for the fact that installation costs will be re-incurred to maintain 10 l/s/p of ventilation throughout the appraisal period.

4.3.3. Operating cost

We calculate the operational cost by investigating the change in annual energy costs for heating of buildings before and after implementation of mechanical ventilation with heat recovery. This approach encompasses all the energy consumption changes when implementing mechanical ventilation, however does not include environmental damages from increased emissions.

Balocco & Leoncini (2020) study the effect of installing an HVAC system with heat recovery, in a refurbished school with annual heating energy consumption of 74 kWh/m^2.[14] The authors find that under an intermittent energy consumption option and no air recirculation energy costs increase by 15%, with a range between 7% and 30%. The range depends on the number of air changes and temperature requirements of the building. The electricity costs from running ventilation account for between 15-25% of energy costs with 75-85% costs due to energy lost from additional heating and cooling of the air in the building as clean fresh air is introduced.

To estimate the increase in energy consumption we calculate the average energy intensity for heating by building type and multiply this by 15% to find the increase in energy consumption for heating and finally multiply this by the price of energy. We use data from the ND-NEED (2021) database to find total energy used to heat space (kWh/m2/year) by building type. Overall annual energy consumption is calculated by adding annual electricity and gas consumption per m^2. This is multiplied by the share of energy used for heating by building types and weighted by the share of energy used for heating across building types.

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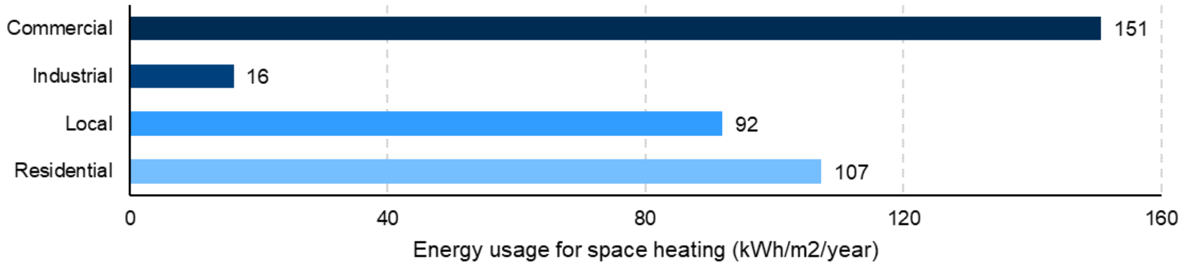
[14] The authors assume a heat recovery efficiency rate of 75%. Heat recovery systems generally cost more to install for an identical ventilation strength but have lower lifetime operating costs.

Figure 23: Heating energy consumption per square meter

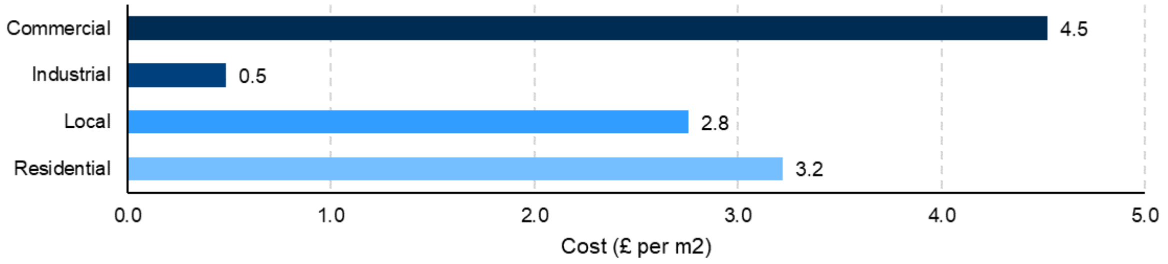


Source: NERA analysis of ND-NEED (2021).

Figure 23 illustrates the calculated heating energy consumption per square meter by building category. Commercial buildings are most energy intensive, while industrial have very low intensities. This seems realistic as commercial buildings such as shops and cafes often have large doors that release a lot of heat when opened, while industrial buildings do not require as much heating as other buildings.

Additional energy use is then calculated by multiplying heating energy intensity by 15% and is multiplied by the energy price in 2020 (£0.20 per kWh) to arrive at the annual operating cost estimates. Figure 24 illustrates the operating costs per square meter by building type. Operating costs are highest for commercial buildings (£4.5 per m^2), residential (£3.2 per m^2) and local (£2.8 per m^2) buildings are approximately the same, and industrial buildings are the lowest at £0.5 per m^2.

Figure 24: Operating costs per square meter by building type



Source: NERA analysis.

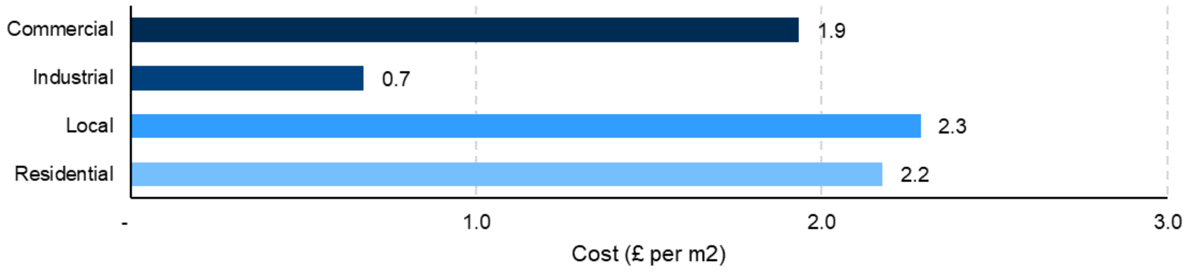
4.3.4. Maintenance costs

We apply a relatively simple approach to estimating maintenance costs of mechanical ventilation. Our main source used is the Hawkins (2011) which contains cost data for building projects. Hawkins (2011) has data on annual maintenance costs across building types for *all* building services, not just ventilation e.g., plumbing, internal drainage, heating, ventilation, and air conditioning, lifts etc. The book also draws upon data from SPONS 2011 which includes data on overall installation costs for the same new buildings.

We estimate the average share of maintenance costs for all services, to total installation costs for the same new buildings. We find this share to be approximately 2.2%. We then apply the

2.2% to our previously estimated installation costs, to arrive at the following average annual maintenance costs by building type.

Figure 25: Maintenance costs per square meter by building type



Source: NERA analysis of BG Rules of Thumb (2011).

We find annual maintenance costs to be cheaper than annual operating costs for each building category. Costs are roughly the same across commercial, local, and residential buildings but much lower for industrial buildings.

4.3.5. Cost options

Based on our review of the costs of implementing, operating, and maintaining ventilation, we find that the cost estimates vary quite widely. We therefore consider four different approaches to implementing ventilation in buildings at scale, with varying associated costs. These approaches are (in order of most expensive to least expensive): installing mechanical ventilation, improved operation of existing mechanical ventilation, mechanical ventilation with lower costs, and mechanical ventilation combined with natural ventilation.

Option (1). In the first cost option, we consider the case of installation and maintenance costs based on our best estimates from the SPONS (2022) price booklet and the middle impact of 15% higher energy costs from Balocco & Leoncini (2020).

Option (2). Some buildings already have adequate ventilation systems installed but are not utilising them effectively. In the second cost option, we take the same assumptions as in option (1) but consider the impact only due to improved operation. We assume that 50% of buildings with poor quality ventilation currently have adequate ventilation systems installed, but are not operating them properly and therefore only consider operational and maintenance costs to get ventilation rates to 10 l/s/p. To improve infection resilience in these buildings, it simply requires ‘switching on’ ventilation systems, therefore we exclude installation costs, but only focus on half of the buildings that could have improved ventilation. This option is, however, still relatively expensive because of how it increases the cost of heating buildings.

Option (3). In the third option, we consider the lower cost estimates for mechanical ventilation from Hawkins (2011) and the lower bound estimate from Balocco & Leoncini (2020) for the increase in energy costs of 7%.

Option (4). Finally, in the fourth option, we consider the operational cost savings due to combining natural ventilation with mechanical ventilation. Although natural ventilation may be unable to provide infection resilience year-round, combining natural ventilation with mechanical ventilation may provide savings in terms of operational cost due to a reduction in electricity usage (Aviv et al., 2021). Electricity costs from running ventilation account for about 15-25% of total operating costs, with the remaining costs being due to lost energy from heating and cooling the building that still occur even when adding natural ventilation (Balocco & Leoncini, 2020). Aviv et al. (2015) find that natural ventilation could provide ventilation 30% of the time in London (as compared to 100% for mechanical ventilation). We apply this estimate and conclude that operational costs decline by approximately 6% (20% x 30%). We maintain the same assumptions on installation and maintenance costs as in the low-cost option (3).

There are several caveats with our cost modelling approach. On the one hand, we are unable to distinguish the costs of installing ventilation in new buildings and retrofitting existing buildings and we do not include the wider energy costs from additional emissions due to the operation of ventilation systems. This may result in an underestimate of the costs of ventilation per square meter. On the other hand, as it is not required to install ventilation in all areas of a building, our cost estimates may be an upper bound for costs when scaled up to all buildings.

5. Results

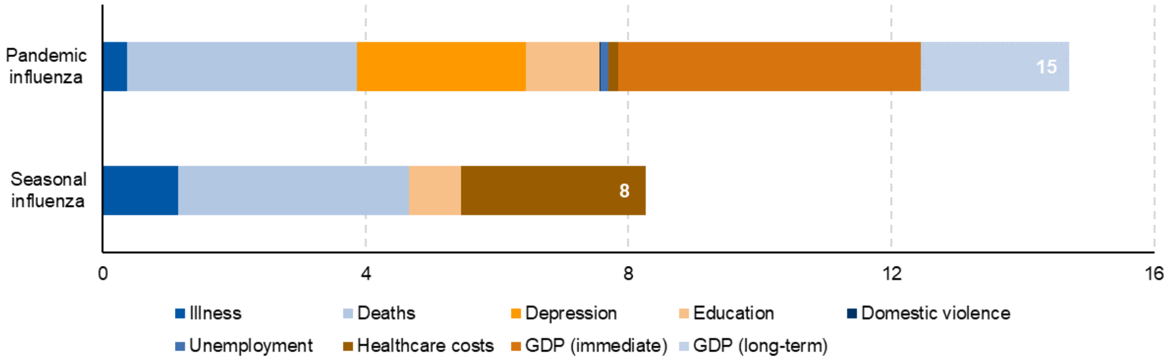
In this section, we apply the methodology and techniques to evaluate the net benefits of infection resilience more generally, and ventilation specifically, across commercial, industrial, local, and residential buildings in the UK. All monetary figures are presented in £ 2020, and are discounted using the appropriate discount factors (HMT, 2020) where necessary.[15]

Section 5.1 presents our estimates for the expected infection costs of influenza (pandemic and seasonal), Section 5.2 illustrates the potential benefits of infection resilience more generally and ventilation more specifically, Section 5.3 presents the net benefits and benefit-cost ratios for four different types of ventilation, and Section 5.4 presents the uncertainty analysis.

5.1. Expected infection costs

Figure 26 presents the annual discounted expected costs of influenza illness over the period we study. We find that the annual expected costs of illness are equal to £15 billion for influenza-type pandemics and £8 billion for seasonal influenza, implying a total annual cost of £23 billion from influenza. This implies an annual cost of influenza of 1% of GDP in 2020, which is higher than what is generally found in earlier studies (see Section 3.1.1). Influenza-type pandemic costs are distributed as follows: 27% health, 26% social, and 48% economic, while seasonal influenza is 58%, 10%, and 31%, respectively. Furthermore, we find that annual expected pandemic costs are approximately twice as large as annual seasonal influenza costs.

Figure 26: Annual discounted expected costs of illness (£ 2020 billions)



Source: NERA analysis.

5.1.1. Influenza-type pandemics

Figure 27 illustrates the undiscounted estimated influenza-type pandemic costs. As can be seen, in 2020 we estimate that the total societal costs of influenza-type pandemics is about £1.3 trillion (or about 60% of GDP in 2020) and the impact is expected to grow over time as GDP, population, and life expectancy increases (note however that in discounted terms, the impact is not increasing, see Figure 30).

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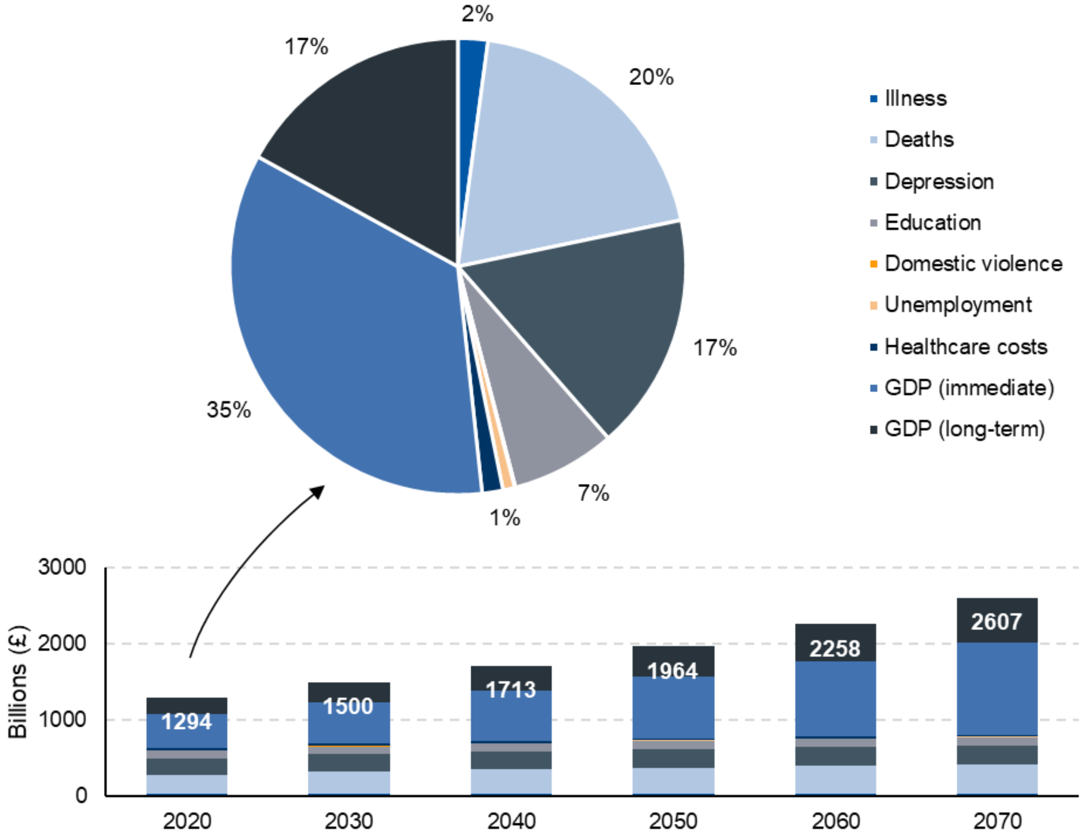
[15] We use a standard discount rate of 3.5% per year up until 30 years, after which it becomes 3% and we use a health discount rate of 1.4% until 30 years, after which it becomes 1.29% (HMT, 2020).

Figure 27: Estimated undiscounted influenza-type pandemic costs



Notes: Total expected influenza-type pandemic costs if pandemic would occur in decade indicated. Costs are higher in later decades due to increase in real GDP, life expectancy, and population (in order of importance). No discounting applied. This estimate represents general severe influenza-type pandemics and does not specifically represent COVID-19. *Source:* NERA analysis.

Several aspects are important to highlight. First, costs of illness are relatively small compared to the overall costs (about 2%) while deaths account for 20% of infection costs. The low cost of illness can be explained by the short duration for which people are ill (and therefore low valuations of illness based on HRQOL and QALYs), while the relatively higher costs of deaths are impacted by the expected age of death due to influenza-type pandemics (based on historical pandemics we assume an average age of death of 75 and a life expectancy in 2020 of 11, corresponding to a valuation of approximately £600,000 per death).

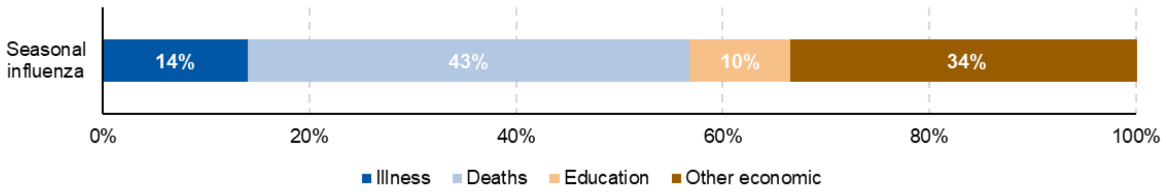
Second, social costs are largely driven by depression and loss in education. This is due to the large increase in people and children that were directly impacted by government lockdowns and other behavioural changes. Meanwhile we find little effect on unemployment and domestic violence, which is likely to be related to the furlough scheme that resulted in people avoiding becoming unemployed and the relatively small impact on reported domestic violence in absolute terms. We note that several of these estimates still lack causal evidence (e.g., unemployment and domestic violence) and therefore we interpret these estimates with caution.

Third, the largest impacts come from reductions in economic activity directly as a result of the pandemic and due to potential long-term economic scarring. The relatively high economic cost compared to health costs can be explained by policy decisions made to safeguard physical health. If the government had adopted a different approach, we might have seen the health and economic impacts of different relative sizes. The size of the overall impacts may also have been different.

5.1.2. Seasonal influenza

Figure 28 illustrates the distribution of seasonal influenza costs over different cost types. As can be seen, approximately 14% of costs are due to illness, 43% death, 10% lost education, and 34% are other economic costs (of which 95% are from missing work due to sickness).

Figure 28: Estimated discounted seasonal influenza costs

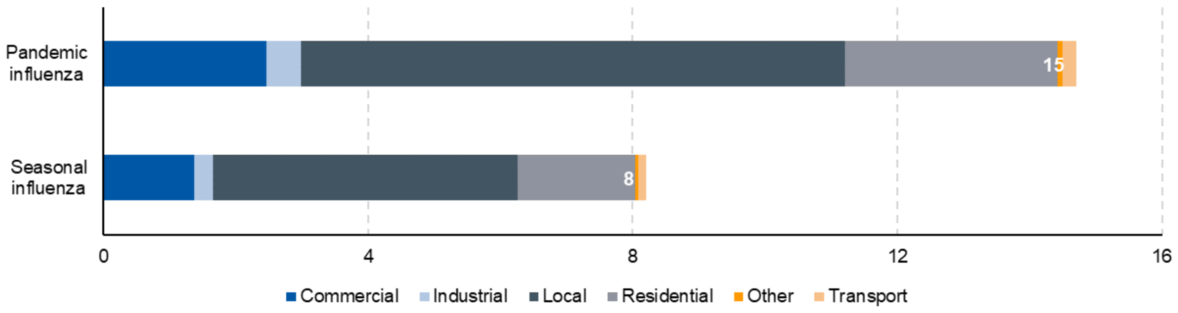


Source: NERA analysis.

5.1.3. Distribution over environments

Figure 29 illustrates the annual expected discounted costs of illness by environment. This is calculated as the total influenza costs multiplied by the share of cases originating in each environment and is the same for both pandemic and seasonal influenza. In line with our estimates of case distribution, the majority of infection costs originate in local buildings (56%), with residential and commercial buildings accounting for a smaller share (20% and 17%, respectively), while industrial buildings, other buildings, and transport account for a very small share of transmission (4%, 1%, and 1%, respectively). Therefore, in our results section we focus on 98% of the expected costs which originate in commercial, industrial, local, and residential buildings, while excluding 2% of the costs originating in other buildings and transport.

Figure 29: Annual discounted expected costs of illness (£ 2020 billions)



Source: NERA analysis.

5.2. Benefits

Based on the infection cost estimates, we first calculate the expected annual benefits from improving infection resilience overall and per square meter by building type. This provides an indication of the total potential benefits, under the assumption that all infection costs can be mitigated, and the expected benefits from implementing ventilation. These figures can then be used as a benchmark to compare different intervention strategies with different costs.

Interpreting average annual benefit and cost estimates. The *average benefit or cost from improving ventilation in all floor space over all buildings within a building type per year over a 60-year period*. Lifetime average benefits and costs can be calculated by multiplying the annualised benefit by 60 years. We note that average benefits and costs mask considerable heterogeneity within building types and does not imply that ventilation would not be effective in some buildings or in some areas within the building. It also does not imply that it should be implemented in all areas within a building. Our estimates are likely to represent a lower bound for benefits as most buildings will not require improved ventilation in 100% of the building, while estimates may be an upper bound for costs, as it may not be required to install ventilation in all areas of a building. Hence, we stress that the net present value and the estimated benefit cost ratios are averages, represent what it would mean to improve ventilation in all buildings of a certain type, and may be conservative.

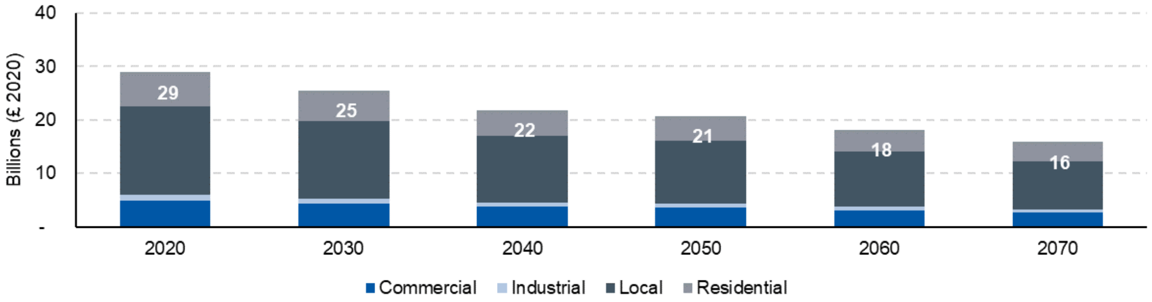
5.2.1. Total potential benefits

Figure 30 illustrates the total annual discounted potential benefits. This gives an upper bound estimate for the maximum amount of benefits that could be obtained, in the scenario that all infection costs in all environments can be mitigated (e.g., via ventilation, distancing, and surface measures that reduce the risk of transmission to zero). This indicates that £1.3 trillion (£ 2020) could be potentially mitigated (the average annual benefits are £23 billion which can be seen in Figure 26). Although this scenario would be extremely difficult to achieve in practice, we include it to demonstrate the maximum obtainable benefits.

Figure 31 presents the annual lifetime discounted potential benefits per square meter by building type. As can be seen, benefits are highest in local buildings, followed by commercial buildings, with low benefits per square meter in industrial and residential buildings. This is related to the relatively large (low) floor space in industrial and residential (local and commercial) buildings, while the share of transmission is low (high).

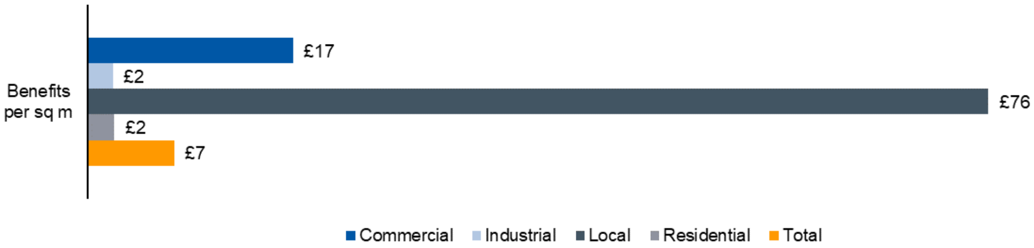
It is important to emphasise that our figures per square meter of floor space assume that each area of floor space gives the same average benefit. In reality, it is likely to be heterogeneous within building types (e.g., some buildings such as catering may be riskier than retail) and will depend on the location within the building (e.g., changing rooms may need ventilation, but not the entire factory floor).

Figure 30: Total annual discounted potential benefits



Source: NERA analysis.

Figure 31: Annual lifetime discounted potential benefits per m^2 (£ 2020)



Source: NERA analysis.

5.2.2. Expected benefits from ventilation

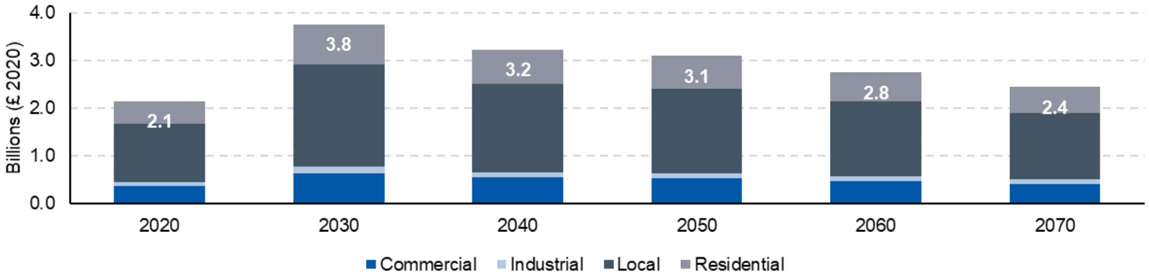
In Figure 32 and Figure 33 we present the expected annual benefits from ensuring effective ventilation (assuming a constant airflow rate of 10 l/s/p). This accounts for the share of buildings requiring ventilation (50% in the baseline), the effectiveness of ventilation systems in building where it is already installed and properly operated, and the lag between starting to install ventilation and when it is ready to be operated. Therefore, as can be seen in Figure 32, the annual benefits are lower in the first decade and higher in the subsequent decades as we assume that only 50% of the installed capacity is operational in 2020 (see Section 2.3 for further discussion on how we model installation and operation of ventilation systems).

Figure 32 indicates that the potential annual benefits of installing sufficient quality ventilation in all buildings without sufficient quality ventilation is about £3 billion per year or £174 billion over the 60-year period of study. This implies that improving ventilation could reduce annual infection costs by around 13% (£3 bn / £23 bn). This owes to the fact that 50% of buildings do not require improved ventilation, so less than 100% of aerosol cases can actually be averted by improving ventilation (see Section 2.3.1), the effectiveness of ventilation is 50%, and some of the benefits in the first decade cannot be obtained (see Section 2.3.3). Therefore, although aerosols account for 40% of transmission in our model, only 13% of transmission can actually be averted.

Figure 33 shows that the highest average benefits per square meter are expected to arise in local buildings (£10.2 per m2) and the lowest benefits per square meter arise in industrial and residential buildings (£0.3 per m2).

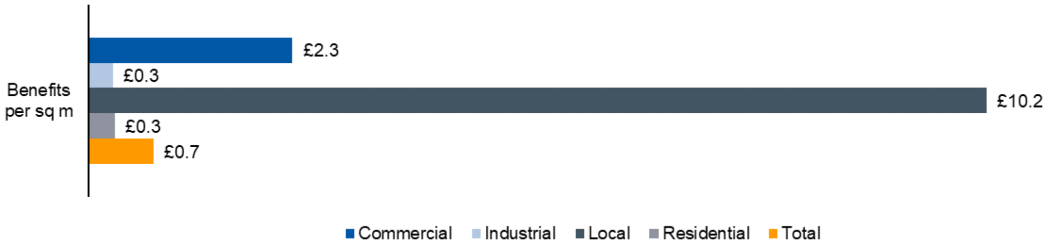
This implies that in order to unlock the potential benefits from ventilation (see Figure 34), with benefits 1.5 times as high as costs (BCR ≥ 1.5)[16], the annual lifetime discounted cost profile per square meter would need to be less than: £1.5 (commercial), £0.2 (industrial), £6.8 (local), and £0.2 (residential). Meanwhile, to unlock benefits three times as high as costs (BCR ≥ 3), the cost profile per square meter would need to be less than: £0.8 (commercial), £0.1 (industrial), £3.4 (local), and £0.1 (residential).

Figure 32: Annual discounted benefits of ventilation (£ 2020 billions)



Note: This accounts for the share of infections that can be averted due to ventilation in each building type. *Source:* NERA analysis.

Figure 33: Annual lifetime discounted benefits of ventilation per m^2 (£ 2020 billions)



Note: This accounts for the share of infections that can be averted due to ventilation in each building type. *Source:* NERA analysis.

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[16] A BCR of 1.5 or higher, rather than 1, is frequently used as a practical threshold in the appraisal of transport projects as a way of ensuring that priority is given to sufficiently high value for money projects.

Figure 34: Annual lifetime discounted cost profile that would unlock benefits 1.5 or 3 times greater than costs

Source: NERA analysis.

5.3. Cost-benefit analysis

In the following section we consider the benefits of ventilation for infection resilience (excluding labour productivity) alongside four different approaches to implementing ventilation in buildings at scale, with varying associated costs. These approaches are (in order of most expensive to least expensive): installing mechanical ventilation, improved operation of existing mechanical ventilation, mechanical ventilation with lower costs, and mechanical ventilation combined with natural ventilation. We take this approach as we find that, based on our review of the costs of implementing, operating, and maintaining ventilation vary quite widely.

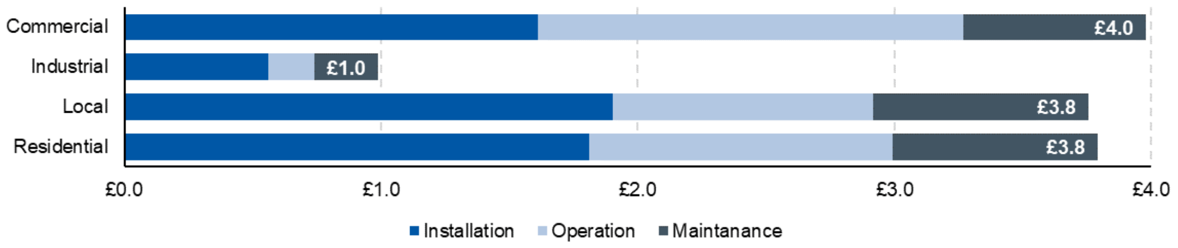
5.3.1. Mechanical ventilation

Figure 35 illustrates the lifetime annual discounted costs of mechanical ventilation per square meter. As can be seen, the annual lifetime costs are approximately £4 per square meter for commercial, local, and residential buildings, with industrial buildings having substantially lower costs of £1 per square meter. Furthermore, commercial buildings have significantly higher operational costs as compared to other building types.

Figure 36 presents the benefits, costs, and net present value of mechanical ventilation by building type and overall. As can be seen, based on these (particularly high) costs, only local buildings have a positive net present value over the period of study (£63 billion), while full scale implementation of mechanical ventilation is likely to be very costly and is expected to result in a net present value of -£428 billion (which is particularly driven by the large costs in residential buildings owing to the share of floor space requiring ventilation).

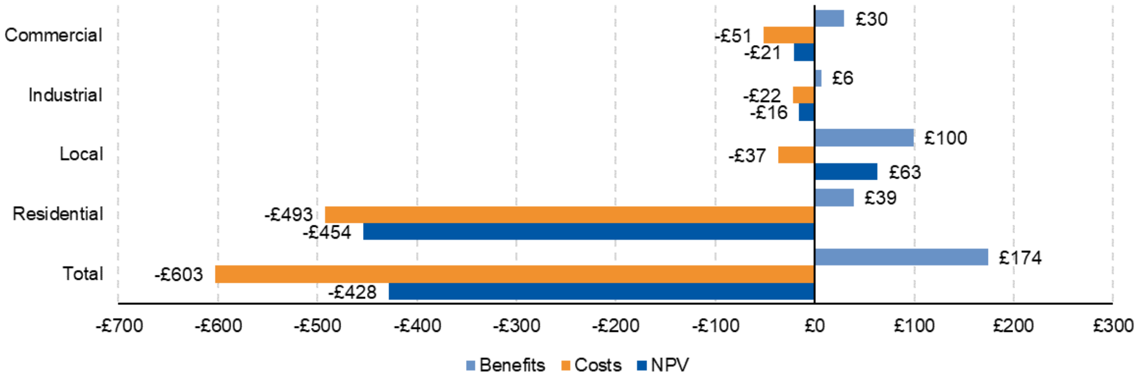
Finally, Figure 37 presents the BCRs by building type. The figure indicates that the benefits of implementing mechanical ventilation in all local buildings far outweigh the costs with a high BCR of 2.7, while implementing mechanical ventilation in all commercial buildings (given these costs) has a BCR of below 1. We stress that this does not imply that implementing ventilation (given these costs) in *some high-risk* commercial buildings is not effective, but rather that the mechanical ventilation should be implemented in a more case-by-case basis, based on a proper risk assessment of the likelihood of aerosol transmission.

Figure 35: Annual lifetime discounted costs (£ 2020 per m^2) of mechanical ventilation



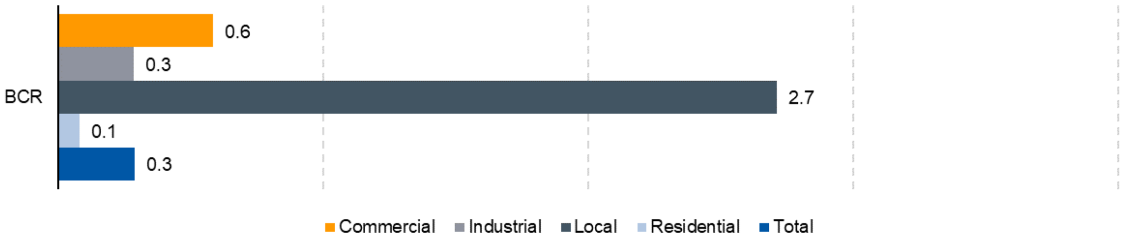
Source: NERA analysis.

Figure 36: Net present value of mechanical ventilation (billions £ 2020)



Source: NERA analysis.

Figure 37: Benefit-cost ratio (BCR) mechanical ventilation



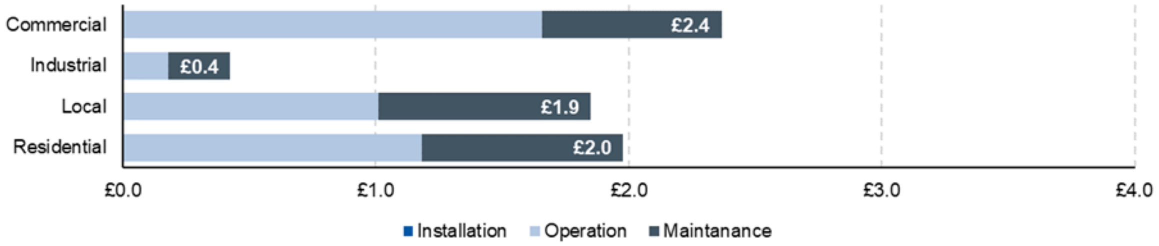
Source: NERA analysis.

5.3.2. Mechanical ventilation with improved operation

We now consider the impact of the extent to which improved operation of ventilation systems in buildings that currently have ventilation systems in place but are not operating them sufficiently. Although hard numbers are difficult to come by for the UK building stock, based on an expert stakeholder meeting with Hywel Davies, our baseline assumption is that 50% of buildings with poor quality ventilation currently have adequate ventilation systems installed, but are not operating them properly and they would only be required to pay for the operation and maintenance costs to get them running at 10 l/s/p. Therefore, in this section we focus on the impact of 'switching on' ventilation systems in buildings with adequate systems already installed.

Figure 38 shows that installation costs become zero, while operation and maintenance costs remain the same, resulting in a reduction in overall costs per square meter of approximately 50%. Figure 39 and Figure 40 illustrates that the net present value of implementing and operating ventilation in all local buildings declines slightly to £41 billion and the BCR increases to 5.5. Although the BCR becomes one for commercial buildings (implying a NPV of zero), the operating and maintenance costs are still too high to justify widespread implementation of ventilation among all non-local building types. It is worth noting that operating and maintenance costs are still relatively substantial, mainly because of how effective ventilation can significantly increase heating costs.

Figure 38: Annual lifetime discounted costs (£ 2020 per m^2) of mechanical ventilation with improved operation



Source: NERA analysis.

Figure 39: Net present value of mechanical ventilation with improved operation (billion £ 2020)

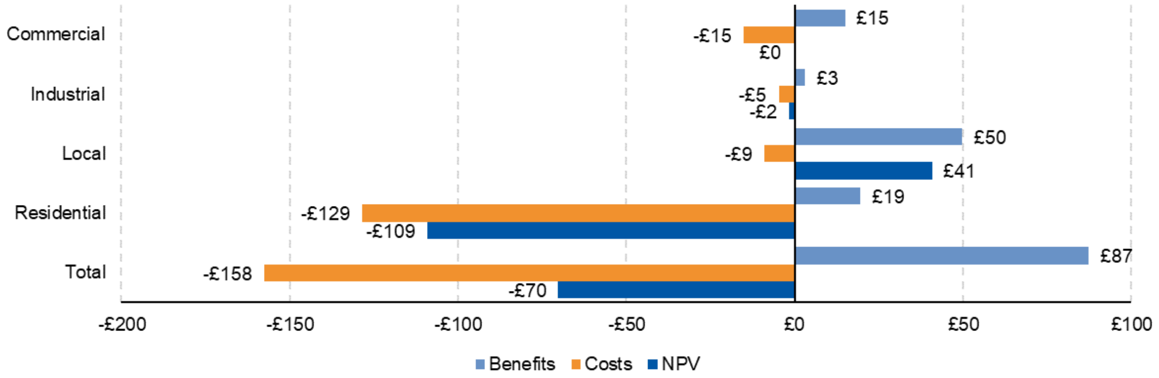
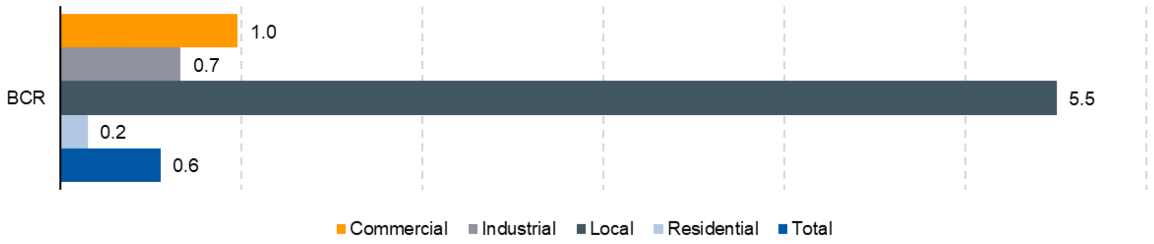


Figure 40: Benefit-cost ratio (BCR) mechanical ventilation with improved operation



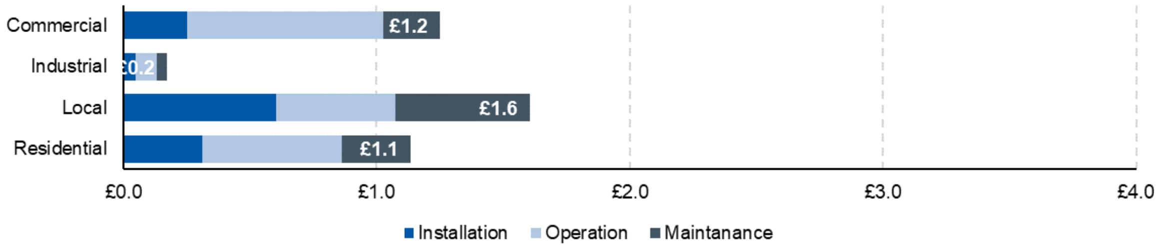
Source: NERA analysis.

5.3.3. Mechanical ventilation with lower costs

Next, we consider the impact of the extent to which lower installation, operation, and maintenance costs may impact the results. This is in line with our finding in Section 4.3.2 that installation costs from SPONS (2022) appear to be significantly higher than other sources, as well as our assumption where we take a higher percentage change in operational costs due to energy efficiency impacts than might be feasible according to Balocco & Leoncini (2020). Therefore, we take the lower figures for installation costs from Hawkins (2011) and assume that mechanical ventilation only increases operational costs by 7% (as compared to 15%).

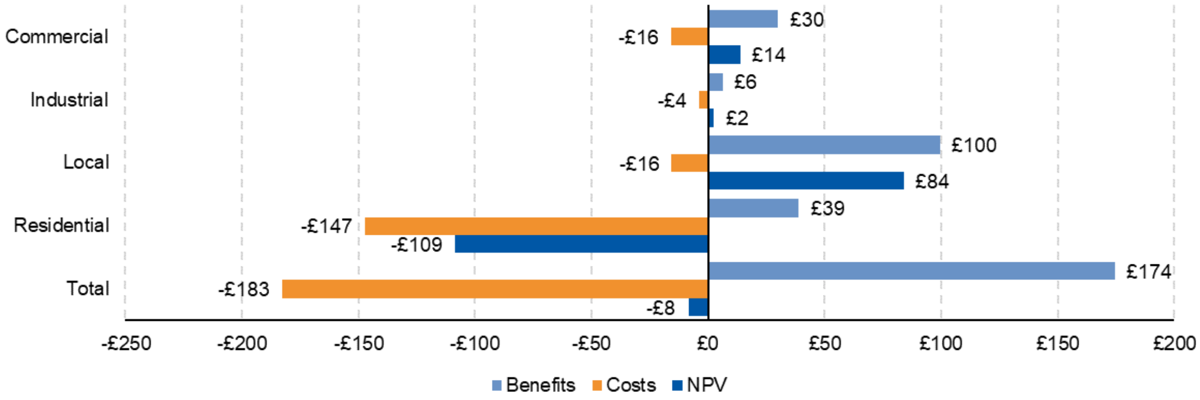
Figure 41 shows that overall costs per square meter effectively become about 75% lower for commercial, industrial, and residential buildings, while costs are about 60% lower for local buildings. Figure 42 and Figure 43 illustrate that the net present value of implementing and operating ventilation in commercial and industrial buildings become positive with BCRs of 1.9 and 1.6, respectively. Furthermore, the BCR for local buildings increases significantly to 6.3, while the BCR in residential buildings remains low.

Figure 41: Annual lifetime discounted costs (£ 2020 per m^2) of mechanical ventilation (lower costs)



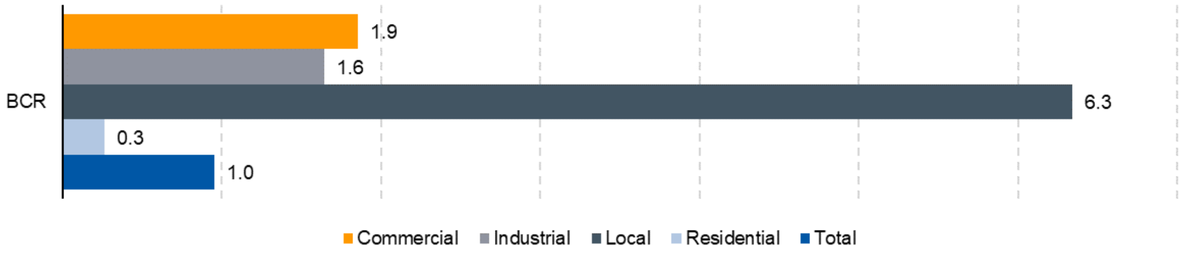
Source: NERA analysis.

Figure 42: Net present value of mechanical ventilation with lower costs (billions £ 2020)



Source: NERA analysis.

Figure 43: Benefit-cost ratio (BCR) mechanical ventilation (lower costs)



Source: NERA analysis.

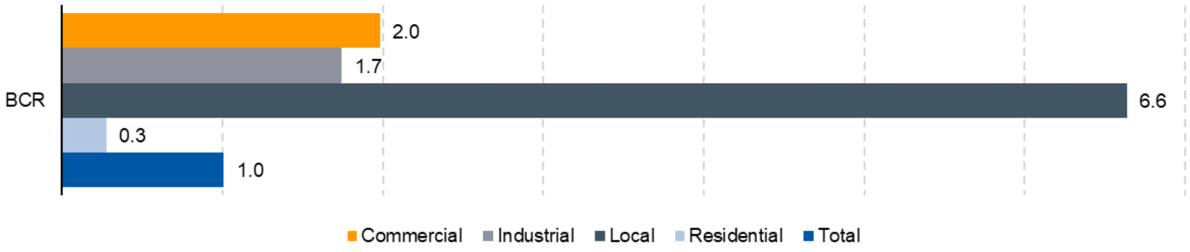
5.3.4. Mechanical ventilation combined with natural ventilation

Natural ventilation may offer operational savings. However, natural ventilation on its own has two key issues: (1) delivery of stable air flow rates that are required to reduce infection transmission and (2) thermal comfort, which are both dependent on outdoor environmental conditions. Furthermore, as the electricity costs of running ventilation only account for a small share of operational costs (between 15-25%), with the remaining share due to energy lost from heating and cooling the building that would still occur, adding natural ventilation may in fact only have a small impact on costs (Balocco & Leoncini, 2020).

Aviv et al. (2021), find that the weather in London is suitable for natural ventilation about 30% of the time (most of the time it is too cold). Given the lack of reliable data on what it actually costs to implement natural ventilation, we apply this estimate and assume that (1) the ventilation system is able to provide a constant flow of air at 10 l/s/p when natural ventilation is being used, (2) that operational costs decline by around 7.5% (25% x 30%), and (3) that installation and maintenance costs of the system remain the same as in Section 5.3.3. Therefore, we anticipate the benefits decline by 6% (20% x 30%). We note however that benefits may be lower if natural ventilation systems are unable to provide a constant flow of 10 l/s/p and that installation costs may in fact be higher due to requiring additional materials to allow for the option to naturally ventilate spaces.

Our findings are very similar to Section 5.3.3 as the only difference in costs is that operational costs decline by 6%, so the BCRs are very similar (see Figure 44), although the BCR of commercial buildings becomes 2.

Figure 44: Benefit-cost ratio (BCR) of mechanical ventilation with natural ventilation



Source: NERA analysis.

5.4. Wider benefits including productivity

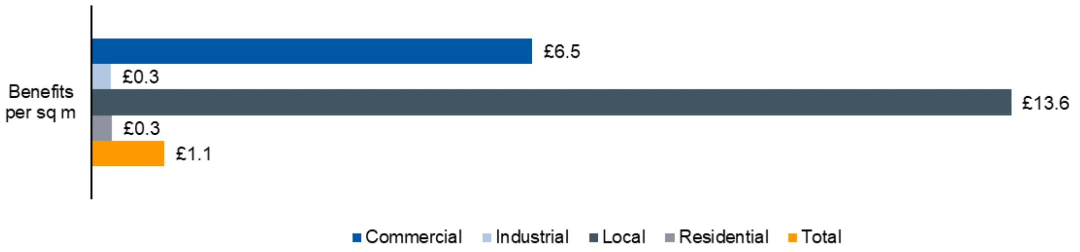
5.4.1. Expected benefits from ventilation including productivity

In the main analysis we focus on the benefits of ventilation for infection resilience. However, ventilation is also expected to have other health, social, and economic benefits. We provide a rough (conservative) estimate of the potential additional benefits from improved productivity. Taking a conservative (lower bound) estimate for the expected increase in productivity, a conservative measure of labour productivity (wages), and roughly accounting for selection effects by highly productive firms into well ventilated buildings, we find that the annual discounted benefits including productivity increase by around 50%, from £174 billion to £262 billion.

Figure 45 illustrates that the implied impact of including productivity on benefits per m^2 differs over building types. Benefits increase by £4.2 per m^2 (180% increase) in commercial buildings and £3.4 per m^2 (34% increase) in local buildings, with no change in industrial and residential buildings. The increase is relatively larger in commercial buildings as the benefits from improved infection resilience in commercial buildings (£2.3 per m^2) are lower than in local buildings (£10.2 per m^2). This implies that including productivity gains from ventilation may increase benefit cost ratios significantly for commercial buildings, to the extent that mechanical ventilation is likely to become cost effective under most cost scenarios.

These estimates are a rough approximation of the benefits from improved productivity and therefore we do not include them in the main cost-benefit analysis of infection resilience. However, this analysis demonstrates that the total societal benefits of improved ventilation may in fact be significantly higher, notably for commercial buildings.

Figure 45: Annual lifetime discounted benefits of ventilation per m^2 incl. productivity (£ 2020 billions)



Source: NERA analysis.

5.5. Uncertainty analysis

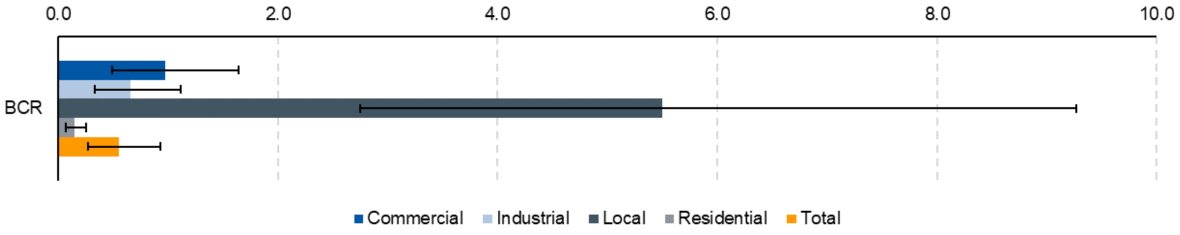
Measures to improve infection resilience and forecasts are inherently uncertain. In order to quantify how variations in underlying assumptions affect the final SCBA result, we consider how our baseline results change for following six areas of uncertainty, summarised in Table 4 below. To narrow the scope of the uncertainty analysis, we consider the 'middle' case of mechanical ventilation with improved operation as the baseline (Section 5.3.2). Furthermore, we refer to the lower bound as assumptions that are likely to reduce our estimated NPVs and BCRs, while upper bound assumptions are expected to increase these estimates.

Table 4: Uncertainty assumptions

Assumption	**Lower**	**Baseline**	**Upper**
Influenza-type pandemic likelihood	0.5%	1.6%	3.3%
Expected infection costs	50% lower	£1.3 trillion	50% higher
Share of aerosol transmission	20%	40%	60%
Effectiveness of ventilation	30%	50%	80%
Case distribution over environments		See Figure 17.	
Share of buildings requiring improved ventilation	25%	50%	75%

Note: See full list of results including descriptions is available in Appendix A.1.

Figure 46: Uncertainty bounds on BCRs for improved operation



Source: NERA analysis.

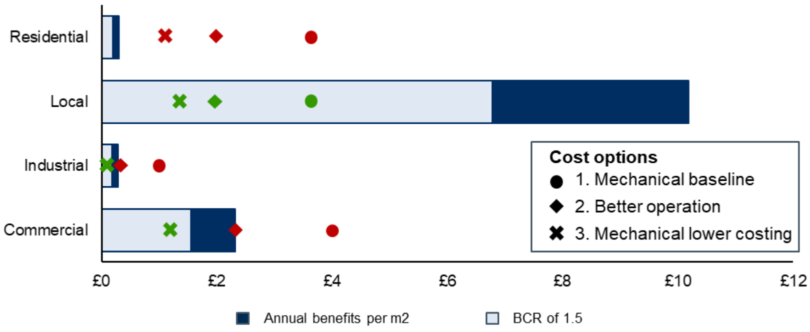
Figure 46 illustrates that although there is a wide range of uncertainty, the BCR in local buildings remains high given the alternative assumptions. Furthermore, given certain upper bound assumptions, implementing ventilation in commercial and industrial buildings becomes more attractive.

5.6. Discussion

We find that there is a very large number of benefits at stake (£1.3 trillion over a 60-year period) when considering infection resilient buildings. There are several ways of unlocking these benefits. We have focused on ventilation because we expect that a large share of transmission is due to aerosols, air quality in buildings is generally considered to be quite a low priority, and implementing ventilation is a long-term intervention that requires up-front investments and planning.

We find that ventilation can unlock about 13% of the total benefits (£174 billion), when the analysis is viewed throughan infection resilience lens. This depends on the effectiveness of ventilation in reducing transmission, the share of aerosol cases, the share of buildings requiring improvements, and the speed with which ventilation can be implemented. Therefore, although this impact is large, there is a lot at stake on the other interventions too. Further research should aim to consider ventilation alongside other interventions such as distancing measures.

Figure 47: Potential benefits that can be unlocked from improved ventilation through an infection resilience lens at various cost levels



Benefits (£ 2020)			
Annual		Lifetime (bn)	
Per m2	Total (bn)	Total	NPV
£0.3	£0.6	£40	-£109
£10.2	£1.7	£100	£84
£0.3	£0.1	£6	£2
£2.3	£0.5	£30	£14

Notes: Annual lifetime discounted benefits and costs in £ 2020. Lifetime benefits are the sum of annual infection resilient benefits over 60 years. Benefits do not include wider benefits of ventilation such as though improved productivity. Costs include installation, operation, and maintenance. Green indicates a benefit-cost ratio (BCR) of at least 1.5, indicating benefits are at least 1.5 times higher than costs (BCR > 1.5) while red indicates the BCR is below 1.5. Mechanical combined with natural ventilation has similar results as the lower costing scenario. The NPV (net present value) column is for the lowest cost option 3.

Figure 47 illustrates that in order to unlock the potential infection resilience benefits from ventilation, with benefits 1.5 times as high as costs (BCR ≥ 1.5), the annual lifetime discounted cost profile per square meter would need to be less than: £1.5 (commercial), £0.2 (industrial), £6.8 (local), and £0.2 (residential). Accounting for some of the wider benefits of ventilation, such as the expected increase in productivity implies that benefits in commercial and local buildings may be even higher.

It seems to us that a crucial policy question on ventilation is that of how best to get ventilation done effectively and efficiently. The benefits are so large that mechanical systems, while enormously costly, might make good sense in local buildings. Meanwhile, accounting for some of the wider benefits of ventilation such as productivity, make investment in commercial buildings far more attractive. If costs can be brought down in various ways, improving ventilation may work in other buildings as well. There are also some 'lower hanging fruits' that could be obtained in the short-term simply by ensuring that current systems work properly.

One might ask what the impact on our results may be if good quality ventilation is only implemented *partially* or in *all* environments. In the case that ventilation is only implemented in one building type, one concern might be that infection transmission simply shifts from one building type to another (i.e. from local to residential). We do not view this as problematic to our analysis because the result may in fact work in the opposite direction – with a reduction in cases in one building type resulting in less overall infection transmission due to a lower R number. Furthermore, it seems reasonable to expect that a lower overall probability of infection translates into fewer lower cases overall.

Meanwhile, if ventilation is implemented in *all* environments, people may change their behaviour due to a higher sense of security in buildings and therefore transmission may shift to different routes (e.g., from aerosols to direct contact or surfaces because they interact more closely or do not use a mask). This is difficult to quantify as one of our main assumptions is that behaviour does not change, however, we expect that the uncertainty analysis (for example that benefits decline by half) will capture this possibility to the best extent possible.

We should stress that our study focuses on average effects by aggregate building types which masks considerable heterogeneity within building types. A key implication is that rather than focusing on the potential adoption of mechanical ventilation in all buildings, we should be selective about what type of ventilation is installed and what the relative risk is in these buildings. This is true at the level of aggregation we have adopted in our analysis, but also suggests that it could be useful to carry out analysis at a more granular level in the future.

It is also important to highlight that these estimates do not account for potential wider benefits of ventilation beyond infection resilience. We attempt to provide a rough quantitative estimate for the impact on one wider benefit, productivity, that has a sufficient basis of evidence to quantify. Using a conservative estimate of the impact of ventilation and the measurement of labour productivity indicates that the discounted benefits per square meter may in fact be significantly higher for commercial (£6.5) and local (£13.6) buildings, although there is considerable uncertainty in these figures.

Finally, we note that the scope of our study does not encompass the negative externalities resulting from increased energy and material usage from the operation and installation of mechanical ventilation. Whilst we do investigate the change in energy costs, we do not investigate the third-party spill over effects or externalities (i.e., the costs of pollution not included in the price of energy). Including these types of negative externalities would increase the costs of intervention and may dampen BCRs. Meanwhile, shifting from heating buildings using gas powered boilers (the conventional approach in most UK buildings) to HVAC systems that can provide heating with electricity may be a long-term solution to shift away from fossil fuels if electricity can be supplied from renewable sources.

6. Conclusions

This is the first study, to our knowledge, to perform a comprehensive evaluation of health, social, and economic costs of pandemic and seasonal influenza and perform a rigorous social cost benefit analysis of ventilation.

We find that the total societal costs of influenza-type infection (health, social, and economic) are large and wide reaching. We estimate that the annual discounted expected cost of influenza type infection (pandemic and seasonal) in the UK is about £23 billion (or 1% of GDP in 2020) over a 60-year period, with influenza-type pandemics accounting for 64% of these costs. We also estimate that the total societal costs of a severe influenza-type pandemics in 2020 are about £1.3 trillion (or 60% GDP).

Most infection costs originate in local buildings such as schools, hospitals, and local community buildings (56%), with residential and commercial buildings accounting for a smaller share (20% and 17%, respectively). Our analysis suggests that industrial buildings, other buildings, and transport account for a small share of transmission (4%, 1%, and 1%, respectively). This corroborates recent findings based on COVID-19 as experts believe that a large share of transmission occurred in schools and hospitals, as these largely remained open during the pandemic, while there are likely to be fewer cases in commercial buildings, that largely remained closed, and public transport, as trip durations are short.

The total potential benefits that could be unlocked by ensuring buildings are fully infection resilient is £1.3 trillion (£ 2020) over a 60-year period. If buildings can be made fully infection resilient, it is reasonable to believe that most transmission can be averted which would effectively mitigate influenza type pandemic risk.

The focus of the cost-benefit analysis is on ventilation because the intervention can be clearly defined, has credible estimates on effectiveness, and requires major long-term investment in buildings to implement. We find that implementing improved ventilation (≥10 l/s/p) from poor ventilation (≤2 l/s/p) is expected to reduce aerosol transmission by about 50%. The total potential annual benefits of implementing improved ventilation (≥10 l/s/p) in all buildings that require improvements (assumed to be 50% in the baseline) is about £3 billion per year or £174 billion over a 60-year period. This is 13% of the total potential benefits and depends on the effectiveness of ventilation in reducing transmission, the share of aerosol cases, the share of buildings requiring improvements, and the speed with which ventilation can be implemented.

The average annual lifetime discounted benefits per square meter of floor space by building type is: £2.3 (commercial), £0.3 (industrial), £10.2 (local), and £0.3 (residential). This implies that the benefits per square meter are highest in local buildings and lowest in residential buildings and suggests that the approach to ventilation should vary by building type. These results suggest that we should prioritise low-cost interventions such as opening windows in residential and industrial buildings, while more expensive mechanical ventilation may be suitable for local and commercial buildings.

In order to unlock the potential benefits from ventilation, with benefits one and a half times as high as costs, the cost profile per square meter would need to be less than: £1.5 (commercial), £0.2 (industrial), £6.8 (local), and £0.2 (residential). Our current estimates for mechanical ventilation range between £1.2 – £4.0 for commercial buildings, £0.2 – £1.0 for industrial buildings, £1.6 – £3.8 for local buildings, and £1.1 – £3.8 for residential buildings. This implies that costs need to decline further for implementation of mechanical ventilation to make sense in residential buildings on average.

There are numerous different ways to unlock these benefits. We considered four main options:

1. Installing mechanical ventilation in all buildings that require improvements. Based on our baseline cost estimates from SPONS (2022), this is only cost effective from an infection resilience perspective in local buildings (NPV of £63 billion and BCR of 2.7).
2. Ensuring mechanical ventilation is operated properly in buildings that already have ventilation installed (behavioural solution) is more cost effective (NPV of £41 billion and BCR of 5.5 in local buildings), but the costs only just equal benefits for commercial buildings and are still too high to warrant improving ventilation in all industrial and residential buildings. This is because operating mechanical ventilation (even with heat recovery) increases the cost of heating buildings compared to the situation of no ventilation (although it may be cost saving compared to natural ventilation).
3. Cheaper mechanical ventilation could unlock significantly more benefits. When considering our lower bound cost estimates for installation from Hawkins (2011) and operation of mechanical ventilation, the net present value becomes positive for commercial (£14 billion), industrial (£2 billion), and local (£84 billion) buildings, with corresponding BCRs of 1.9, 1.6, and 6.3, respectively.
4. Cheaper mechanical ventilation combined with natural ventilation may also reduce operating costs further. However, this appears to only have a small impact on cost effectiveness as overall operating costs are expected to decline by about 6%.

These estimates do not account for potential wider benefits of ventilation beyond infection resilience. These potential wider benefits include reduced prevalence of sick building syndrome, lowers rates of asthma, lower exposure to air pollutants and improvements in productivity. We attempt to provide a rough quantitative estimate for the impact on productivity and show that using conservative estimates of the impact of ventilation and labour productivity suggests that the discounted benefits per square meter may in fact be significantly higher for commercial (£6.5) and local (£13.6) buildings. Although there is considerable uncertainty in these wider benefits, it seems plausible that the benefits of ventilation may be significantly larger if the wider benefits are fully accounted for.

Although we attempt to quantify the potential uncertainty in the analysis, there remain various quantifiable and unquantifiable unknowns. The modelling tool we have developed for RAEng will allow them, and potentially others, to explore the impact of a wide range of assumptions or interventions as society's understanding of key issues (such as transmission, infection impacts, and the costs of various interventions) develops over time It would for example be fairly easy to run the model with air cleaning interventions, such as HEPA filters, instead of ventilation, assuming that it delivers benefits comparable to improving ventilation, as it just requires replacing the installation, operation, and maintenance costs for ventilation with appropriate costs for air cleaning devices.

Further research should also consider the wider benefits of ventilation, the costs of retrofitting existing buildings, the costs and effectiveness of natural ventilation in more depth, the externalities of ventilation on the environment, the wider effects of ventilation, and carrying out the analysis at a more granular level. Uncertainty about other types of non-influenza-type viruses and how governments will respond to the next pandemic may also be important to account for. Finally, testing other non-linear mechanisms through which the ventilation impacts transmission and societal costs may also be relevant.

It is important to highlight that our model focuses on average effects which masks considerable heterogeneity in risk factors within aggregate building types and between social groups. Rather than adopting mechanical ventilation in all buildings, it will make sense to be selective about what type of ventilation is installed based on the relative risk in these buildings. Furthermore, although it is outside the scope of this analysis to capture distributional impacts, it is important to note that pandemics have been shown to have differential impacts along dimensions of gender, race, ethnicity, and social deprivation. Future research should therefore consider the analysis at a more granular level and the distributional impacts in more detail.

It is also important to acknowledge that we focus on mechanical ventilation because it was not clear whether conventional approaches to natural ventilation are sufficiently effective to provide a constant flow of fresh air under various conditions and we were unable to find reliable estimates of the costs of implementing natural ventilation at scale. Future research should also consider the effectiveness of natural ventilation in more depth.

Finally, we note that the scope of our study does not encompass the negative externalities resulting from increased energy usage due to mechanical ventilation. Whilst we do investigate the change in energy costs, we do not investigate the third-party spill over effects or externalities (i.e., the costs of pollution not included in the price of energy). Including these types of negative externalities would increase the costs of intervention and may dampen BCRs. Meanwhile, shifting from heating buildings using gas powered boilers (the conventional approach in most UK buildings) to HVAC systems that can provide heating with electricity may be a long-term solution to shift away from fossil fuels if electricity can be supplied from renewable sources.

Appendix A. Model assumptions and uncertainty analysis

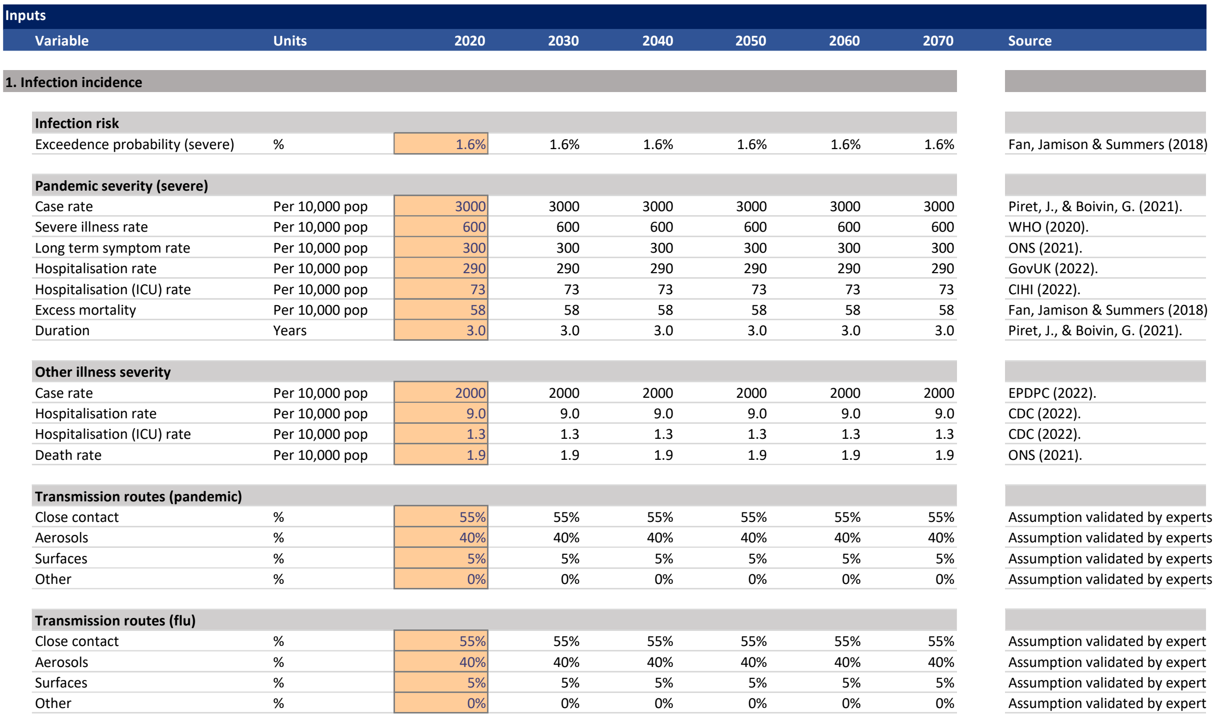
A.1. Model assumptions

The model assumptions and calculations are documented in the main model framework as well as several supplementary Excel files. Together with the report, we have provided RAEng with:

1. 220606 Model framework SCBA.xlsx – Main model framework where we document all assumptions, perform key CBA calculations, and prepare key figures in the report.
2. 220309 Transmission model environments.xlsx – Document how we estimate the distribution of cases over environments.
3. 220304 Cost model.xlsx and 220304 Cost model (low).xlsx – Documents how we estimate installation, operation, and maintenance costs for ventilation cost options (1) and (3).
4. 220301 List infection impacts.xlsx – Documents additional notes on calculations and complete list of impacts (including those that we were unable to quantify).

These files can be requested from RAEng, subject to a review process. See Figures 48 to 51 for baseline assumptions and Figure 52 for intervention assumptions. Orange cells indicate input assumptions, while other cells are calculations or are assumed to remain the same over time. The rationale for each assumption is documented in the main report.

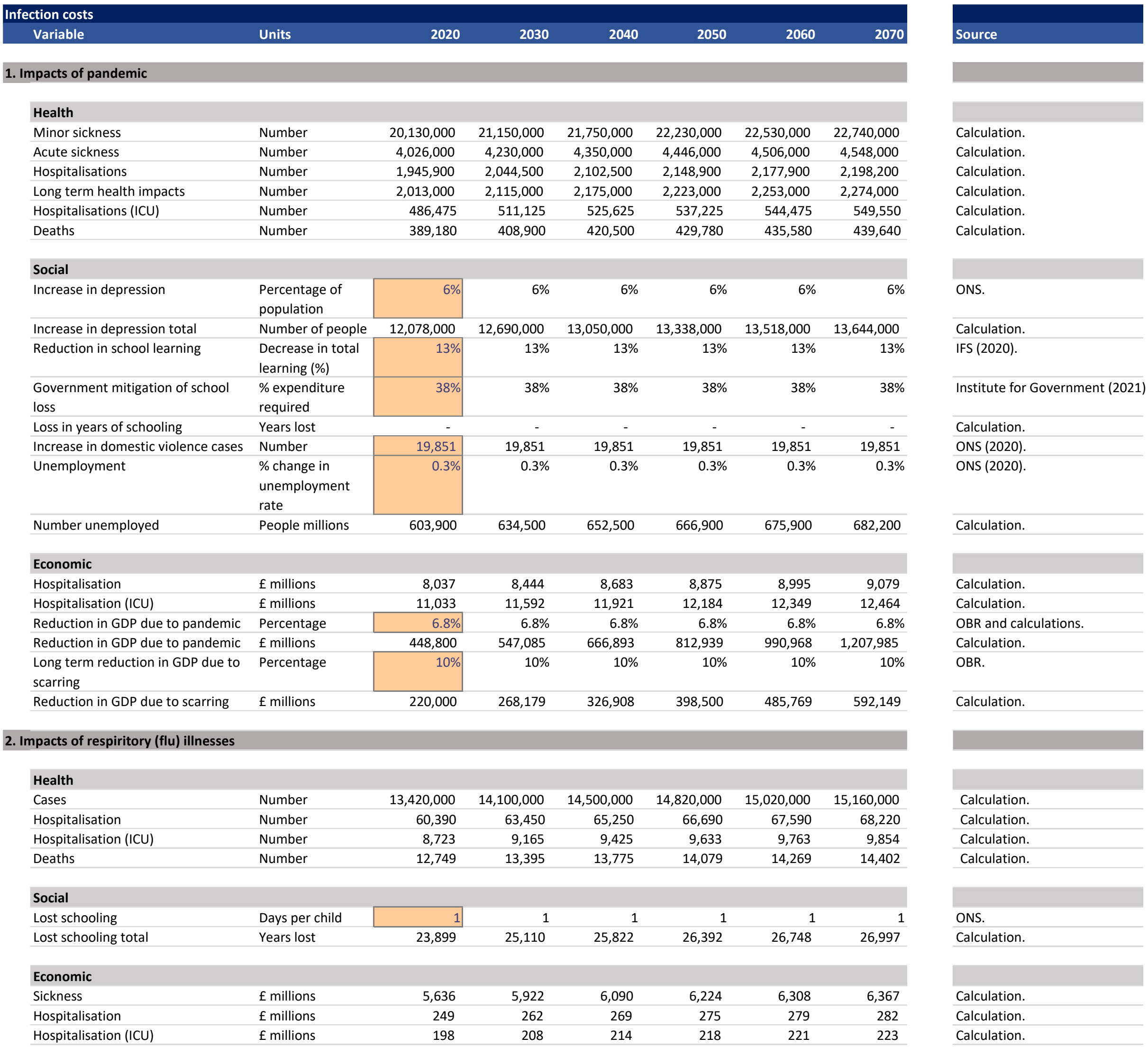
Figure 48: Model assumptions – Infection incidence



Inputs								
Variable	Units	2020	2030	2040	2050	2060	2070	Source
1. Infection incidence								
Infection risk								
Exceedence probability (severe)	%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	Fan, Jamison & Summers (2018)
Pandemic severity (severe)								
Case rate	Per 10,000 pop	3000	3000	3000	3000	3000	3000	Piret, J., & Boivin, G. (2021).
Severe illness rate	Per 10,000 pop	600	600	600	600	600	600	WHO (2020).
Long term symptom rate	Per 10,000 pop	300	300	300	300	300	300	ONS (2021).
Hospitalisation rate	Per 10,000 pop	290	290	290	290	290	290	GovUK (2022).
Hospitalisation (ICU) rate	Per 10,000 pop	73	73	73	73	73	73	CIHI (2022).
Excess mortality	Per 10,000 pop	58	58	58	58	58	58	Fan, Jamison & Summers (2018)
Duration	Years	3.0	3.0	3.0	3.0	3.0	3.0	Piret, J., & Boivin, G. (2021).
Other illness severity								
Case rate	Per 10,000 pop	2000	2000	2000	2000	2000	2000	EPDPC (2022).
Hospitalisation rate	Per 10,000 pop	9.0	9.0	9.0	9.0	9.0	9.0	CDC (2022).
Hospitalisation (ICU) rate	Per 10,000 pop	1.3	1.3	1.3	1.3	1.3	1.3	CDC (2022).
Death rate	Per 10,000 pop	1.9	1.9	1.9	1.9	1.9	1.9	ONS (2021).
Transmission routes (pandemic)								
Close contact	%	55%	55%	55%	55%	55%	55%	Assumption validated by experts
Aerosols	%	40%	40%	40%	40%	40%	40%	Assumption validated by experts
Surfaces	%	5%	5%	5%	5%	5%	5%	Assumption validated by experts
Other	%	0%	0%	0%	0%	0%	0%	Assumption validated by experts
Transmission routes (flu)								
Close contact	%	55%	55%	55%	55%	55%	55%	Assumption validated by expert
Aerosols	%	40%	40%	40%	40%	40%	40%	Assumption validated by expert
Surfaces	%	5%	5%	5%	5%	5%	5%	Assumption validated by expert
Other	%	0%	0%	0%	0%	0%	0%	Assumption validated by expert

Source: NERA analysis.

Figure 49: Model assumptions – Infection costs



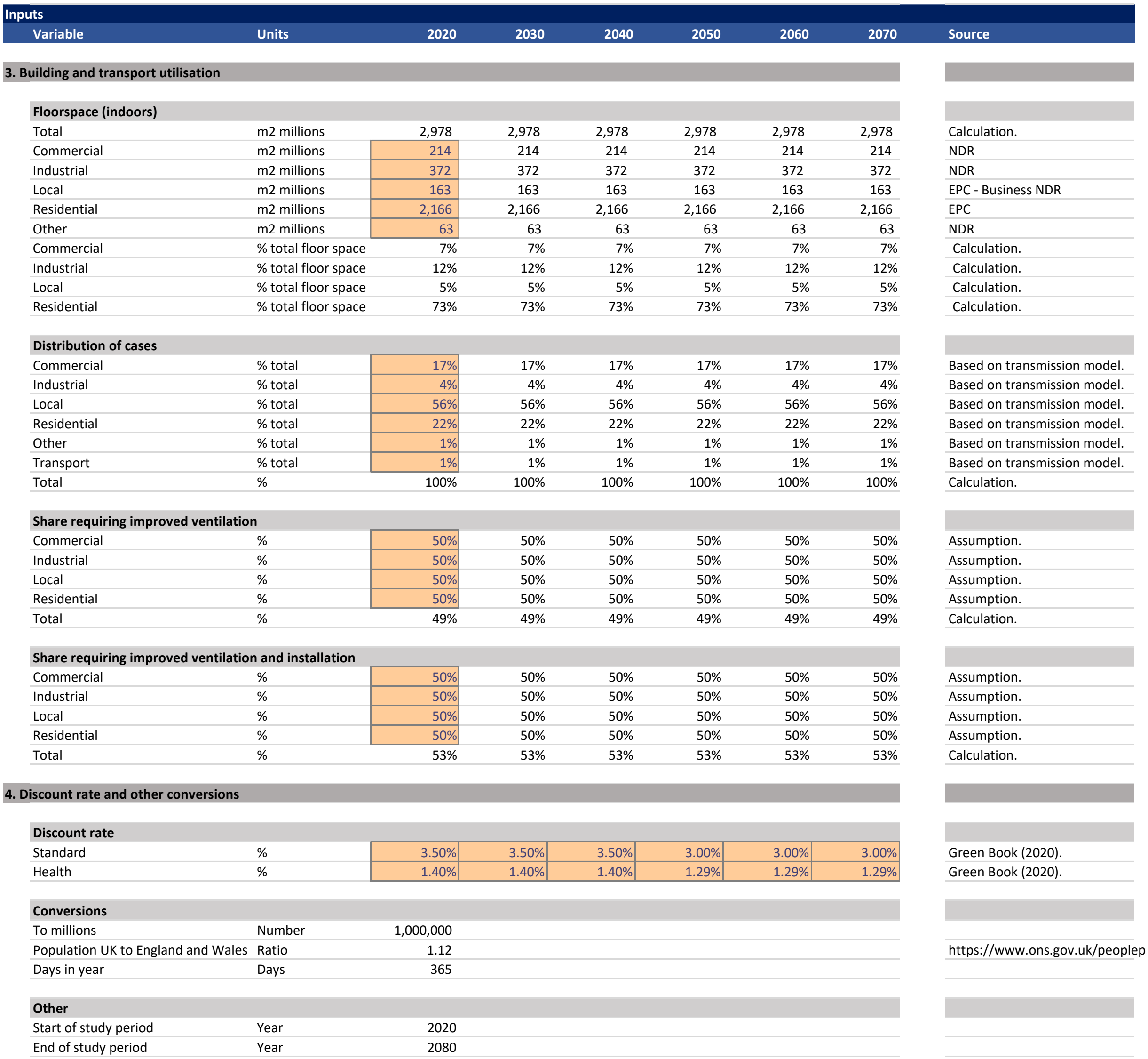
Infection costs								
Variable	**Units**	**2020**	**2030**	**2040**	**2050**	**2060**	**2070**	**Source**
1. Impacts of pandemic								
Health								
Minor sickness	Number	20,130,000	21,150,000	21,750,000	22,230,000	22,530,000	22,740,000	Calculation.
Acute sickness	Number	4,026,000	4,230,000	4,350,000	4,446,000	4,506,000	4,548,000	Calculation.
Hospitalisations	Number	1,945,900	2,044,500	2,102,500	2,148,900	2,177,900	2,198,200	Calculation.
Long term health impacts	Number	2,013,000	2,115,000	2,175,000	2,223,000	2,253,000	2,274,000	Calculation.
Hospitalisations (ICU)	Number	486,475	511,125	525,625	537,225	544,475	549,550	Calculation.
Deaths	Number	389,180	408,900	420,500	429,780	435,580	439,640	Calculation.
Social								
Increase in depression	Percentage of population	6%	6%	6%	6%	6%	6%	ONS.
Increase in depression total	Number of people	12,078,000	12,690,000	13,050,000	13,338,000	13,518,000	13,644,000	Calculation.
Reduction in school learning	Decrease in total learning (%)	13%	13%	13%	13%	13%	13%	IFS (2020).
Government mitigation of school loss	% expenditure required	38%	38%	38%	38%	38%	38%	Institute for Government (2021)
Loss in years of schooling	Years lost	-	-	-	-	-	-	Calculation.
Increase in domestic violence cases	Number	19,851	19,851	19,851	19,851	19,851	19,851	ONS (2020).
Unemployment	% change in unemployment rate	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	ONS (2020).
Number unemployed	People millions	603,900	634,500	652,500	666,900	675,900	682,200	Calculation.
Economic								
Hospitalisation	£ millions	8,037	8,444	8,683	8,875	8,995	9,079	Calculation.
Hospitalisation (ICU)	£ millions	11,033	11,592	11,921	12,184	12,349	12,464	Calculation.
Reduction in GDP due to pandemic	Percentage	6.8%	6.8%	6.8%	6.8%	6.8%	6.8%	OBR and calculations.
Reduction in GDP due to pandemic	£ millions	448,800	547,085	666,893	812,939	990,968	1,207,985	Calculation.
Long term reduction in GDP due to scarring	Percentage	10%	10%	10%	10%	10%	10%	OBR.
Reduction in GDP due to scarring	£ millions	220,000	268,179	326,908	398,500	485,769	592,149	Calculation.
2. Impacts of respiritory (flu) illnesses								
Health								
Cases	Number	13,420,000	14,100,000	14,500,000	14,820,000	15,020,000	15,160,000	Calculation.
Hospitalisation	Number	60,390	63,450	65,250	66,690	67,590	68,220	Calculation.
Hospitalisation (ICU)	Number	8,723	9,165	9,425	9,633	9,763	9,854	Calculation.
Deaths	Number	12,749	13,395	13,775	14,079	14,269	14,402	Calculation.
Social								
Lost schooling	Days per child	1	1	1	1	1	1	ONS.
Lost schooling total	Years lost	23,899	25,110	25,822	26,392	26,748	26,997	Calculation.
Economic								
Sickness	£ millions	5,636	5,922	6,090	6,224	6,308	6,367	Calculation.
Hospitalisation	£ millions	249	262	269	275	279	282	Calculation.
Hospitalisation (ICU)	£ millions	198	208	214	218	221	223	Calculation.

Source: NERA analysis.

Figure 50: Model assumptions – Valuation techniques

Inputs								
Variable	**Units**	**2020**	**2030**	**2040**	**2050**	**2060**	**2070**	**Source**
2. Valuation techniques								
Health (pandemic)								
QALY	£	60,000	60,000	60,000	60,000	60,000	60,000	Green Book (2020).
HRQOL minor sickness	Difference	0.2	0.2	0.2	0.2	0.2	0.2	Approximation.
Duration minor sickness	days	7	7	7	7	7	7	Nuffield Trust. (2021).
Health cost of minor sickness	£	230	230	230	230	230	230	Calculation.
HRQOL acute sickness	£ per day	0.4	0.4	0.4	0.4	0.4	0.4	Guest et al. (2020).
Duration acute sickness	days	7	7	7	7	7	7	Nuffield Trust. (2021).
Health cost of hospitalisation	£	460	460	460	460	460	460	Calculation.
HRQOL acute sickness ICU	£ per day	0.52	0.52	0.52	0.52	0.52	0.52	Guest et al. (2020).
Duration acute sickness ICU	days	14	14	14	14	14	14	Shryane et al. (2020).
Health cost of hospitalisation ICU	£	1,197	1,197	1,197	1,197	1,197	1,197	Calculation.
HRQOL long-term symptoms	Difference	0.2	0.2	0.2	0.2	0.2	0.2	Poudel et al. (2021).
Health cost of long-term illness	£	12,000	12,000	12,000	12,000	12,000	12,000	Calculation.
Age of death due to pandemic illness	Median age	75	75	75	75	75	75	ONS (2021) and Luk (2001).
Years of life lost due to pandemic illness	Life expectancy at ag	11	12	13	13	14	15	Life tables, principal projection, U
Value of each life lost due to pandemic illness	£ per death	652,020	722,347	756,029	797,328	839,731	881,853	Calculation.
Health (other resipiratory)								
HRQOL minor sickness	Difference	0.1	0.1	0.1	0.1	0.1	0.1	Approximation.
Duration minor sickness	days	7	7	7	7	7	7	CDC.
Health cost of minor sickness	£	115	115	115	115	115	115	Calculation.
HRQOL acute sickness	£ per day	0.2	0.2	0.2	0.2	0.2	0.2	Guest et al. (2020).
Duration acute sickness	days	6	6	6	6	6	6	Milenkovic et al. (2006)
Health cost of hospitalisation	£	197	197	197	197	197	197	Calculation.
HRQOL acute sickness ICU	£ per day	0.2	0.2	0.2	0.2	0.2	0.2	Guest et al. (2020).
Duration acute sickness ICU	days	14	14	14	14	14	14	Shryane et al. (2020).
Health cost of hospitalisation ICU	£	460	460	460	460	460	460	Calculation.
Average age of death due to (non-pandemic) respiritory illness	Age	85	85	85	85	85	85	ONS.
Years of life lost due to (non-pandemic) respiritory illness	Life expectancy at ag	5	6	6	7	7	7	Calculation.
Value of each life lost due to (non-pandemic) respiritory illness	£ per death	309,069	349,541	368,481	393,954	421,159	448,664	Calculation.
Social								
Population size	Millions	67.1	70.5	72.5	74.1	75.1	75.8	PopulationPyramid
Share children in education	%	13%	13%	13%	13%	13%	13%	IFS (2021).
Share of working age adults in employment	%	48%	48%	48%	48%	48%	48%	ONS.
Number of children in education	Millions	8.7	9.2	9.4	9.6	9.8	9.9	Calculation.
Number of working age adults in employment	Millions	32.2	33.8	34.8	35.6	36.0	36.4	Calculation.
HRQOL depression	Difference	0.3	0.3	0.3	0.3	0.3	0.3	Jia et al. (2015)
Cost of depression	£	18,000	18,000	18,000	18,000	18,000	18,000	Jia et al. (2015)
Societal return to year of education	% share of lifetime earnings	9%	9%	9%	9%	9%	9%	Psacharopoulos and Patrinos (20
Discounted lifetime earnings	£	515,000	515,000	515,000	515,000	515,000	515,000	GovUK.
Value of lost year of education	£	45,320	45,320	45,320	45,320	45,320	45,320	Calculation.
Societal cost of unemployment	£	18,000	18,000	18,000	18,000	18,000	18,000	Fujiwara & Campbell (2011).
Annual economic and social cost of domestic violence per victim	£	34,015	34,015	34,015	34,015	34,015	34,015	Home Office (2019).
Economic								
Cost of hospital bed	£ per day	590	590	590	590	590	590	Guest et al. (2020).
Duration in hospital bed	days	7	7	7	7	7	7	Nuffield Trust. (2021).
Cost of non-ICU hospitalisation	£	4,130	4,130	4,130	4,130	4,130	4,130	Calculation.
Cost of ICU bed	£ per day	1620	1620	1620	1620	1620	1620	Guest et al. (2020).
Duration in ICU bed	days	14	14	14	14	14	14	Shryane et al. (2020).
Cost of ICU hospitalisation	£	22,680	22,680	22,680	22,680	22,680	22,680	Calculation.
Time off work due to severe illness	days	7	7	7	7	7	7	Nuffield Trust. (2021).
Sickness costs due to severe illness	£ per day	175	175	175	175	175	175	ONS.
Time off work due to isolation	days	5	5	5	5	5	5	UK isolation rules.
Cost of days off due to severe illness	£	1225	1225	1225	1225	1225	1225	Calculation.
Costs of days off due to isolation	£	875	875	875	875	875	875	Calculation.
Real GDP growth rate	Annual %	2%	2%	2%	2%	2%	2%	Green Book (2020).
Real GDP	£ millions	2,200,000	2,681,788	3,269,084	3,984,995	4,857,687	5,921,494	ONS and forecast is calculated.
Productivity								
Wage growth	%	2%	2%	2%	2%	2%	2%	Assumption.
Wage adjustment	%	50%	50%	50%	50%	50%	50%	Assumption.
Share of employees in commercial	%	35%	35%	35%	35%	35%	35%	ONS and calculations.
Wages commercial	£ per year	36,830	36,830	36,830	36,830	36,830	36,830	ONS.
Wages commercial adjusted	£ per year	18,415	22,448	27,364	33,356	40,661	49,566	ONS.
Number of employees in commercial	Millions	11.3	11.8	12.2	12.4	12.6	12.7	Calculation.
Total wages commercial impacted	£ millions	207,589	265,872	333,290	415,245	513,012	631,188	Calculation.
Share of employees in local	%	30%	30%	30%	30%	30%	30%	ONS and calculations.
Wages local	£ per year	26,686	26,686	26,686	26,686	26,686	26,686	ONS.
Wages local adjusted	£ per year	13,343	16,265	19,827	24,169	29,462	35,914	ONS.
Number of employees in local	Millions	9.7	10.2	10.4	10.7	10.8	10.9	Calculation.
Total wages local	£ millions	128,925	165,123	206,994	257,893	318,612	392,007	Calculation.

Figure 51: Model assumptions – Behaviour, environments, and discount rates



Inputs Variable	Units	2020	2030	2040	2050	2060	2070	Source
3. Building and transport utilisation								
Floorspace (indoors)								
Total	m2 millions	2,978	2,978	2,978	2,978	2,978	2,978	Calculation.
Commercial	m2 millions	214	214	214	214	214	214	NDR
Industrial	m2 millions	372	372	372	372	372	372	NDR
Local	m2 millions	163	163	163	163	163	163	EPC - Business NDR
Residential	m2 millions	2,166	2,166	2,166	2,166	2,166	2,166	EPC
Other	m2 millions	63	63	63	63	63	63	NDR
Commercial	% total floor space	7%	7%	7%	7%	7%	7%	Calculation.
Industrial	% total floor space	12%	12%	12%	12%	12%	12%	Calculation.
Local	% total floor space	5%	5%	5%	5%	5%	5%	Calculation.
Residential	% total floor space	73%	73%	73%	73%	73%	73%	Calculation.
Distribution of cases								
Commercial	% total	17%	17%	17%	17%	17%	17%	Based on transmission model.
Industrial	% total	4%	4%	4%	4%	4%	4%	Based on transmission model.
Local	% total	56%	56%	56%	56%	56%	56%	Based on transmission model.
Residential	% total	22%	22%	22%	22%	22%	22%	Based on transmission model.
Other	% total	1%	1%	1%	1%	1%	1%	Based on transmission model.
Transport	% total	1%	1%	1%	1%	1%	1%	Based on transmission model.
Total	%	100%	100%	100%	100%	100%	100%	Calculation.
Share requiring improved ventilation								
Commercial	%	50%	50%	50%	50%	50%	50%	Assumption.
Industrial	%	50%	50%	50%	50%	50%	50%	Assumption.
Local	%	50%	50%	50%	50%	50%	50%	Assumption.
Residential	%	50%	50%	50%	50%	50%	50%	Assumption.
Total	%	49%	49%	49%	49%	49%	49%	Calculation.
Share requiring improved ventilation and installation								
Commercial	%	50%	50%	50%	50%	50%	50%	Assumption.
Industrial	%	50%	50%	50%	50%	50%	50%	Assumption.
Local	%	50%	50%	50%	50%	50%	50%	Assumption.
Residential	%	50%	50%	50%	50%	50%	50%	Assumption.
Total	%	53%	53%	53%	53%	53%	53%	Calculation.
4. Discount rate and other conversions								
Discount rate								
Standard	%	3.50%	3.50%	3.50%	3.00%	3.00%	3.00%	Green Book (2020).
Health	%	1.40%	1.40%	1.40%	1.29%	1.29%	1.29%	Green Book (2020).
Conversions								
To millions	Number	1,000,000						
Population UK to England and Wales	Ratio	1.12						https://www.ons.gov.uk/peoplep
Days in year	Days	365						
Other								
Start of study period	Year	2020						
End of study period	Year	2080						

Source: NERA analysis.

Figure 52: Model assumptions – Intervention parameters, effectiveness, and costs

Interventions								
Variable	**Units**	**2020**	**2030**	**2040**	**2050**	**2060**	**2070**	**Source**
1.Policy parameters								
Construction: installation in period								
Commercial	%	100%	0%	0%	100%	0%	0%	Assumption (see Figure 7).
Industrial	%	100%	0%	0%	100%	0%	0%	Assumption (see Figure 7).
Local	%	100%	0%	0%	100%	0%	0%	Assumption (see Figure 7).
Residential	%	100%	0%	0%	100%	0%	0%	Assumption (see Figure 7).
Total	%	98%	0%	0%	98%	0%	0%	Calculation.
Benefits: share of buildings that require improved ventilation that get improved ventilation								
Commercial	%	50%	100%	100%	100%	100%	100%	Assumption (see Figure 7).
Industrial	%	50%	100%	100%	100%	100%	100%	Assumption (see Figure 7).
Local	%	50%	100%	100%	100%	100%	100%	Assumption (see Figure 7).
Residential	%	50%	100%	100%	100%	100%	100%	Assumption (see Figure 7).
Total	%	49%	98%	98%	98%	98%	98%	Calculation.
2. Effectiveness								
Effectiveness (pandemic)								
Reduction in aerosol cases (direct)	% cases	50%	50%	50%	50%	50%	50%	See Section 4.2.
Effectiveness (respiritory illnesses)								
Reduction in aerosol cases (direct)	% cases	50%	50%	50%	50%	50%	50%	See Section 4.2.
Performance at work								
Value of additional productivity	Annual %	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	Seppanen, Fisk & Lei (2006).
3. Costs								
Installation costs								
Installation frequency	Years	30	30	30	30	30	30	CIBSE (2014).
Installation								
Commercial	£ m2	27	27	27	27	27	27	See cost model.
Industrial	£ m2	5	5	5	5	5	5	See cost model.
Local	£ m2	64	64	64	64	64	64	See cost model.
Residential	£ m2	33	33	33	33	33	33	See cost model.
Residual value	£/m2	0	0	0	0	0	0	Assumption (see Figure 7).
Share of benefits from installation that will materialise if installation occurs in decade								
Years remaining	Years	60	50	40	30	20	10	See cost model.
Installation lifetime not materialising	Years	0	0	0	5	15	25	Calculation (see Figure 7).
Benefits that will materialise	%	100%	100%	100%	83%	50%	17%	Calculation (see Figure 7).
Operational costs								
Operation (electricity + energy)								
Commercial	£ m2 year	2.1	2.1	2.1	2.1	2.1	2.1	See cost model.
Industrial	£ m2 year	0.2	0.2	0.2	0.2	0.2	0.2	See cost model.
Local	£ m2 year	1.3	1.3	1.3	1.3	1.3	1.3	See cost model.
Residential	£ m2 year	1.5	1.5	1.5	1.5	1.5	1.5	See cost model.
Maintanance costs								
Maintenance	£ m2 year							
Commercial	£ m2 year	0.6	0.6	0.6	0.6	0.6	0.6	See cost model.
Industrial	£ m2 year	0.1	0.1	0.1	0.1	0.1	0.1	See cost model.
Local	£ m2 year	1.4	1.4	1.4	1.4	1.4	1.4	See cost model.
Residential	£ m2 year	0.7	0.7	0.7	0.7	0.7	0.7	See cost model.

Source: NERA analysis.

A.2. Valuation techniques

See Table 5 and Table 6 for measurement approach and sources, documented more fully in supplementary Excel file: 220301 List infection impacts.

Table 5: Valuation techniques per incident (influenza-type pandemic impacts)

Type	Measurement	Value	Source
Health			
Sickness	[1- HRQoL minor COVID] x QALY x Duration years	£230	Approximation.
Hospitalisation	[1 - HRQoL acute COVID] x QALY x Duration years	£460	Poudel et al. (2021).
Long-term illness	[1 - HRQoL long COVID] x QALY x Duration years	£12,000	Poudel et al. (2021).
Hospitalisation (ICU)	[1 - HRQoL acute COVID ICU] x QALY x Duration years	£1,200	Poudel et al. (2021).
Death	Life expectancy at average age of death x QALY	£652,000	Calculations.
Social			
Deterioration in mental health			
Depression	[HRQoL no depression - HRQoL depression] x QALY x Duration years	£18,000	Jia et al. (2015).
Unemployment	Subjective well-being value of unemployment per year	£18,000	Fujiwara & Campbell (2011).
Lost education	Private value of year of education x Discounted lifetime earnings	£45,000	Psacharopoulos and Patrinos (2018).
Domestic violence	Value of domestic violence	£34,000	Home Office (2019).
Economic			
Hospitalisation	Cost of hospital bed x Duration days	£4,130	Guest et al. (2020).
Hospitalisation (severe)	Cost of ICU bed x Duration days	£22,680	Guest et al. (2020).
Reduction in GDP during pandemic	Direct valuation	NA	OBR and calculations.
Long-term reduction in GDP (scarring)	Direct valuation	NA	OBR and calculations.

Notes: See 220301 List infection impacts Excel file for additional notes on calculations and complete list of impacts (including seasonal influenza and those that we were unable to quantify). Values are rounded.

Table 6: Valuation techniques per incident (seasonal influenza impacts)

Type	Measurement	Value	Source
Health			
Sickness	[1- HRQoL minor COVID*0.5] x QALY x Duration years	£115	Approximation.
Hospitalisation	[1 - HRQoL acute COVID*0.5] x QALY x Duration years	£200	Poudel et al. (2021).
Hospitalisation (ICU)	[1 - HRQoL acute COVID ICU*0.5] x QALY x Duration years	£460	Poudel et al. (2021).
Death	Life expectancy at average age of death x QALY	£310,000	Calculations.
Social			
Lost education	Private value of year of education x Discounted lifetime earnings	£45,000	Psacharopoulos and Patrinos (2018).
Economic			
Lost work hours	Average value added per day x Duration days	£875	ONS (2020).
Hospitalisation	Cost of hospital bed x Duration days	£4,130	Guest et al. (2020).
Hospitalisation (severe)	Cost of ICU bed x Duration days	£22,680	Guest et al. (2020).

Notes: See 220301 List infection impacts Excel file for additional notes on calculations and complete list of impacts (including influenza-type pandemics and those that we were unable to quantify). Values are rounded.

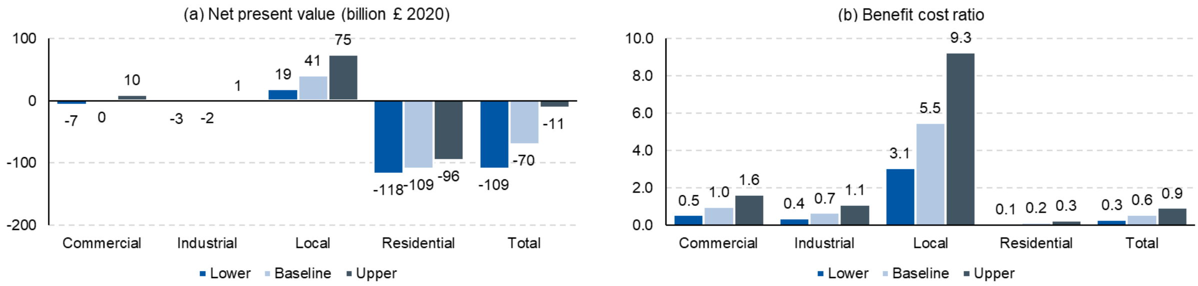
A.3. Uncertainty analysis

A.3.1. Influenza-type pandemic likelihood

Due to the irregularity and infrequency of severe pandemics historically, the empirical literature is inconclusive on the exact exceedance probability of a future influenza-type pandemic. Therefore, we test the sensitivity of our results in Section 5.3.2 with an assumed lower bound for the exceedance probability of 0.5% and an upper bound of 3.3%. This implies an average frequency of major pandemics of every 200 years and 30 years, respectively.

Figure 53 illustrates the NPV and BCR given our range of assumptions on infection likelihood. If infection likelihood is a lower, this implies smaller NPVs and BCRs as the benefits of investing in infection resilient infrastructure decline (there is no effect on costs of installation, operation, and maintenance). The results suggest that investing in ventilation in local buildings still has high returns and may be significantly larger if infection likelihood is greater than our baseline assumption (BCR of 9.3).

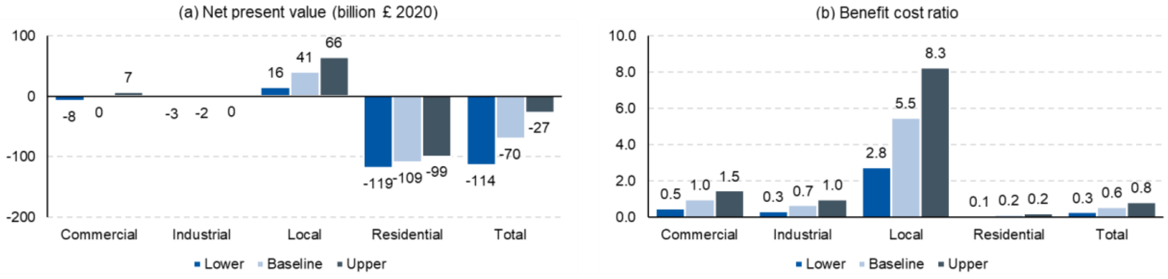
Figure 53: Uncertainty analysis infection likelihood



A.3.2. Expected infection costs

Our current analysis of infection costs includes many subcomponents relating to the health, social and economic impacts of pandemics and subsequent lockdowns. We explore uncertainty in this aspect by considering the overall baseline estimate of infection costs and applying 50% variation (lower and higher) to this estimate. For example, increasing (decreasing) the infection cost by 50% will lead to a total infection cost of £2 trillion (£0.7 trillion) over the entire period and therefore a greater (smaller) impact of implementing ventilation since the mitigated costs of infection are greater. Figure 54 shows that the BCR when investing in local buildings increases from 5.5 to 8.3 if infection costs are 50% higher. When infection costs are 50% smaller the BCR decreases from 5.5 to 2.8.

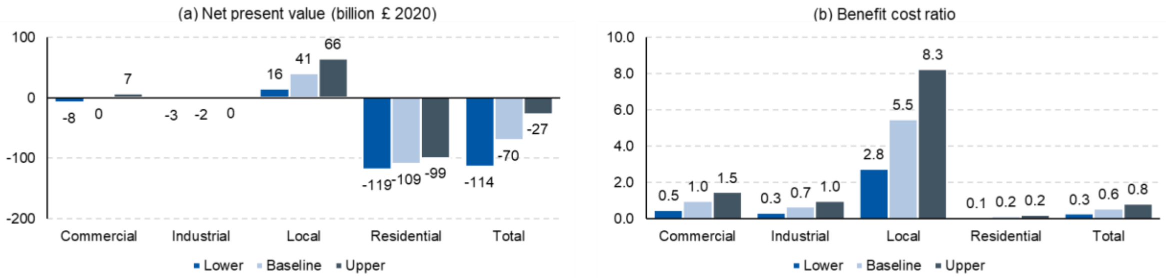
Figure 54: Uncertainty analysis expected infection costs



A.3.3. Share of aerosol transmission

Assessing the importance of the aerosol transmission route is important given that ventilation only impacts aerosol transmission. In the baseline we assume that aerosol transmission accounts for 40% of transmission. Increasing this percentage will increase the effectiveness of ventilation since ventilation only impacts the aerosol transmission route. This in turn will lead to higher net present values and higher BCRs. Figure 55 shows that increasing the share of aerosol transmission to 60% (a 50% increase) also results in a BCR in local buildings to 8.3. On the other hand, reducing the share of aerosol transmission to 20% (a 50% reduction) results in a BCR in local buildings to 2.8. As can be seen, the impact of changing the size of the benefits and the share of aerosol transmission has the same impact on the baseline results because each assumption targets the benefits of ventilation in the same way.

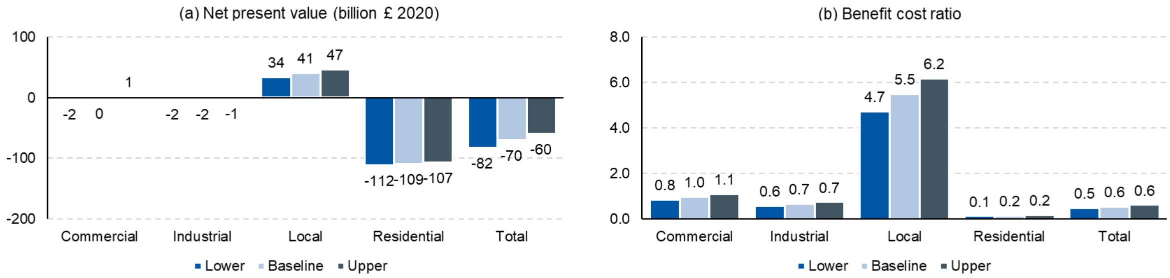
Figure 55: Uncertainty analysis aerosol transmission



A.3.4. Effectiveness of ventilation in reducing case rates

Figure 56 indicates how implementation of ventilation in local buildings increases the BCR from 5.5 to 6.2 when the effectiveness increases from 50% to 80%. The effect is not linear as a higher effectiveness also means a smaller share of cases can be averted as ventilation is more effective at averting cases in well ventilated buildings (see Section 2.3.1 for a discussion on how we calculate the share of cases that can be averted). When decreasing the effectiveness from 50% to 30%, we find that the BCR for local buildings decreases from 5.5. to 4.7.

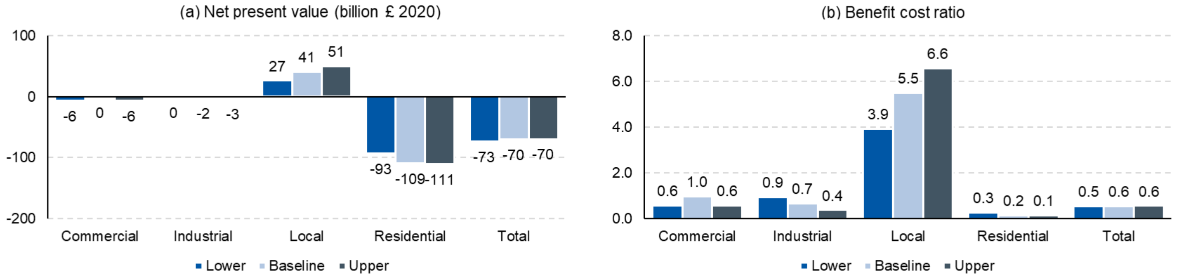
Figure 56: Uncertainty analysis effectiveness of ventilation



A.3.5. Case distribution over environments

Our baseline assumption is that more cases occur in local buildings rather than commercial, industrial, or residential. Figure 57 illustrates our alternative lower and upper bound assumptions. Our lower bound estimate changes the case distribution over environments by increasing the percentage of cases occurring in residential buildings and reducing the percentage of cases in local buildings. This reduces the BCR to 3.9 in local buildings and increases the BCR to 0.3 in residential buildings.

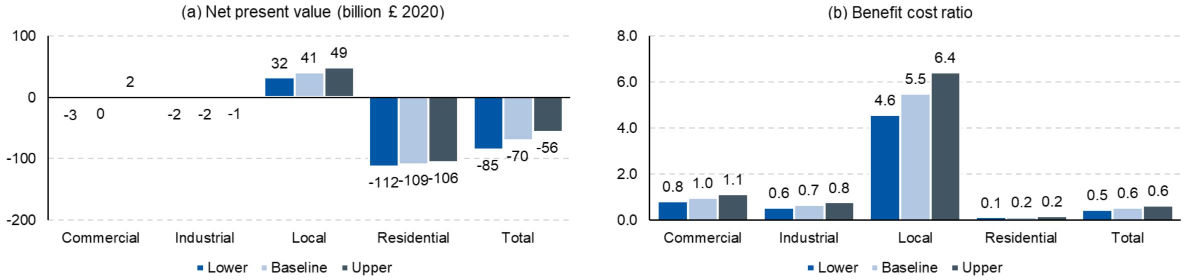
Figure 57: Uncertainty analysis case distribution over environments



A.3.6. Share of buildings requiring improved ventilation

Our baseline assumption is that 50% of buildings already have good quality ventilation installed and operating. We vary the 50% assumption by 25% on either side (higher and lower). If the share of buildings requiring improved ventilation increases the cost of the intervention increases. This mainly results in a lower net present value and only has a small effect on the BCR because costs also decline. Figure 58 highlights how the BCR decreases from 5.5. to 4.6 for local buildings when the share of buildings requiring improved ventilation increases from 50% to 25% and increases from 5.5 to 6.4 when the share goes up to 75%

Figure 58: Uncertainty analysis buildings requiring improved ventilation



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