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Poor indoor climate, its impact on child health, and the wider societal costs

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Preface

This report presents the findings of a project that has combined five different analyses:

- A rapid evidence assessment (REA) concerning the impact of poor indoor climate on child health;
- An analysis of statistical datasets concerning the prevalence of various indoor climate-related hazards in the EU and the number of children exposed to them;
- A regression analysis concerning the associations between poor indoor climate and child health;
- An estimation of the burden of disease (in terms of health and educational impacts) of children who are exposed to damp and mould in their homes;
- A modelling of the economic benefits associated with reducing children's exposure to selected aspects of poor indoor climate, more specifically (a) damp and mould in their homes and (b) poor ventilation in schools.

The report will be of interest to policy-makers in the fields of public health, housing and education, and at the same time to a much broader spectrum of readers, including house owners, tenants, as well as private sector agents, in particular in the construction, renovation and property management domains.

VELUX Group commissioned RAND Europe to carry out this research project. RAND Europe had full editorial control and independence of the analyses performed and presented in this report. This work informs the public good and should not be taken as a commercial endorsement.

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Abbreviations and acronyms

AMR	anti-microbial resistance
CGE	computable general equilibrium
CO	carbon monoxide
CO_2	carbon dioxide
CoI	cost of illness
DALY	disability adjusted life year
DCGE	dynamic computable general equilibrium
ERMI	environmental relative mouldiness index
EU-SILC	European Union Statistics on Income and Living Conditions
GBD	global burden of disease
GDP	gross domestic product
GOLM	generalised ordinal logit model
GTAP	Global Trade Analysis Project
LPM	linear probability model
NO_2	nitrogen dioxide
OLM	ordinal logit model
OLS	ordinary least squares
OR	odds ratio
PAF	population attributable fraction
PM	particulate matter
REA	rapid evidence assessment
RoW	rest of the world
RR	risk ratio
SAM	Social Accounting Matrix
UN	United Nations
VOC	volatile organic compound
WHO	World Health Organisation
WPAI	work productivity and activity impairment
YLD	years lived with disability

YLL	years of life lost

Executive summary

Background

The ‘healthiness’ of indoor environments, such as homes, schools and workplaces, has recently received increasing attention and been the subject of publications and guidelines by governmental agencies and the World Health Organization (WHO 2018). The WHO has distinguished between the following aspects of the indoor environment:

- Thermal environment – covering temperature, humidity, heat radiation, and air movement;
- Air quality environment – covering gaseous matter (including non-radioactive and radioactive gases), liquid matter and particulate matter (including non-biological and biological matter);
- Noise environment; and
- Light environment.[1]

Many, if not all of these aspects, are directly influenced by the condition and structure of buildings. For the purpose of this report, we would like to adopt the term *indoor climate* to cover all these aspects.

There is increasing evidence, both in terms of prevalence of housing inadequacies and in terms of the negative health impacts that these have on residents. This report focusses specifically on the negative health impact on children. As shown by our report, 30 per cent of children in the 28 countries that currently make up the European Union (EU-28) are exposed to one or more of the following four housing deficiencies: (1) leaking roof, damp in walls, floors and/or foundations or rot in window frames or floors; (2) lack of daylight; (3) noise; and (4) inability to keep the house comfortably warm. Furthermore, evidence shows that bad housing conditions increase the risk of severe ill health or disability by up to 25 per cent during childhood and early adulthood. For example, it has been estimated that children who live in humid homes are 7.6 times more likely to develop asthma and to require up to 10 times more acute care visits. While there are already important direct medical costs related to the diseases that are attributable to these indoor climate hazards, the indirect costs to society are much higher.

Objectives and research questions

This study aimed to take a detailed look at the impact of the indoor climate on human health, and in particular on children’s health, and to estimate the overall societal costs related to this. It covers the following research questions:

1) What is the evidence in terms of existing studies and literature concerning the impact of poor indoor climate on human and in particular on children’s health? More specifically, what is the impact of the following hazards: damp, mould, indoor air pollution, noise, radiation through radon, excess cold, and lack of daylight?

[1] WHO (1990).

2) How prevalent are problems related to non-optimal indoor climate in European homes? How does the prevalence of the above issues differ between different countries and regions and between different types of homes (single- or multi-family homes) and of ownership (rented, loan, fully owned)?
3) Which correlations can be observed between the prevalence of non-optimal indoor climate and the health status of affected children?
4) Following on all the above, what is the health and educational burden of poor indoor climate?
5) What would be the economic benefits associated with reduction in children's exposure to poor indoor climate?

Study design

Our study examined the above research questions through several distinct tasks, which partially build upon each other.

We conducted a **rapid evidence assessment (REA)**, which addressed primarily research question 1, by identifying studies that examine the association between the above hazards and a number of specific diseases and health conditions. In doing so, the REA also informed the subsequent estimation of the health burden and the educational burden, as well as the macroeconomic modelling (see below), by identifying quantified information concerning attributable health risks related to those hazards. In this way, the REA was also related to research questions 4 and 5.

In parallel, we addressed research question 2 through an **analysis of statistical databases** in order to identify data sources concerning the prevalence of the above hazards in the EU. The European Union Statistics on Income and Living Conditions (EU-SILC) database was identified as a data source that provides annual statistics at microdata (i.e. household) level for the following four hazards: damp, noise, lack of daylight, excess cold. It also provides data on the health status of household members.

We also analysed data from the Global Burden of Disease (GBD) database. GBD is an open access dataset that quantifies the health burden associated with hundreds of diseases, injuries and risk factors globally (IHME 2019a). These data were then used for our estimation of the health burden and the educational burden, as well as for the macroeconomic modelling (see below).

Using the EU-SILC microdata provided to us by Eurostat, we then carried out a **multivariate regression analysis** addressing research question 3, with the aim of identifying correlations between the four above-mentioned hazards and the self-reported health status of children living in the same households. In doing so, we controlled for various confounding factors, such as deprivation.

In the next step, we carried out an **estimation of the health burden and the educational burden** of children exposed to damp in their homes. We focused on damp because there is a high correlation between damp and mould and because the latter was identified by the REA as a risk factor with regard to the following four diseases: asthma, atopic dermatitis, lower respiratory infections, and upper respiratory infections. The following indicators were used to measure the health burden and the educational burden, respectively: disability adjusted life years (DALYs) and school days missed.

Finally, in our **macroeconomic modelling**, we developed a bespoke model that allowed us to assess the economic benefits associated with improving indoor climate in households with children in the EU. The model is a multi-country dynamic computable general equilibrium (DCGE) model, which treats the many markets of goods and inputs as an interrelated system, whereby values at equilibrium for all variables are simultaneously determined. It focusses on the reduction of effective labour supply through the following three channels: (a) increased mortality; (b) reduced labour productivity of the affected child's parents/ caregivers; and (c) reduced labour productivity of the affected child in later life. In addition, we also modelled the economic benefits associated with improving ventilation rates in European primary and secondary schools.

The **report structure** largely follows the order of the above tasks, before summarising the key findings and drawing overall conclusions. Figure 1 in section 1.4 shows the logical structure of research questions, tasks and corresponding sections in this report. The executive summary largely follows the same structure, with some slight deviations which allowed for a better high-level summary of the results.

Specific indoor climate hazards covered

While the above-cited WHO categorisation of various aspects of the indoor climate is very useful for a definition of the scope of the term, the interest of this study lies in identifying the impacts of specific hazards. We defined the following hazards as the key focus for the study:

- Damp
- Mould[2]
- Indoor air pollution
- Noise
- Radiation (through radon)
- Excess cold
- Lack of daylight
- Poor ventilation[3]

This selection was guided by an initial scoping of what the most important risk factors are, and it was decided upon in an iterative process between the study team and the funder of the study.

Please note that not all hazards could be covered by all tasks. While the REA (task 1) aimed at identifying literature concerning all the above hazards (except for poor ventilation[4]), this was not possible for the other tasks. The regression analysis, the estimation of the burden of disease as well as the macroeconomic modelling relied on the availability of quantitative information. Because such data could only be

[2] Please note that due to the strong correlation between the two, damp and mould are often discussed in conjunction with each other in both academic and grey literature. Our study follows this approach.

[3] Please note that poor ventilation was only added as a hazard to be covered once the REA had already been completed.

[4] Idem.

identified for a limited number of hazards, these tasks were in function of that. Please see the table below for an overview of the hazards covered by each study task.

Hazard	REA	Multivariate regression analysis	Estimation of health and educational burden	Macroeconomic modelling
Damp and mould	✔	✔	✔	✔
Indoor air pollution	✔			
Noise	✔	✔		
Radiation (linked to radon)	✔			
Excess cold	✔	✔		
Lack of daylight	✔	✔		
Poor ventilation				✔

The prevalence of various indoor climate hazards and their impact on child health

Damp and mould

The EU Statistics on Income and Living Conditions (EU-SILC) database indicates that one in six children in Europe (15 per cent) live in a house with a leaking roof, damp in walls/floors/foundations or rot in window frames or floors. In certain countries, this figure is even significantly higher, e.g. 21 per cent of children in the UK, 22 per cent in Belgium, 26 per cent in Portugal and 30 per cent in Hungary.

While the academic literature identified by our rapid evidence assessment (REA) does not provide us with sufficient evidence to state that damp in itself constitutes a direct risk for health, the indirect link between damp and negative health effects is established. According to the existing evidence, damp promotes the growth of microorganisms, such as mould, other fungi and bacteria, which subsequently emit spores, cells, fragments and inhalable particles into indoor air. Our REA found some evidence for an association, although not always statistically significant, between human exposure to mould and other microorganisms and the risk of developing asthma as well as other respiratory diseases, atopic conditions and allergies.

We also used EU-SILC data to carry out multivariate regression analysis, quantifying the association between existence of damp and health status of children affected. Our analysis, which controlled for a number confounding factors, such as deprivation, identified a statistically significant association between the two conditions.

Indoor air pollution

We did not find any data concerning the overall prevalence or the percentage of children affected by indoor air pollution on European or national level.

In our REA, we identified a number of studies exploring the health impacts of indoor air pollution, such as particulate matter and nitrogen dioxide (NO_2), on children. In general, these studies suggest that indoor air pollution has a negative impact on the health of children. Depending on the specific type of indoor pollution (e.g. particulate matter, volatile organic compounds (VOCs), carbon dioxide (CO_2) and NO_2), these negative effects particularly concerned respiratory health (including 'simple' cough, wheezing, and asthma), as well as the quality of sleep. The likelihood of negative health impacts depends on the vulnerability of the child.

Noise

Using the EU-SILC data, we calculated the percentage of children affected by noise, either from the street or from neighbours. Across all EU member states, 17 per cent of children are affected. Germany and Portugal (with a rate of 24 per cent each) as well as the Netherlands (with 23 per cent) seem to be particularly affected.

Our REA has identified only limited studies on the impacts of noise on children's health. They found that exposure to noise was statistically significantly associated with annoyance, emotional problems, cognitive dysfunction, behavioural dysfunction and abnormal growth hormone release. Also, our regression analysis using EU-SILC data suggests a significant association between noise and self-reported child health.

Radiation (through radon)

Radon is a radioactive gas which occurs naturally in many regions of Europe. It can enter buildings from the ground and, among other things, increase the risk of lung cancer. While there is data on the concentration levels of radon in ground-floor rooms across Europe, such as provided by the Joint Research Centre of the European Commission, we have not identified a dataset or study that would indicate the percentage of children who are exposed to more-than-acceptable levels of radon. In our REA, we identified only three academic papers exploring the health impact of radiation on children. One of these studies identified an increased risk of leukaemia for younger children, which decreased by adolescence. The results of the other two studies were inconclusive.

Excess cold

Based on the EU-SILC microdata, we could also identify the percentage of children living in a household that does not have the 'ability to keep home adequately warm'. Across the EU as a whole, the percentage of children affected is 7 per cent. In several Eastern and south-eastern European countries; however, this number exceeds 20 per cent, such as in Cyprus (23 per cent), Greece (25 per cent), Lithuania (26 per cent) and Bulgaria (35 per cent).

Our REA has identified only three studies exploring the health impacts of children living in homes with cold temperatures. Although this evidence is limited to a small number of studies, these papers found statistically significant links between low indoor temperatures and asthma and, in younger children, allergic rhinitis. Low temperatures were also linked to hypothermia in children aged 17 and under, although no information on statistical significance was provided.

Also, our regression analysis using the above-mentioned EU-SILC microdata identified a statistically significant association between the inability to keep the home adequately warm and the health status of affected children.

Lack of daylight

Another type of hazard affecting the indoor climate is that of homes that are considered as too dark, with not enough daylight. According to the EU-SILC database, on average 5 per cent of children in the EU are affected by this. This figure exceeds 10 per cent in certain countries, such as Portugal and Hungary.

While our REA did not identify high-quality studies on the health impacts of insufficient daylight on children, our regression analysis using EU-SILC was able to identify a statistically significant association between this type of hazard and the health of the children affected.

The economic and educational impacts of health conditions identified

Impact on parents' economic outcomes

In order to be able to inform the quantitative analysis in the later tasks, our REA also searched for studies that looked at the impact of indoor climate-related health conditions on parents' economic outcomes. We identified four studies examining the impact of childhood asthma. All four studies suggested that parents lose workdays as a result of their children having asthma, even though this was found to be statistically significant in only two of the four studies. The studies also showed that the impact depends on how well controlled the asthma is. One study examined the economic impact on parents as a result of their child having atopic dermatitis and demonstrated an impact both in terms of direct medical costs and in terms of workdays lost.

Impact on education of individuals affected

Our REA also identified a number of studies looking at the impact of indoor climate-related health conditions on education of affected individuals. The majority of those studies focused on asthma and found that children with asthma missed a greater number of school days as a result of their illness. However, many of these studies did not provide information on the significance of this link.

A smaller number of studies also looked at allergic conditions, sleep disruption and psychological conditions. Although it is difficult to synthesise the results of these studies at a high level, we can say that the general trend confirmed an impact of these various conditions.

Quantifying the burden of poor indoor climate

Overall, across Europe, the self-reported health status of children seems to be good, with 95 per cent of children being in 'good' or 'very good' health. While there are variations between countries, all EU-28 member states report that at least 90 per cent of children are in 'good' or 'very good' health.

Our REA, as well as our multivariate regression analysis, showed that the majority of indoor climate hazards that we looked at are associated with poorer self-reported child health.

In order to quantify the overall societal burden of poor indoor climate, two more things are required:

1) Indications of **attributable health risks** linked to specific hazards. More concretely, such an attributable risk would describe the percentage difference in observed morbidity between the population exposed to the hazard in question and the unexposed population.

2) Depending on which burden one wishes to quantify, one of the following impact indicators related to the various health diseases or conditions:
    a. Indications of the **impact on mortality and/or morbidity**;
    b. Indications of the **impact in terms of parents'/carers' workdays lost**; or
    c. Indications of the **impact on education**.

With regard to the first point, our REA has provided us with quantitative indications of attributable health risks linked to damp and mould (with the former serving as a proxy for the latter). More specifically, we identified indications of attributable risks with regard to the following four disease areas: asthma, acute rhinitis, upper respiratory infections and lower respiratory infections.

As for the various aspects of the second point, we made use of two distinct sources. For point 2a, we used the data provided by the Global Burden of Disease database, which quantifies the health burden associated with more than 350 specific diseases and injuries in 195 countries worldwide. For points 2b and 2c, we used information that we identified through the REA.

The health burden and the educational burden of children exposed to damp and mould

Combining information of points 1 and 2a above, we then calculated the burden of disease in terms of disability adjusted life years with regard to the four above-mentioned diseases that are associated with exposure to damp and mould. While damp alone is not proven to increase the risk of asthma or other respiratory diseases, there is a high correlation between damp and mould, and there is some evidence for an association between the latter and the risk of developing asthma. We have therefore adopted the approach of many other studies and reports (including the WHO Guidelines on Dampness and Mould from 2009) that essentially took damp as a proxy indicator for mould.

We estimate that the burden of disease from indoor damp and mould exposure of children (aged 0 to 15) in relation to asthma, atopic dermatitis, and upper and lower respiratory infections is 37,500 DALYs for the EU as a whole. This corresponds to about 4 per cent of the total DALYs associated with these four disease areas.

Related to the same diseases, we have also calculated the burden of disease in terms of school days missed, now combining points 1 and 2c above. Once again, this is based on the assumption that there is a high correlation between damp and mould. The total number of school days missed per year by children (aged 5 to 15) across the EU and attributable to the prevalence of damp and mould in their homes is about 1.7 million days per year, which corresponds to about 00.014 per cent of all annual school days.

The economic benefits associated with reduction of children's exposure to damp and mould

Based on the burden of disease calculated in the previous task and using a multi-country computable general equilibrium model (CGE),[5] we were able to estimate the economic implications associated with children's reduction in exposure to poor indoor climate. As specified above, the model focusses on the reduction of effective labour supply through the following three channels: (a) increased mortality; (b)

[5] See Appendix C for more details on the model.

reduced labour productivity of the affected child's parents/caregivers; and (c) reduced labour productivity of the affected child in later life. According to our model, the total macroeconomic benefits associated with eliminating children's exposure to damp and mould in the EU-28 can be estimated to be US$62 billion over the next 40 years. The benefits occur over time due to lower levels of carer missed days from work, as well as better future health of children when they enter the labour market (and hence have, themselves, lower absenteeism days due to the better health). By breaking down those benefits to household level and dividing it by the number of damp-affected households with children, we estimate that by 2040 the estimated benefit per affected dwelling would be US$2,523, by 2050 it would be US$4,626 and by 2060 it would be US$7,384.

The economic benefits associated with improving ventilation rates in European primary and secondary schools

In addition to the above analyses relating to children's exposure to damp and mould in their homes, we carried out an economic analysis related to the potential economic implications associated with improving ventilation rates in European primary and secondary schools. In particular in institutions of learning, it is vital to ensure good indoor air quality through efficient ventilation, as this is an important condition for good cognitive performance and thus productivity of the students.

The results of our modelling indicate that improving ventilation rates in European schools may lead to economic benefits. For instance, we estimate that a relatively small improvement in ventilation rates, of 0.5 litres per second (l/s) per person, in European schools could be associated with a cumulative total increase in the current EU-28 gross domestic product (GDP) by 2050 of US$24.4 billion and by 2060 of US$57 billion. The estimated economic benefits are larger for more substantial improvements in ventilation rates. For instance, a 2.5 l/s improvement across European schools may be associated with an increase in cumulative GDP of the current EU-28 by 2050 of US$120.5 billion and by 2060 of US$281.4 billion.

Implications for key stakeholders

On the basis of these findings, we can state that housing deficiencies constitute a very important health risk for children across Europe. While there are important differences among countries, types of dwellings and settlements, as well as socio-economic status, 30 per cent of children in the EU-28 are exposed to one of the following four housing deficiencies for which the EU-SILC database provides data: (1) leaking roof, damp in walls, floors and/or foundations or rot in window frames or floors; (2) lack of daylight; (3) noise; and (4) inability to keep the house comfortably warm. Our study has found some evidence that all those four types of hazards may constitute a risk for children who are exposed to them. We have demonstrated that these health risks may translate into significant costs for society.

These findings are relevant to a wide variety of stakeholders. First, they have an important bearing for house owners, tenants and landlords. The good condition of dwellings should be seen not only as an issue of comfort, but also as an essential basic requirement for good health of the residents, and even more so when they are families with children. Second, all kinds of private sector bodies, in particular in the construction, renovation and property management domains, should also take these findings into consideration and design and maintain buildings in such a way that decreases the likelihood of any of the deficiencies to occur. Third, there is also a task for policy making. Less well-off households who cannot afford to improve the condition of their dwellings or who may simply have to prioritise other things may need the support of public authorities in order to improve the condition of their dwellings.

We can also state that the results of our modelling concerning the benefits of improved ventilation in schools show that there is a strong case for improving the air quality in schools. In addition to the positive impact this will have on the health of the children, it would potentially have a positive effect in terms of educational outcomes. This, in turn, would lead to substantial economic benefits overall. These findings have bearings in particular for policy-makers in the education sector, as they indicate that air quality in schools may be important for educational outcomes.

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1. Introduction

1.1 Background

The 'healthiness' of indoor environments, such as homes, schools and workplaces, has recently received increasing attention and been the subject of publications and guidelines by governmental agencies and the World Health Organization (WHO 2018). The WHO has distinguished among the following aspects of the indoor environment:

- Thermal environment (covering temperature, humidity, heat radiation and air movement);
- Air quality environment (covering gaseous matter, liquid matter and particulate matter (PM));
- Noise environment; and
- Light environment.[6]

Many, if not all of these aspects, are directly influenced by the condition and structure of buildings. For the purpose of this report, we adopt the term *indoor climate* to cover all these aspects.

Housing inadequacies that have a negative impact on the indoor climate affect a significant number of EU citizens. According to the EU Statistics on Income and Living Conditions (EU-SILC)[7] database, 13 per cent of EU residents are living in dwellings with a *leaking roof, damp walls, floors or foundation, or rot in window frames or floor*, 8 per cent are *unable to keep their home adequately warm*, 5 per cent *consider their dwelling as too dark*, and 18 per cent are exposed to *noise from neighbours or from the street*. All these are averages, and in various countries, the numbers are even significantly higher. For example, 29 per cent of Cypriotes live in a dwelling with a *leaking roof, damp walls, floors or foundation, or rot in window frames or floor*, 37 per cent of Bulgarians are *unable to keep their home adequately warm*, 11 per cent of Portuguese *consider their dwelling as too dark* and 26 per cent of Germans state that they are exposed to *noise from neighbours or from the street*.[8]

There is also evidence that these housing inadequacies do indeed have a significant impact on people's health. Looking at the situation at EU level, a Eurofound study from 2012 which analysed both direct and indirect healthcare costs related to inadequate housing found that €194 billion in total economic costs could be saved per year if housing conditions were improved.[9]

Inadequate housing conditions have detrimental health impacts also on children. One study has shown that bad housing conditions increase the risk of severe ill health or disability by up to 25 per cent during childhood and early adulthood (Harker 2006). Physical, chemical and biological aspects of the child's

[6] WHO (1990).

[7] Eurostat (2019c).

[8] EU-SILC data 2017 (latest available data at the time of writing of this report). The EU-SILC database is maintained by Eurostat, and the data are provided by the national statistical offices of the EU Members States and several additional European countries.

[9] Ahrendt et al. (2016).

home, such as cleanliness, moisture, pests, noise, accessibility, and injury risks, all have the potential to influence multiple aspects of the child's health and development. Problems with regard to indoor temperature, humidity level, and air composition, as well as the existence and amount of contaminants, respirable dust and microbes, may be of particular importance. For example, it has been estimated that children who live in humid homes are 7.6 times more likely to develop asthma and to require up to 10 times more acute care visits (Weitzman et al. 2013). Further evidence suggests that the symptoms of respiratory and other infections associated with cold and damp homes can affect young children's mental health and development, as they can cause sleep loss and restrictions on children's daily activities (Harker 2006).

While there are already direct medical costs related to the diseases that are attributable to these indoor climate hazards, the indirect costs to society are much higher (Ahrendt, Dubois et al. 2016). These latter can, be related to the following three types of factors, among others: (1) a higher mortality risk for children; (2) parents having to take leave from work in order to take care of their sick children; and (3) potential work impairment of the affected individuals in later life, should the health condition persist into adulthood. All three of these factors reduce the effective labour supply, which is seen as a key resource in the economy.

When speaking about the impact of the indoor climate on child health, it is also relevant to consider schools, where children spend most of their time when not at home. A number of studies[10] have focused on ventilation rates in classrooms (either directly or indirectly by measuring the concentration of CO_2 and/or NO_2) and the impact on school performance. Several of these studies have found a significant correlation between the 'freshness' of the indoor air and the performance of the students.

1.2 Objectives and research questions

The overall objective of the present study was to take a detailed look at the impact of the indoor climate on human and in particular on child health, and to estimate the overall societal costs related to this. The study had the following underlying research questions:

1) What is the evidence in terms of existing studies and literature concerning the impact of poor indoor climate on human and in particular on children's health? More specifically, what is the impact of the following hazards: damp, mould, indoor air pollution, noise, radiation through radon, excess cold, and lack of daylight?
2) How prevalent are problems related to non-optimal indoor climate in European homes? How does the prevalence of the above issues differ between different countries and regions and between different types of homes (single- or multi-family homes) and of ownership (rented, loan, fully owned)?
3) Which correlations can be observed between the prevalence of non-optimal indoor climate and the health status of affected children?

[10] For further details, see section 4.3.

4) Following on all the above, what is the health and educational burden of poor indoor climate?
5) What would be the economic benefits associated with reduction in children's exposure to poor indoor climate?

1.3 Study design

Our study examined the above research questions based on four distinct tasks, which partially build upon each other.

Rapid evidence assessment

We conducted a rapid evidence assessment (REA) which addressed primarily research question 1, by identifying studies that examine the association between the above hazards and a number of specific diseases and health conditions. In doing so, the REA also informed the estimation of the health burden and the educational burden, as well as the macroeconomic modelling (see below), by identifying quantified information with regard to attributable risks. Hence, it was also related to research questions 4 and 5.

An REA is a systematic approach to searching literature to capture as much of the available evidence as possible while minimising bias. What distinguishes it from a fully fledged systematic literature review is the fact that it sets certain limits with regard to the scope of the search, such as publication date or place of publication. This way, it balances the benefits of the structured approach with the need to conform to limited resources and time constraints. Hence, while it does (purposefully) not achieve full coverage, an REA constitutes a robust, systematic and replicable method providing a reliable indication of the evidence available in a particular domain.

Please see more details on the method in section 2.1 and details of the search protocol as well as inclusion/exclusion criteria in Appendix A.

Analysis of statistical databases

In parallel, we carried out an analysis of statistical databases which addressed research question 2 by identifying data sources concerning the prevalence of the above hazards in the EU. The European Union Statistics on Income and Living Conditions (EU-SILC) database was identified as a data source that provides annual statistics at microdata (i.e. household) level for the following four hazards: damp, noise, lack of daylight, excess cold. It also provides data on the health status of household members. All EU-SILC data are self-reported.

Furthermore, this task also analysed data from the Global Burden of Disease (GBD) database. GBD is one of the most comprehensive data sources with regards to the collection of a range of factors (e.g. mortality and morbidity) associated with a large number of diseases. It is an open access dataset that quantifies the health burden associated with hundreds of diseases, injuries and risk factors globally (IHME 2019a). These data were then used for our estimation of the health burden and the educational burden and for the macroeconomic modelling (see below).

Regression analysis

Using the EU-SILC microdata provided to us by Eurostat, we then carried out a multivariate regression analysis addressing research question 3, with the aim of identifying correlations between the four hazards for which EU-SILC provides data and the self-reported health status of children living in the same households. In doing so, we controlled for various confounding factors, such as deprivation.

Please see more details on the method in section 3.2.1 and in Appendix B.

Estimation of the health burden and the educational burden

In the next step, we made an estimation of the health burden and the educational burden of children exposed to damp in their homes. The reason to focus on damp is the fact that there is a high correlation between damp and mould and that the latter has been identified by the REA as a risk factor with regard to the following four diseases: asthma, atopic dermatitis, lower respiratory infections, and upper respiratory infections. The following indicators were used to measure the health burden and the educational burden, respectively: disability adjusted life years (DALYs) and school days missed.

Please see more details on the method in section 3.2.2.

Macroeconomic modelling

We have developed a bespoke macroeconomic model that allows us to assess the economic benefits associated with improving indoor climate in households with children in the EU. The model is a multi-country dynamic computable general equilibrium (DCGE) model, which treats the many markets of goods and inputs as an interrelated system. It focusses on the reduction of effective labour supply through the following three channels: (a) increased mortality; (b) reduced labour productivity of the affected child's parents/caregivers; and (c) reduced labour productivity of the affected child in later life. In additional, we also modelled the economic benefits associated with improving ventilation rates in European primary and secondary schools.

Please see more details on the method in section 4.1 and in Appendix C.

Study tasks and their interaction

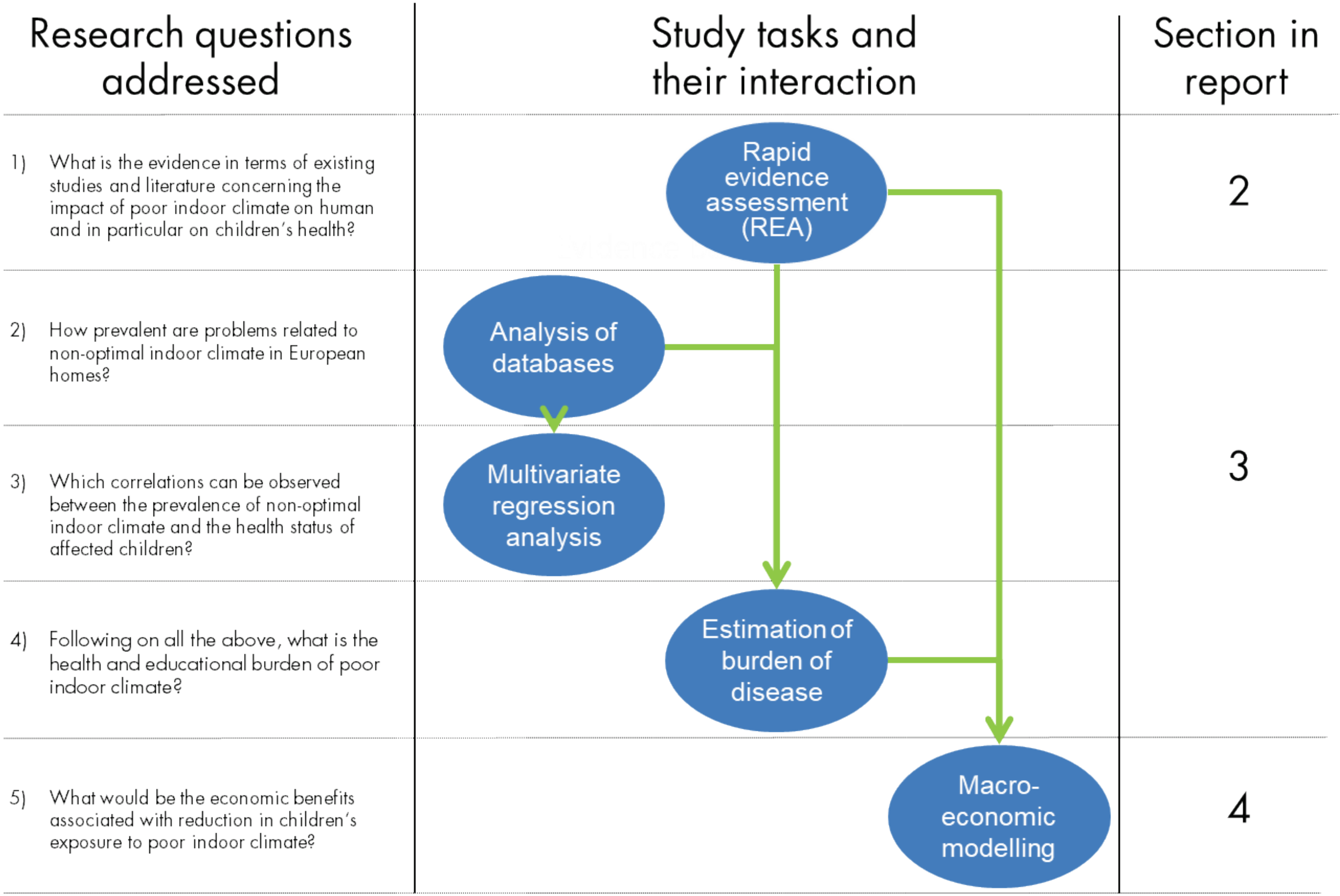

Figure 1.1: Study tasks and their interaction

1.4 Specific indoor climate hazards covered

While the above-cited WHO categorisation of various aspects of the indoor climate is very useful for a definition of the scope of the term, the interest of this study lies in identifying the impacts of specific hazards. We defined the following hazards as the key focus for the study:

- Damp;
- Mould[11];
- Indoor air pollution;
- Noise;
- Radiation (through radon);
- Excess cold;
- Lack of daylight; and
- Poor ventilation.[12]

This selection was guided by an initial scoping of what the most important risk factors are and decided upon in an iterative process between the study team and the funder of the study.

Please note that not all hazards could be covered by all tasks. While the REA (task 1) aimed at identifying literature concerning all the above hazards (except for poor ventilation[13]), this was not possible for the other tasks. The regression analysis, the estimation of the burden of disease, and the macroeconomic modelling relied on the availability of quantitative information. Because such data could only be identified for a limited number of hazards, these tasks were in function of that. Please see Table 1.1 for an overview of hazards covered per study task.

[11] Please note that due to the strong correlation between the two, damp and mould are often discussed in conjunction with each other in academic literature. Our study follows this approach.

[12] Please note that poor ventilation was only added as a hazard to be covered once the REA had already been completed.

[13] Idem.

Table 1.1: Hazards covered by the various research tasks

Hazard	Rapid evidence assessment	Multivariate regression analysis	Estimation of health and educational burden	Macroeconomic modelling
Damp and mould	✔	✔	✔	✔
Indoor air pollution	✔			
Noise	✔	✔		
Radiation (linked to radon)	✔			
Excess cold	✔	✔		
Lack of daylight	✔	✔		
Poor ventilation				✔

1.5 Structure of this report

The structure of this report largely follows the order of the study tasks.

Section 2 of this report presents the methods and findings of the REA carried out concerning the impact of poor indoor climate on child health.

Section 3 discusses the methods and results of the following three tasks carried out: (1) the analysis of statistical databases and the prevalence rates concerning various indoor climate hazards that we could obtain through them; (2) the multivariate regression analysis concerning the association between poor indoor climate and children's health; (3) and the estimation of the health burden and the educational burden in all EU member states.

Building on the results of the analyses discussed in sections 2 and 3, section 4 presents the methods and results of an analysis, showing an estimate of economic benefits associated with a reduction of children's exposure to poor indoor climate. It also presents the results of the additional analysis concerning the economic effects associated with improving ventilation rates in European primary and secondary schools.

Finally, section 5 summarises the key findings and suggests some implications for key stakeholders.

2. Poor indoor climate and children: A review of the literature

This first subsection of this chapter will describe the method and the search strategy applied during the REA. The subsequent subsections will provide details on its findings. More specifically, subsection 2.2 will discuss the evidence found for the impact of poor indoor climate on children's health, subsection 2.3 the impact of this on parents' economic outcomes and subsection 2.4 the impact on children's academic achievements. Section 2.5 will point out some important considerations with respect to the interpretations of the results.

2.1 Method and search strategy

An REA is a systematic approach to searching literature to capture as much of the available evidence as possible while minimising bias. What distinguishes it from a fully fledged systematic literature review is the fact that it sets certain limits with regard to the scope of the search, such as publication date or place of publication. This way, it balances the benefits of the structured approach with the need to conform to limited resources and time constraints. Hence, while it does (purposefully) not achieve full coverage, an REA constitutes a robust, systematic and replicable method providing a reliable indication of the evidence available in a particular domain. We carried out the following steps for the REA:[14]

1) Scope the review and define research questions;
2) Establish inclusion/exclusion criteria;
3) Carry out the literature search;
4) Screen the results against the inclusion/exclusion criteria;
5) Critically appraise the included studies;
6) Analyse the results; and
7) Write up the results.

We explain these steps in more detail below and in Appendix A.

As discussed in the previous chapter, we defined five overarching research questions. The REA aimed primarily to explore research question 1:

- What is the evidence in terms of existing studies and literature concerning the impact of poor indoor climate on human and in particular on children's health? More specifically, what is the impact of the following hazards: damp, mould, indoor air pollution, noise, radiation through radon, excess cold, and lack of daylight?

In addition, however, the REA also had the objective of supporting the estimation of the health burden and the educational burden as well as macroeconomic modelling by identifying attributable health risks. In this way, it was also linked to research questions 4 and 5:

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[14] This is based on the approach for systematic reviews outlined in Petticrew & Roberts (2006).

- Following on all the above, what is the health and educational burden of poor indoor climate? What would be the economic benefits associated with reduction in children's exposure to poor indoor climate, e.g. in terms of decreased learning abilities for children, salary losses of parents due to necessary leave days and salary losses of affected children in their later adult life due to the persistence of the disease?

The search strategy and inclusion/exclusion criteria were developed with these key research questions in mind. Please see our search protocol in Appendix A.1.

Exclusion and inclusion criteria are used to help develop the search protocol to ensure that the search terms used are broad enough to identify as much of the relevant literature as possible, while also refining the number of articles to a manageable number. The criteria also support the research team in the screening process to ensure that only relevant articles are selected for full-text analysis. The exclusion and inclusion criteria, and the reasons behind these, can be found in Appendix A.2.

The criteria helped to inform the development of the search protocol, which can be found in Appendix A. This went through a number of iterations to ensure that the number of search hits was manageable and that the articles returned were of relevance to the research. This protocol was used to search PubMed, a biomedical and life sciences literature database; it was selected because the articles it includes are the most relevant to this research. Using the search protocol in Annex A, the PubMed search returned 3,602 articles. That number was reduced to 1,291 after duplicates were removed.

The titles and abstracts of these 1,291 articles were screened by the research team against the inclusion and exclusion criteria to decide which ones to take forward for a full-text quality review. A total of 155 of these articles were deemed to be relevant, and a quality assessment was conducted on each of these. This ensured that the analysis of the available literature was based on the highest possible quality of evidence. The criteria used to assess the quality of the 155 articles were based on those used previously by RAND Europe (Guthrie et al. 2017):

- Does the study directly address at least one of the research questions?
- Does the study have clear research questions/aims?
- Is the study well designed to meet the research aims/questions?
- Is the sampling approach appropriate and well justified?
- Is the data collection approach appropriate and well justified?
- Are data appropriately analysed and findings adequately corroborated?
- Does the interpretation of the findings adequately reflect the assumptions made, limitations of the method, and any issues around generalisability of the findings?

Each of these criteria was marked as either addressing the criteria clearly and fully, partially addressing the criteria or not addressing the criteria. Any article with a quality criterion marked as not being addressed was excluded at this stage. A total of 33 articles were deemed to be of low quality based on this assessment and thus excluded at this stage, and 122 were taken forward for full-text extraction.

To extract the relevant data from the 122 identified articles, an extraction template was created using Excel. This covered:

- Indoor climate factor.

- Disease/health condition.
- Type of building, e.g. multiple/single parent, apartment.
- Age of children.
- Impact of the indoor climate factor:
    - Direction of impact;
    - Details of the impact; and
    - Any differences in the populations at risk.
- Economic impact on parents from children's poor health (for those health conditions we linked to indoor climate in the previous bullet point):
    - Type of impact;
    - Direction of impact; and
    - Details of the impact.
- Academic impacts for the child as a result of the health impacts we linked to indoor climate:
    - Type of impact;
    - Direction of impact; and
    - Details of the impact.
- Later health and economic impacts for the child as a result of the health impacts we linked to indoor climate:
    - Type of impact;
    - Direction of impact; and
    - Details of the impact.
- Details on generalisability/limitations.
- Any other information deemed relevant by the research team.

Reading the full text, rather the title and abstract alone, provides additional detail on the scope and focus of the study. After this reading, an additional 56 articles were excluded that were deemed to be out of scope (either geographically or topically). This left 66 articles which were reviewed and had data extracted.

The PRISMA diagram below outlines the REA process and the number of articles at each stage.

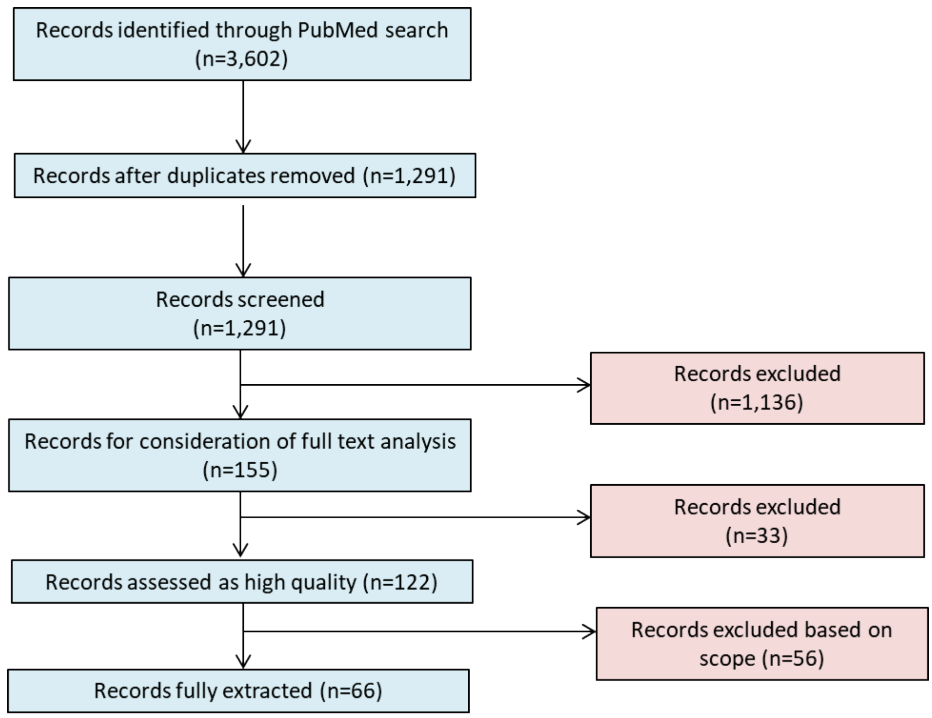

Figure 2.1: PRISMA flow diagram[15]

2.2 The health effects of poor indoor climate on children

This section provides an overview of how living in homes with poor indoor climate affects children's health outcomes. We have structured this section to provide an overview of the different health outcomes associated with specific factors of poor indoor climate. A summary of this section can be found in the box below.

[15] Adapted from Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G., The PRISMA Group (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. PLoS Med, 6(7).

Box 2.1: Health effects of poor indoor climate on children (summary)

- Exposure to mould and/or damp could lead to an increase in the risk of multiple respiratory outcomes, however, the size of this risk depends on whether damp and mould were found separately or in combination, the extent of the damage from mould/damp and the location of it in the home. There is stronger evidence for the negative impact on health as a result of mould compared to damp.
- Some types of indoor air pollution is linked to significant increases in poor respiratory health, as well as eczema and sleep disturbances. Children more at risk of developing respiratory conditions appear to be more susceptible to these negative health impacts.
- Noise exposure is significantly associated with annoyance, emotional problems, cognitive dysfunction, behaviour dysfunction and abnormal growth hormone release in children.
- The impact of indoor radiation on children's health is inconclusive in the reviewed studies, although one indicates a risk of leukaemia for younger children but that the risk reduces by adolescence.
- Studies exploring the effects of excess indoor temperatures on children's health indicate mixed results.
- The type of structural damage appears to influence the development respiratory and allergic conditions, with stronger evidence linking these to water damage and cracks in the wall/ceiling compared to homes in need of general repair.

2.2.1 Damp and mould

The studies we reviewed that explored the impact of damp and mould on children's health mainly focusing on respiratory outcomes (including asthma, respiratory infections and wheezing) and atopic diseases. One paper explored the effects on sleep.

Atopic conditions

Atopic conditions include a broad spectrum of allergy-related issues, including atopic dermatitis (eczema), allergic rhinitis (hay fever) and asthma. However, as many of the studies we reviewed explored the impacts of indoor climate hazards on asthma, we have included this in a separate section. Many of these studies found that indoor climate hazards have a negative impact on atopic conditions; however, others found no association between the two. The difference in findings appears to depend on the type of atopic outcomes measured.

Richter et al. (2018) studied the effect of mould and damp on atopic sensitisation[16] and found a negative impact on the health of immigrant children in Sweden. This relationship was found to be statistically significant if moisture and mould were present in the bathroom specifically (p=0.022).[17] However, it is

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[16] Atopic sensitisation refers to the production of IgE antibodies after exposure to common allergens, leading to allergic reactions (Science Direct, n.d.). It can also be referred to as IgE sensitisation.

[17] P-values and confidence intervals demonstrate the effects size of a parameter of interest, allowing the robustness of the results to be inferred. P-values show us the likelihood of the relationship having occurred by chance, or whether there is a statistically significant link between two parameters. In the health literature, this is generally demonstrated by having a p-value of maximum 0.05 (meaning a 5 per cent likelihood of the relationship having occurred by chance). However, in the economics literature, it is common to report significance levels of up to 10 per cent and to indicate the significance level with one, two or three stars on the coefficients (representing p-values of 0.1, 0.05 and 0.001, respectively). Confidence intervals provide a range of values within which the true (but unknown) value is

important to note that this study relied on self-reported data and focused on a child population that is not reflective of the general Swedish child population. Beck et al. (2015) explored similar outcomes in children from the United States, looking at the impact of dust sensitisation. The authors found that 55–60 per cent of children exposed to two types of indoor mould were sensitised to dust allergens. African American children were found to be at a significantly higher risk of developing mould sensitisation than white children (p=<0.01). However, this study only focuses on a small population in the United States, which may be difficult to generalise to other geographical areas, and the study also relied on self-reported data. Karvonen et al. (2015) studied the effect of mould and damp on atopy by conducting an initial study at birth and a follow-up after 6 years in Finland and found a negative effect on health from both mould and damp. A significant relationship (p=<0.01) was found between major moisture damage or any moisture damage[18] with visible mould and children with atopy (wheezing for those aged 3 and below). Hurrass et al. (2017) reviewed studies examining the impact of mould on the risk of developing various respiratory conditions and found that homes with mould and damp led to greater risk of allergic respiratory conditions and exogenous allergic alveolitis[19] (no p-values provided).

A small number of papers we reviewed found an increased risk of developing rhinitis when children were exposed to indoor climate hazards. A literature review by Hurrass, Heinzow et al. (2017) examined the impact of mould on the risk of developing allergic rhinitis and found that damp and mould increased the risk of this condition (no p-values provided). Thacher et al. (2017) evaluated the effect of mould and damp on rhinitis, using a Swedish population in both urban and suburban homes and found a significantly positive trend for non-allergic rhinitis (p=0.03; odds ratio (OR) 1.41 (1.03–1.93)). Similarly, Weber et al. (2017) found a significant association between visible mould and allergic rhinitis symptoms in the 12 months the study covered.

Despite Thacher, Gruzieva et al. (2017) identifying negative outcomes, such as non-allergic rhinitis, as a result of damp and mould, some of the other atopic outcomes the authors measured were found to not be associated with damp and mould. This included IgE sensitisation[20] to airborne or food allergens and allergic rhinitis (OR 0.88, 95% CI: 0.74–1.05; p=0.14). When this study explored the different impacts of damp and mould, the significant association between rhinitis and dampness was lost (OR 1.04, 95%CI: 0.72–1.50; p=0.84 at the follow-up of children), suggesting that the negative impact of rhinitis is

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likely to fall. We also provide odds ratios (OR) where this is included in a study's results, which quantifies the association between two interventions. If the OR is greater than 1, then it is likely that two events are correlated (the presence of one event increases the likelihood of another event happening).

[18] These authors measured moisture damage on a 6-point scale. No damage was defined as class 0 or 1. Major moisture damage was defined as '(1) a need for repair class 2 with the area of damage ≥1 m^2; (2) a need for repair class 3 with the area of damage ≥0.1 m^2 ; or (3) a need for repair class 4 or 5'. Damage other that these types was classed as minor. Damage was assessed using observation only, which may be a limiting factor of this study.

[19] This illness is an allergic reaction to inhaled organic material, most often caused by bird or fungal allergens in children (European Management Platform for Childhood Interstitial Lung Diseases n.d.).

[20] IgE sensitisation refers to the production of IgE antibodies after exposure to common allergens, leading to allergic reactions (British Society for Immunology n.d.). This can also be referred to as atopic sensitisation.

due to mould, rather than damp. However, all results from this study were based on self-reported data, a factor which should be considered when interpreting the results.

Asthma

Multiple studies found statistically significant associations between asthma in children and exposure to damp and mould. Madureira, Paciencia, Cavaleiro-Rufo & Fernandes Ede (2016) found that signs of visible mould growth and noticeable mould odour in the general building were observed mostly in the homes of asthmatic children (47% Vs 20% for mould growth and 8% Vs 3% for mould odour). The difference in mould exposure for asthmatic children was statistically significantly greater than those without asthma (p=0.022). However, the authors note that because they relied on self-reported data, there may have been recall bias. Karvonen, Hyvarinen et al. (2015) found a statistically significant association between major moisture damage, or any moisture damage with visible mould, and asthma diagnosed first time in Finnish children aged 2 and below (p=<0.01). Thacher, Gruzieva et al. (2017) also explored the impacts of both damp and mould, in Swedish children, and found that exposure to any mould or dampness indicator was associated with asthma up to 16 years of age (p=0.002). In addition, in children who had been exposed to any mould or dampness indicator during infancy, the authors observed an increased risk for non-allergic asthma. But this relationship was not seen when looking at allergic asthma. Breysse et al. (2014) found that children with asthma living in weatherised homes in the United States showed statistically significant improvements in controlling their asthma compared with children with asthma living in homes that had not been weatherised (p= 0.04).[21] However, due to the nature of the physical housing changes, it was not possible to blind the control group, meaning that they were aware of the changes introduced to their home.

Certain studies specifically looked at asthma outcomes as a result of mould exposure alone. Polyzois et al. (2016) evaluated the effect of mould on asthma in a student population in Canada and found a significant relationship (p=<0.05) between mould in the basement and asthma with persistent colds, as well as mould in the bathroom and asthma. This study sampled mould in the summer months, when mould levels are higher in Canada due to the warm temperatures, a factor which may have influenced these relationships. Weber, Fuchs et al. (2017) found a significant association between visible mould and doctor-diagnosed asthma with symptoms in the past 12 months. However, the authors note multiple limitations to this study, including relying on self-reported data and a sample skewed towards parents of higher education level, which may reduce exposure to mould. Finally, Oluwole et al. (2017) used data from the Canadian Indoor Air and Children's Respiratory Health Study to evaluate the effect of mould on asthma and found a borderline significant interaction (p=0.06) between home dampness and mould atopy for asthma, as well as a stronger relationship between mildew smell in the home and a higher risk of asthma (p=0.01). However, the authors note that there may have been some misclassification bias, as the selection of children included those with wheeze that had not been clinically diagnosed with asthma.

[21] Weatherising a home involves protecting the building (both inside and out) from harsh weather conditions. It can also involve improving the energy efficiency of a building.

Other studies identified negative asthma outcome associated with damp and mould but did not provide information on the significance of this relationship. Hurrass, Heinzow et al. (2017) reviewed studies examining the impact of damp and mould damage and found that these were associated with a worsening of asthma outcomes (manifestation, progression and exacerbation) (no p-values provided). Vesper & Wymer (2016) explored the impact of mould and found that infants who had lived in homes with a high Environmental Relative Mouldiness Index (ERMI) value (>5.2) were at more than twice the risk of developing asthma than those in low ERMI value homes (<5.2) (no p-values provided). Thacher, Gruzieva et al. (2017) explored the impacts of damp alone and found that it was associated with a greater risk of late-onset asthma in children and that children exposed to any mould or dampness indicator during infancy had an increased odds of persistent asthma. Finally, Fabian et al. (2014) reported that broken kitchen exhaust fans lead to greater risk of serious asthmatic events from greater humidity (fixing exhaust fans in this study led to 7–12 per cent fewer serious asthma events). Although this study was conducted in a small population in Boston, United States, and so may be difficult to generalise to other populations, the findings could be applied to similar groups (low-income households in high-income countries with cold climates).

Multiple studies explored the association between damp, mould and asthma but did not find a statistically significant link between them. Madureira, Paciencia, Cavaleiro-Rufo & Fernandes Ede (2016) found that mould odour was not statistically significantly associated with asthma in children living in the home (p=0.400) and neither was dampness in children's bedrooms with developing asthma (p=0.466). However, as mentioned previously, the authors note that the study may have faced recall bias due to the reliance on self-reported data. Although Karvonen, Hyvarinen et al. (2015) found significant relationships between major moisture damage and asthma and between any moisture damage alongside mould and asthma in Finnish children, the same relationship was not seen when looking at minor moisture damage alone. Similarly, although Thacher, Gruzieva et al. (2017) found significant associations between damp and mould and late-onset asthma and persistent asthma, the same relationship was not seen for allergic asthma. Finally, Oluwole, Kirychuk et al. (2017) used data from the Canadian Indoor Air and Children's Respiratory Health Study to evaluate the effect of mould on asthma. Despite finding a significant link between asthma and damp and mould, they found that this relationship was not significant when looking at home play area and mattress mould (p=0.27 and p=0.09, respectively). Finally, Breysse, Dixon et al. (2014) found that children living in homes in the United States that had been weatherised did not have statistically significant reductions in the need for urgent clinical care and in asthma attacks in the previous 3 months (p=0.553 for urgent care and 0.092 for asthma attacks), despite showing improvements in asthma control.

The other three studies did not find an association between asthma and any of the outcomes or indicators assessed. Lu et al. (2018) evaluated the effect of mould and damp on the risk of developing asthma in children aged 6 to 11 years in Romania and found no significant impact (p=>0.05). Polyzois, Polyzoi et al. (2016) and Madureira, Paciencia, Cavaleiro-Rufo & Fernandes Ede (2016) explored the impact of mould alone on asthma outcomes. Polyzois, Polyzoi et al. (2016) evaluated the effect of mould on asthma on a student population in Canada and found non-significant relationships between asthma and mould in the basement and kitchen, and between asthma with persistent colds with mould in the bathroom and kitchen. Finally, Bjerg et al. (2015) found no statistically significant link between current asthma and a damp home (OR (95% CI)= 0.38–1.59), although this study did not use an objective diagnosis of asthma, defining children with asthma as those who had used asthma medication in the past 12 months/suffered from wheeze.

Respiratory infections

Three studies explored the impact on respiratory infections, including bronchitis, cough and colds, and found mixed results as to whether the risk of developing respiratory infections changes after exposure to damp or mould.

A literature review conducted by Hurrass, Heinzow et al. (2017) examined the impact of mould and found an increased risk in respiratory tract infections/bronchitis (no p-values provided). Similarly, Lu, Lin et al. (2018) evaluated the effect of mould and damp combined on the risk of having a cold on children aged 6 to 11 years in Romania. The study found a significant negative effect of reported visible mould in the past 12 months on self-reported allergy symptoms (p=<0.05). The authors speculated that the significant effect related to allergy symptoms may be a result of several variables unique to Romania: Romanian homes have higher levels of pollutants related to indoor combustion due to higher prevalence of gas heaters and solid fuel use and Romania has a higher level of indoor smoking compared with the rest of Europe and North America. Cable et al. (2014) found that growing up in a damp house as a child (aged 10) increases the risk of cough and phlegm (RRR= 2.73 (95% CI=0.99–3.99)) as well as phlegm only (RRR= 2.05 (95% CI=1.07–3.91) in adulthood, though not to a statistically significant degree. As this study relied on self-reported data, there was no objective measure of lung function and no information on how long children were exposed to damp.

Polyzois, Polyzoi et al. (2016) evaluated the effect of mould on persistent colds on a student population in Canada and found mixed results depending on the outcome measured and on the location of the mould in the home. A significant relationship (p=<0.05) was found for the following connections: mould in the basement with persistent colds and asthma in combination with persistent colds; mould in the bathroom with persistent colds; and mould in the kitchen with persistent colds. Non-significant relationships were established for these remaining variables: mould in the bathroom with asthma in combination with persistent colds; and mould in the kitchen with asthma in combination with persistent colds. However, as mentioned previously, this study sampled homes during summer, when mould levels are higher, which may have influenced these relationships.

Wheeze

Five studies investigated the relationship between damp and mould and wheeze, and these studies, too, found mixed results as to the risk of developing a wheeze.

Karvonen, Hyvarinen et al. (2015) studied the effect of mould and damp combined on wheeze through conducting an initial study at birth and a follow-up after 6 years in Finland and found a significant relationship (p=<0.01) between major moisture damage or any moisture damage with visible mould and non-cold-related wheezing. Castro-Rodriguez et al. (2016) conducted a meta-analysis of 17 studies exploring the effect of mould and damp combined on wheeze and found that damp and mould at home is associated with 53 per cent greater chance of developing childhood wheeze. However, no p-value was provided, and the paper does not clarify whether the data on endotoxin, toxin and air pollution exposure is from an indoor or an outdoor source. In addition, Weber, Fuchs et al. (2017) found a significant association between visible mould and wheeze in the 12 months the study covered.

Although Karvonen, Hyvarinen et al. (2015) identified a worsening of wheeze after exposure to major moisture damage and to moisture damage alongside mould, the relationship between minor moisture damage and wheeze or nocturnal cough was not found to be significant. In addition, Alvarez-Alvarez et al. (2016) studied the effect of mould on wheeze and found no significant associations between mould stains at home and 'wheezing ever' ($p=0.153$) or 'recurrent wheezing' ($p=0.992$). However, it is important to note here that only a small number of participants reported mould in their home (6 per cent). Finally, Bjerg, Hedman et al. (2015) found no statistically significant link between current wheeze and a damp home (OR (95% CI) = 0.72–1.99).

Non-infectious respiratory symptoms

North et al. (2017) followed Canadian women and their babies from pregnancy until the child was 2 years old to evaluate the effect of mould on non-infectious respiratory symptoms and found that mould in the home was significantly associated with the occurrence of respiratory symptoms before 2 years of age ($p=< 0.001$).

Sleep disturbances

One study explored the impact of damp on sleep and found negative sleep outcomes (Tiesler et al. 2015). These authors reported that exposure to visible mould and damp was associated with a higher risk for any sleep problems, problems sleeping through the night, and a short sleep time compared with children living in homes without parent-reported damp (no p-values provided). As we only identified one study relating to sleep disturbances, and it is based on self-reported data, it is difficult to make an overall conclusion based on this for sleep quality.

2.2.2 Indoor air pollution

Multiple studies we reviewed explored the impact of indoor pollution on a range of health outcomes, including wheeze, infectious respiratory conditions, atopic conditions, asthma and sleep disturbances.

Atopic conditions

Two papers explored the impact of indoor pollutant exposure on atopic conditions, and both found statistically significant associations with some types of pollution.

Cibella et al. (2015) examined the impact of indoor NO_2 in an urban setting in Italy on the health of children aged 10 to 17. Exposure to high levels of NO_2 had a statistically significant association with the likelihood of children having rhinoconjunctivitis ($p=0.02$). However, no association was found between NO_2 and allergic sensitisation ($p=0.69$). This study was conducted in a small region of Italy and so it may be difficult to generalise the findings to elsewhere.

Shah et al. (2016) examined the relationship between particulate matter exposure in 128 preschool age children (0 to 5 years) and eczema. A statistically significant association was found between PM concentration and eczema ($p=0.049$). Further multivariate analysis for eczema demonstrated a strong association with PM (OR = 1.81 (95% CI 0.996, 3.301, p=0.052). However, the authors note that these results are only suggestive, as they are only approaching statistical significance.

Asthma

Four papers explored the link between indoor pollution and asthma in children. These studies found mixed results as to the direction of this impact on asthma.

Hansel et al. (2008) showed that higher NO_2 concentrations were associated with increased asthma symptoms in preschool inner-city children (coughing without a cold: p=<0.01; limited speech due to wheeze: p=<0.01). Cibella, Cuttitta et al. (2015) examined the impact of indoor NO_2 in an urban setting in Italy on the health of children aged 10 to 17. Exposure to high levels of NO_2 had a statistically significant association with the likelihood of children having asthma (p=0.0005). However, as noted previously, this study was conducted on a small population in Italy, which may make it difficult to apply the results to other areas.

Three papers we reviewed found no association between indoor pollution and asthma in children. Madureira, Paciencia, Cavaleiro-Rufo & de Oliveira Fernandes (2016) found no statistically significant difference with indoor pollutants, such as benzene, in asthmatic children's homes (p=>0.05 across all measured pollutants). The two studies by Stockton and colleagues we reviewed also found no significant relationship between indoor pollutants and asthma. Singleton et al. (2018) estimated that high levels of CO_2, which reflects reduced ventilation, was, surprisingly, inversely related to asthma (OR 0.27, p=0.038). However, the authors highlight how this result lost its statistical significance when the regression model was adjusted for crowding, age and high-risk status. Singleton et al. (2017) examined the prevalence and impact of particulate matter and found associations between included elevated particulate matter and health provider-reported asthma (OR 3.01 (significant), p=0.31 (not significant)). However, this study was conducted in a small number of homes in Alaska, which, the authors note, has worse indoor air quality than the rest of the United States.

Respiratory infections

Four studies we reviewed investigated the association between infectious respiratory conditions, including cough, in children and exposure to indoor pollution. Three of these found significant relationships between respiratory infections and indoor pollution, and the other found no significant link.

Singleton, Salkoski et al. (2017) examined the prevalence and impact of PM and found some associations with respiratory symptoms in children with existing lung disease and healthy children living in the same home. The strongest statistically significant association was found between volatile organic compounds (VOCs)[22] and cough between colds in all children (OR=4.42, p=<0.001). Other associations with significant OR values (although not significant p-values) included elevated particulate matter and cough between cold (OR 2.18, p=0.26), and VOC and wood used as primary source of heating with cough

[22] VOCs are emitted from many different types of products, including household products, such as paint, and can be concentrated in the indoor environment, and it is estimated that VOCs are ten times higher indoors than out (United States Environmental Protection Agency n.d.).

between colds (OR 3.18, p=0.27). However, as noted previously, this study was conducted on a small number of homes in Alaska, which has higher average levels of indoor pollution compared with the rest of the United States. A later study by Singleton and colleagues evaluated the impact of poor indoor air quality in Alaska and found that an intervention to reduce VOCs, PM and CO_2 resulted in improved respiratory symptoms and decreased lower respiratory tract infection-related doctor visits for children. When adjusted for age increase over time, the decrease in all clinic visits and lower respiratory tract infection visits remained significant for high-risk children with existing lung conditions, but not for other children or overall. This may suggest that children with existing (respiratory) conditions may be more susceptible to developing the negative health impacts associated with poor indoor air quality. Statistically significant adjusted decreases were also noted for colds or runny nose (p=0.003), cough between colds (p=0.004) and wet cough (p=0.037) (Singleton, Salkoski et al. 2018). Finally, Cibella, Cuttitta et al. (2015) examined the impact of indoor NO_2 in an urban setting in Italy on the health of children aged 10 to 17. Exposure to high levels of NO_2 had a statistically significant association with chronic phlegm (p=0.032).

Although Cibella, Cuttitta et al. (2015) found significant relationships between NO_2 and chronic phlegm, they found no association between NO_2 and cough (p=0.46). In addition, Ferrero et al. (2017) examined the impact of indoor exposure to benzene on infants aged up to 1 year. No statistically significant link was found between the levels of benzene and symptoms of cough and lower respiratory tract infections. However, as discussed previously, this study was conducted on a small sample in one region of Italy and so it may be difficult to generalise the results.

Wheeze

Three studies explored the impact of indoor pollutant exposure on wheeze in children, with mixed results.

One study found that wheeze and indoor air quality are significantly related. Singleton, Salkoski et al. (2018) evaluated the impact of poor indoor air quality in Alaska and found statistically significant decreases in wheezing with colds (p=0.057) and wheezing between colds (p=0.02) after introduction of an intervention to reduce air pollution, suggesting air pollution impacts negatively on wheeze symptoms. As mentioned in the previous section, the study participants were children with existing chronic lung conditions that may contribute to these outcomes, but these results may suggest that poor indoor air quality contributes (or exacerbates the symptoms of) existing lung conditions in children.

The other two studies found no significant relationship between indoor pollution and wheeze. Shah et al. (2016) examined the relationship between PM exposures, defined by these authors as inhalable matter within a child's breathing zone, in 128 preschool-age children (0 to 5 years) and wheeze and did not find a significant association. Ferrero, Esplugues et al. (2017) examined the impact of indoor exposure to benzene on infants aged up to 1 year and found no statistically significant link with wheeze.

Sleep disturbances

One systematic review explored the association between sleep disturbances in children and exposure to indoor pollution. Tenero et al. (2017) showed that indoor pollution is associated with sleep disturbances in children. The only paper from this review that focused on a country that satisfied our inclusion criteria (Italy) showed that adjusted ORs of snoring by children with medium (30–60 microg/m3) and high exposures (> 60 microg/m3) to NO_2 were 2.5 (95% CI: 0.7–8.7) and 4.5 (95% CI: 1.4–14.3). This suggests that the higher the exposure to NO_2, the higher the risk of snoring in children.

2.2.3 Noise

Three papers we reviewed looked at the impacts of noise on children's emotional and health outcomes, and each of these studies found worsening of these outcomes after noise exposure.

Grelat et al. (2016) analysed data relating to 517 children aged 7 to 11 years in France who experienced noise annoyance due to traffic or other outdoor sources. They found that annoyance (which in children includes feelings of discomfort, dissatisfaction and irritation and can lead to a stress response) was associated with the noise level in front of the child's bedroom (p=<0.01).

Dreger et al. (2015) studied the effects of 'unacceptable' noise exposure in German children aged 5 to 6 years. There was a statistically significant relationship (p=<0.05) between excess noise and emotional problems, as measured by emotional symptoms, conduct problems, peer relationship problems and hyperactivity. However, the authors note that the noise exposure is self-reported by parents and so may be subjective to recall bias and that children who repeated a year of school were not followed up in the study and that these children may have repeated the year due to mental health illness.

A literature review on the effects of noise provided evidence that exposure to noise has a negative impact on children's health (Gascon et al. 2016). Ambient noise at night was found to be associated with cognitive dysfunction, behaviour dysfunction and abnormal growth-hormone release. Some further evidence identified in this review, limited due to small number of studies or limitations to the study design, indicates than an increase in noise may lead to an increase in blood pressure, increased stress hormones and respiratory symptoms.

2.2.4 Radiation (through radon)

Three studies we reviewed explored the impacts of indoor radiation on the risk of cancer, multiple sclerosis and cognitive outcomes in children. Two of these found inconclusive results.

Nikkila et al. (2016) found evidence that background radiation is associated with childhood leukaemia ($p<0.05$) in children aged 2 to 6 years in Finland. However, they found no significant relationship for children aged 7 to 15 years. The authors note the low statistical power due to the small expected effect size.

A study by Groves-Kirkby et al. (2016) in England and Wales could not confirm whether radon exposure in children aged 15 to 19 years was associated with the development of multiple sclerosis, as the available data were insufficient. Similarly, Guxens et al. (2016) studied the impact of electromagnetic fields on children's cognitive function, but the associations were inconsistent.

2.2.5 Excess cold

We reviewed three studies that explored the health impacts in children after exposure to excess cold at home, including asthma, allergic conditions and hypothermia.

A study conducted in Portugal by Madureira, Paciencia, Cavaleiro-Rufo & de Oliveira Fernandes (2016) comparing the living conditions of 38 asthmatic school-age children to those of 30 non-asthmatic school-age children (8 to 10 years) showed that median indoor temperature was significantly lower in the bedrooms of the asthmatic children (16.7 vs 17.7 °C; p=0.045). However, as mentioned previously, this study may suffer from recall bias due to the reliance on self-reported data.

In a study by Piekarska et al. (2018) that assessed the impact of having central heating in urban homes in Poland, which was used as a proxy for adequate indoor temperature, the risk of children developing allergic rhinitis was not found to be significant when central heating was present (OR 1.12 (95% CI 0.91–1.40) for ages 6 to 7 and OR 1.04 (95% CI 0.85–1.28) for ages 13 to 14, p>0.05 for both age groups). Using standardised questionnaires and medical examinations, the research team estimated a significant link between the use of central heating and fungal sensitisation, although only for a subgroup of children aged 6 to 7 (OR 1.79, p=<0.01). For children aged 13 to 14, the presence of central heating was not associated with allergic rhinitis or fungal sensitisation.

A study conducted in New York City by Lane et al. (2018) on the reasons behind excess cold-related winter deaths and hospitalisations showed that 25 per cent of cases were associated with indoor exposure to cold temperatures. For children aged 0 to 17, lack of indoor heating was associated with incidence of hypothermia. However, cold-related illness resulting from indoor exposure to excess cold was not responsible for any child deaths (0 to 17 years) between 2005 and 2014 in New York City.

2.2.6 Lack of daylight

Although lack of daylight was part of our search protocol, our REA did not identify any high-quality studies on the health impacts of insufficient daylight on children.

2.3 The impact of health conditions linked to indoor climate hazards on parents' economic outcomes

This section provides an overview of the evidence linking the conditions we have outlined in the previous section with parental economic outcomes, for example, loss of working days or increased healthcare costs. This section is divided into the two health outcomes these papers cover: asthma and atopic dermatitis. A summary of these findings can be found in the box below.

Box 2.2: Impact of health conditions linked to indoor climate hazards on parents' economic outcomes (summary)

- When looking at the impact of childhood asthma on loss of parental working days, the studies we identified suggest that parents lose additional workdays as a result of having a child with asthma. This was found to be statistically significant by two of the four studies on asthma and not significant by the third paper. The final study did not provide information on significance. Although these data suggest that having a child with asthma leads to parents losing workdays, the number of days lost appears to depend on how well controlled the asthma is, with uncontrolled asthma leading to significantly more days of work lost for parents.
- One study provided information on the economic impact on parents as a result of their child having atopic dermatitis, including medical costs and other expenses as a result of missing work and requiring additional childcare. These data suggest that atopic dermatitis costs parents US$274 per month and that for those parents who missed work to care for their child (41 per cent of the study population) it led to a loss of 21 working hours a month.

2.3.1 The link between childhood asthma as well as atopic dermatitis and parental economic status

Five papers explored the economic impact of children's asthma on their parents. Four of these studies focused on the productivity loss resulting from parents missing work, while one paper examined the direct healthcare costs that parents incur if their child has asthma.

The link between childhood asthma and parental economic outcomes

The four papers exploring the impact of childhood asthma on parents' economic outcomes focused on children of a range of ages, up to 18. Each of these papers identified a negative impact on parents' attendance at work as a result of their child having asthma. In addition, one paper found that parents of children with asthma face additional healthcare costs.

Sullivan et al. (2018) found a statistically significant increase in lost workdays for parents and carers with asthmatic children aged 6 to 17 (p=0.034), although their findings were not significant when looking at two separate age groups within that (p=0.181 for ages 6 to 11 and p=0.080 for ages 12 to 17). This led to an average of 1.16 times more workdays missed for parents compared with those with healthy children. However, the authors note that this study may suffer from recall bias because it relies on self-reported data and because requirements for inclusion were based on a questionnaire asking if children had been diagnosed with asthma, rather than using a doctor's diagnosis. A further study by Sullivan et al. (2018) explored the impact on parental work attendance as a result of their child's asthma, this time focusing on the difference in outcomes as a result of the level of asthma control. The authors found a significant link between increased loss of workdays of parents and carers and their children, both those having poorly controlled and those having well-controlled asthma, compared with parents with non-asthmatic children (p=<0.001 for both). Parents of children with uncontrolled asthma did miss more workdays than parents of children with controlled asthma; however, this was not statistically significant. The authors note some limitations of this study, including that unemployed parents were not included in the sample, although they may have been unemployed in order to look after a child with asthma. In addition, as does the other Sullivan study, this study relies on self-reported data.

Nurmagambetov et al. (2017) identified a similar relationship as those described by both of the Sullivan et al. papers. Across asthmatic children of all ages, parents missed an additional 1.5–1.7 days of work compared with parents of healthy children, but no information on the significance of this difference was provided.

A randomised control trial by Fiks et al. (2015) explored the outcome of an asthma intervention for children aged 6 to 12 but also reported on the parents' lost workdays as a result of their children having asthma. Thirty-two per cent of parents of asthmatic children lost more than 1 additional workday compared with parents of non-asthmatic children at baseline, and 37 per cent lost at least 1 day 6 months later. Parents of children on the asthma intervention had a significant reduction in missed workdays ($p=<0.001$) from baseline to 6 months. This may indicate that the extent of parental loss of workdays depends on how well the child's asthma is controlled. The authors note that the data were self-reported, which may lead to some bias, and that the sample of asthmatic children may not be representative of the general asthmatic population because primary care providers recommended children to take part in the study.

A study conducted in the United States by Fabian, Adamkiewicz et al. (2014) calculated the financial burden of asthma on parents due to healthcare costs. They estimated that parents of children with asthma face average costs of US$2,503, while parents of children without asthma face average costs of US$1,762, based on data from 2008. The United States has a very different healthcare system to the UK and much of Europe, which means that the costs incurred in other countries may differ. The authors also note the complexity of the model they used, which doesn't take into account the wider influences of this relationship.

The link between childhood atopic dermatitis and parental economic outcomes

One paper explored the impact of childhood atopic dermatitis on the parents' economic outcomes. Filanovsky et al. (2016) investigated the link between atopic dermatitis in children aged 6 months to 12 years from the United States on various economic outcomes for parents, including healthcare costs and expenses, as well as lost working days. Overall, parents paid US$274 per month for atopic dermatitis costs. US$75 of this was spent on direct costs, which included medical visits, medication and medical products. The majority, US$199, was spent on indirect costs, which included money lost as a result of missed work and additional childcare costs. This resulted in an average of 35 per cent of parents' monthly available money being spent on atopic dermatitis. When looking more closely at lost workdays, the authors found that 41 per cent of caregivers of children with atopic dermatitis missed work to care for their child, losing an average of 21 hours a month (no information on the significance of this difference compared with parents of healthy children is provided). The authors note some limitations with this study, including that data on other additional costs, such as travel and changes at home, were not collected, that costs were calculated over 3 years but not adjusted for inflation, and that it relied on the use of self-reported data from caregivers.

2.4 The impact of health conditions linked to indoor climate hazards on children's academic achievement

This section provides an overview of the evidence that links the health conditions we have found to be associated with poor indoor climate with children's academic achievements. The majority of these focused on how asthma affects academic achievement; however, a small number of others also looked at allergic conditions, sleep disruption and psychological conditions. A summary of this section can be found in the box below.

Box 2.3: Impact of health conditions linked to indoor climate hazards on children's academic achievement (summary)

- There is conflicting evidence regarding the link between asthma and poorer academic outcomes in children: some studies found a statistically significant association, while others did not. The studies we identified indicate that children with asthma missed a greater number of school days as a result of their illness; however, many of these studies did not provide information on the significance of this link or compare the number of days lost to that of non-asthmatic children. As mentioned previously, the extent to which a child's asthma is controlled may influence the degree of impact. This is also the case with academic achievement. One paper identified a statistically significant link between uncontrolled asthma and poorer school outcomes, and another did not find a significant link.
- One study conducted a literature review to explore the academic outcomes of children with allergic conditions. The results of this were very mixed for the impact on missed school days, productivity and grades, with the seven studies assessed in this review indicating negative, no and positive impacts on these outcomes. Although the general trend indicates a negative impact on academic outcomes, the impact cannot be ascertained for certain based on these results.
- Studies investigating the link between sleep disturbances on academic outcomes in adolescents found mixed results: one found no statistically significant link between lack of sleep and academic performance, whereas the other two did.
- Finally, one paper investigated the link between psychological and psychosomatic health complaints in children and their educational attainment. A statistically significant link was found between these conditions and a lower likelihood of enrolling in university.

2.4.1 The impact of asthma on children's academic achievement

Multiple papers explored the impact of asthma on children's grades, school days missed and educational attainment. These studies were conducted in a range of countries, including the UK, the United States, Sweden and the Netherlands, and they primarily focused on children of school age.

The Impact of asthma on grades and educational attainment

Around half of the papers investigating impacts on academic achievement specifically looked at the effects of asthma on children's grades and educational attainment.

Ruijsbroek et al. (2015) explored the link between asthma and grades by following children in the Netherlands from birth until they turned 17. They found that the presence of asthma throughout childhood is significantly linked to lower school performance (−0.46; –0.04 95% CI); however, this was not significant if asthma was only present in early life. The authors note some limitations of the study, including the slightly skewed nature of the sample (more highly educated parents than the baseline), and that grade may be affected by other factors in addition to asthma.

Jones et al. (2017) followed children aged 8 to 17 in the United States and found a significant impact of asthma on school functioning (p=<0.001) between autumn and spring. It should be noted that this study did not compare children with asthma to those without asthma.

Nilsson et al. (2018) explored the link between asthma and school grades in adolescents in Sweden. Children who had ever had asthma were significantly more at risk of performing worse in school (OR 1.43, 95% CI=1.09–1.88). The level of significance differed between the age of asthma onset and degree of control over the condition. Asthma onset at school age was significantly linked to worse school performance (OR 1.61, 95% CI 1.02–2.16), whereas early transient onset and persistent asthma were not significantly linked. The level of asthma control (fully controlled, partially controlled, or uncontrolled) was not significantly linked to school performance. The authors note selection bias in their sample population, as half of the sample dropped out of the study after the researchers asked for consent.

Irani et al. (2017) conducted a meta-analysis to explore the differences in cognitive function of children with and without asthma. The authors found a statistically significant link (p=<0.001) between poorer academic achievement and asthma. However, the authors note that some of the studies they reviewed did not provide adequate information on treatment-related moderators, such as whether, and how well, the asthma was controlled, medication dose and comorbidities.

Although the studies we outlined above found a negative impact on grades as a result of asthma, Bhagat et al. (2018) found no significant link between the presence of mild asthma and moderate/severe asthma in children aged 4 to 10 and reading or maths skills (p=0.917 for reading and p=0.330 for maths). However, the authors did not compare these results with those of non-asthmatic children, so it is unclear if this difference would be significant. The study population was based on children from urban, minority and low-income homes in a specific area of New York City, making it difficult to generalise the findings to other populations. Similar results were obtained by Brew et al. (2019), in that they found no significant link between asthma in children at ages 9 to 12 and academic outcomes at age 15 in Sweden. However, the authors highlight that Sweden provides free healthcare for children and that different results may be seen in countries with healthcare inequality due to wealth differences.

The results from these studies indicate that there is a link between asthma and poorer school performance; however, there are differing data on whether, or to what extent, this link is statistically significant. There are also some limitations to these studies, such as skewed study populations (Jones, DeWalt et al. 2017; Nilsson, Odling et al. 2018; Ruijsbroek, Wijga et al. 2015), studies conducted on specific populations and locations, making it difficult to generalise to other groups (Bhagat, Fagnano et al. 2018; Jones, DeWalt et al. 2017), some missing data (Ruijsbroek, Wijga et al. 2015) and some data that is self-reported (Bhagat, Fagnano et al. 2018).

The impact of asthma on missed school days

Five studies investigated whether asthmatic children miss additional school days as a result of the illness. Four of these were conducted in the United States and one in Sweden

Stridsman et al. (2017) found that 32 per cent of children aged 14 to 15 with asthma in their study population had stayed home from school due to their symptoms in 2013 (down from 40 per cent in 2003, which is not a statistically significant difference).

Sullivan et al. (2018) found that school-aged children with poorly controlled asthma were significantly more likely to miss school days than children without asthma ($p=<0.001$). However, as noted previously, the authors highlight some limitations of this study, including that unemployed parents were not included in the sample and that it relies on self-reported data. In a later study, Sullivan and colleagues (Sullivan et al. 2018) explored the impact of asthma on missed school days in school-age children across all 50 United States. On average, children aged 6 to 17 with asthma missed 1.54 additional school days a year due to asthma compared with children without asthma. As discussed previously, this study relies on self-reported data, and asthma was not confirmed by a doctor diagnosis.

Fiks et al. (2015) found that 57 per cent of children having asthma (and who were not involved in an asthma intervention that was the focus of their study) lost more than 1 day of school at baseline (an average of 2.3 days) and 41 per cent 6 months later (an average of 1.9 days) (this was not a significant difference, $p=0.7$). However, this study did not report days of school missed by healthy children, so it is unclear if the difference between these groups is significant. As mentioned previously, the authors note some limitations, including reliance on self-reported data and that the sample of asthmatic children may not be representative of the general asthmatic population because primary care providers recommended children to take part in the study.

In general, these results indicate that children miss a greater number of school days as a result of having asthma. However, the significance of this difference between children with asthma and healthy children is not explored in most of these papers, making it difficult to conclude whether asthmatic children miss a significantly greater number of school days.

The impact of allergic conditions on children's academic outcomes

One paper investigated the effects of allergic rhinitis on children's academic outcomes through a literature review (Blaiss et al. 2018). These authors identified six papers that met our criteria of the research taking place in the United States or Europe and that explored the link between allergic rhinitis and allergic rhinoconjunctivitis on missed school days, school productivity and exam grades in children of secondary school age (10 to 18). When looking at missed school days, two papers reviewed by Blaiss, Hammerby et al. (2018) found different results in the number of days taken off by children with allergic conditions. These two papers did not specify the difference between these groups of children and those without these conditions. Therefore, whether allergic conditions have a significant impact on missing school days cannot be determined based on this information. Similar results were seen in the two papers exploring the impact of schoolwork productivity in children with allergic conditions. Both papers indicate worse productivity in children with these illnesses, with productivity worsening with increased severity; however, there is no information on comparisons with healthy children that would allow us to understand if this is a statistically significant impact. Finally, two papers found a negative impact on grades. Severe nasal symptoms were associated with a reduction in grades, although this wasn't significant ($p=0.09$). A large, case-controlled study in the UK found that adolescents with seasonal allergic rhinitis were significantly more likely to drop grades between winter mock exams and summer exams ($p=0.002$).

The information on the impact of allergic conditions on children's academic outcomes provided in the Blaiss et al. (2018) review is fairly mixed and does not make clear whether the link between these illnesses and academic outcomes is statistically significant compared with healthy populations. However, the evidence from this study indicates that allergic conditions may have a negative impact on academic outcomes. Particularly for allergic conditions, poor indoor climate is one of multiple factors that can contribute to illnesses, such as allergic rhinitis.

2.4.2 The impact of sleep disturbances on children's academic outcomes

Three papers explored the link between children's academic outcomes and sleep disturbances.

One of these papers found no significant link between sleep disturbances and academic outcomes. In adolescents aged 15 to 18 years in the United States, no statistically significant link was found between sleep duration and academic performance ($p=0.07$) (Pecor et al. 2016). However, the authors highlight that the study population may have been slightly skewed, as students with better grades were more likely to self-select to take part in the survey. The study authors did not compare the distribution of grades in the study to that of the high schools the students attended.

The other two papers found that sleep disturbances have a negative impact on academic outcomes. According to Pujol et al. (2014), there was a significant association between noise exposure (which we assume leads to sleep disturbances) at home and children's performance at school. More specifically, children who experienced high noise levels in front of their bedroom had lower grades in French tests ($p=<0.01$). This was attributed primarily to night-time exposure to noise, which has an impact on the quality of sleep and hence affects cognitive function. However, the authors note that children were not pre-screened for normal hearing before the study began (although there were no children enrolled in the school with clinical hearing impairment), and there was no adjustment in the results for children's health, such as low birth weight or chronic illness.

Finally, a systematic review of 76 studies by Medic et al. (2017) showed that sleep disruption had a negative effect on school performance.

2.4.3 The impact of psychological conditions on children's academic outcomes

One paper investigated the link between tertiary educational attainment of study subjects in Sweden and the psychological health complaints these study subjects had reported when they were children aged 10 to 18 years. The authors found a statistically significant link between psychological (i.e. a mental condition) ($p=<0.01$) and psychosomatic (i.e. a physical condition exacerbated by mental factors) ($p=<0.01$) complaints between the ages of 10 and 18 and a lower likelihood of enrolling in university. There are some limitations that should be taken into account with this study, including attrition between the two phases of the project, the likelihood that study participants may have attended university in the period after the researchers followed up, and the fact that grade point average was measured before reporting health conditions for some respondents and after for others.

2.5 Important points to be considered when interpreting the evidence

As outlined in this chapter, the evidence suggests that indoor climate hazards can have a significant impact on the health of children living in homes with these hazards, particularly in the form of respiratory and atopic conditions, but also in the form of sleep disturbances and emotional/mental health impacts. It appears that asthma and atopic conditions in particular have a negative impact on children's academic attainment through lost school days and poorer grades, as well as on their parents' economic status due to lost workdays and additional healthcare expenses.

There may be some differences in health outcomes depending on certain factors. For example, some of the studies we reviewed appear to indicate that the age and existing health of children influences the likelihood of developing certain health conditions when exposed to indoor climate hazards. Younger children may be more at risk of the health conditions, particularly indoor radiation and low indoor temperatures, compared with older children. In addition, children with existing medical conditions appear to be at a higher risk of developing certain health condition and/or may have a slower recovery. For example, evidence we reviewed suggests that children with existing asthma were less likely to recover when interventions were introduced to mitigate climate hazards. The age at which an existing medical condition occurs may also influence the extent to which an indoor climate hazard impacts academic outcomes and health. For example, onset of asthma earlier in childhood appears to have less of an impact on academic achievement than onset later in childhood. Finally, the extent of the damage in the home appears to influence the risk to health. Unsurprisingly, worse damage is linked to worse health outcomes in children.

Indoor climate hazards are not the only cause of illness in children. There are many other factors influencing health, and it is likely that indoor climate factors contribute to worsening of health but may not be a direct cause (or that there may be multiple factors contributing to poor health, including indoor climate). In addition, children's exposure to indoor climate hazards is unlikely to be limited to the home. Children spend much of their time in school or childcare facilities in which exposure may also occur, and it can be difficult to distinguish the effects of exposure at home vs exposure at school. Additional detail on the effects of poor climate in schools is discussed in the following chapter. Exposure to these factors may also come from outside. This is particularly relevant to air pollution, which often crosses indoor and outdoor sources.

Although the evidence is fairly strong to make this overall conclusion, there are some limitations of the studies we reviewed that needs to be considered when interpreting the data. First, there was much variation across the studies in the types of outcomes and indoor climate factors that were measured. Some studies measured broad health impacts, e.g. allergic rhinitis, and others looked at more specific conditions, e.g. sensitisation to specific types of allergens. There was also variation in the studies across the type of indoor climate measured and the detail they went into. For example, some studies only assessed whether damp and/or mould were present (sometimes not distinguishing between the two), whereas other studies described in more detail the extent of the damp/mould and its location in the home. These variations in study designs can make direct comparisons difficult in a review such as this. Second, the studies we reviewed appear to have some limitations in common. For example, many of the studies relied on self-reported data, which can lead to bias and inaccuracies in recall. In addition, the nature of some study samples meant the results can be difficult to generalise across wider populations.

3. Quantifying the burden of poor indoor climate on children and their parents

This chapter examines the associations between different indicators of poor indoor climate and corresponding health and educational outcomes of children. For that purpose, we use a combination of different suitable and relevant data sources, including the EU-SILC database and the Global Burden of Disease database, as well as information provided by our REA.

We begin the chapter with an overview of the prevalence of certain indicators of poor indoor climate across the 28 EU member states and then look at what household characteristics are associated with the self-reported prevalence of these poor indoor climate indicators. We then investigate empirically the associations between poor indoor climate indicators and children's health and educational outcomes. Specifically, we analyse the following:

1) The associations between the prevalence of damp, noise, lack of daylight and the inability to keep the house adequately warm and self-reported child's health;
2) The health burden on children associated with damp and mould in residential buildings in Europe, including the calculation of disability adjusted life years; and
3) Overall school days missed associated with damp and mould in residential buildings in Europe.

The key findings of this chapter can be summarised as follows:

Box 3.1: The burden of poor indoor climate on children and their parents (summary)

- **Prevalence of sub-optimal housing quality**: About one in three children across the EU-28 lives in a dwelling that is affected by at least one of the following self-reported poor indoor climate indicators: (1) a leaking roof, damp or rot; (2) lack of light; (3) noise; and (4) inability to keep dwelling adequately warm.
- **Determinants of sub-optimal housing quality**: While we found a series of factors associated with sub-optimal housing quality (e.g. measured as the prevalence of self-reported issues with dampness) the socio-economic status of a household, as well as living in a rented accommodation or a single-household dwelling are on average more likely associated with sub-optimal housing quality at the EU level.
- **Children's health and indoor climate:** We find statistical evidence that poor housing quality, such as leaking roof, damp, and rot in windows, as well as lack of daylight, are associated with poorer child health. It is predicted that improving four poor indoor climate housing quality indicators would improve the health status of about 1.2 million children across the 28 EU member states.
- **Burden associated with dampness:** Damp is prevalent in almost 13 per cent of households across Europe, with potentially negative health consequences for children. It is estimated that the exposure to damp across the EU-28 member states is associated with the loss of about 37,000 disability adjusted life years (a metric taking into account mortality and morbidity caused by a disease).

The first section of this chapter provides a description of relevant data sources used in the analysis and an overview of the statistical methods applied.

3.1 Data sources

In our empirical analysis, we draw on a variety of different data sources. For instance, the analysis on the prevalence of certain poor indoor climate indicators and their implications for children's health across Europe is based on the EU-SILC database, which is provided by Eurostat. The EU-SILC database is a comprehensive household survey that is conducted every year, which includes a variety of different variables, such as metrics for poor indoor climate or inadequate housing situations. The database has been applied in the past to examine the associations between inadequate housing and the corresponding health burden (e.g. Braubach et al. 2011). Furthermore, in order to determine the overall health burden related to specific diseases associated with poor indoor climate, we use the GBD data in combination with parameters on the associated relative risks between different poor indoor climate indicators and specific diseases identified through the systematic literature review presented in the previous chapter. The GBD data are a comprehensive database on all aspects of the burden (e.g. mortality and morbidity) associated with a large variety of diseases.

In turn, we describe each of the data sources in more detail.

3.1.1 EU-SILC

The EU-SILC is an annual, pan-European survey of private households and their current members which collects cross-sectional and longitudinal microdata on a variety of social indicators, including income, poverty, social exclusion and living conditions. As described by Iacovou et al. (2012), the initial release, regarding data collected in 2004, included information on 13 EU member states plus Norway and Iceland.[23] From 2007 onwards, it has included all EU member states at time of collection, as well as some non-member states.[24] Data are available from 2004 to 2017. EU-SILC data are collected by national statistical institutes in each country, with information extracted from administrative registers or obtained through interviews. Information on social exclusion and housing conditions is largely collected at the household level, while information on health, education and labour is collected at the individual level, with interviews undertaken with all individuals aged 16 years and over in the household (Eurostat 2019b). Although only those aged 16 years and over are interviewed, all members of the household are surveyed.

Every year, around 130,000 households and 270,000 individuals are interviewed across the EU countries for the collection of the cross-sectional microdata, while around 100,000 households and 200,000 individuals are interviewed for the longitudinal microdata in the same region. In order to enable descriptions and comparisons of population characteristics across the countries and regions of the EU, data need to be collected using probability sampling, in line with the appropriate procedures outlined by the EU (Iacovou, Kaminska et al. 2012). Although the majority of countries followed the appropriate sampling procedures, a few countries followed different procedures (Iacovou, Kaminska et al. 2012). As a result, slight discrepancies may exist between the national-level statistics provided in the EU-SILC database and those calculated from the EU-SILC microdata, even when applying the weighting provided in the microdata.[25]

Each year, an ad-hoc module is developed to complement the variables collected on an annual basis and to gain a more in-depth understanding of otherwise-unexplored aspects of social inclusion. Detailed information on all EU-SILC ad-hoc modules can be found on the Eurostat website (Eurostat 2019a). Previous versions of the Velux Healthy Homes Barometer (e.g. VELUX 2017) focussed on the *Housing Conditions* ad-hoc module from 2012 (Eurostat 2019a), whereas our analysis focussed on the *Health and Children's Health* ad-hoc module (Eurostat 2019a) from the most recent EU-SILC microdata, collected in 2017. The household respondent (typically the parent or guardian) was asked to provide additional information on the health of all children living in the household, answering questions on the general health of the children, whether their activities are limited because of their health, and whether the children have any unmet medical needs and the reason for this.

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[23] These 13 member states are Austria, Belgium, Denmark, Estonia, Finland, France, Greece, Ireland, Italy, Luxembourg, Portugal, Spain and Sweden.

[24] E.g. such as Turkey or Norway, which have not been included for the scope of the analysis of this report.

[25] For the purpose of this analysis, we have applied the weighted summary statistics provided directly from the EU-SILC microdata. Note that we detected no relevant discrepancies between what is provided in Eurostat and the EU-SILC microdata for the poor indoor climate indicators included.

3.1.2 Poor indoor climate indicators used in the analysis

For this analysis, we use four different indicators related to poor indoor climate from the EU-SILC database, namely, (1) whether the household suffers from a leaking roof, damp walls/floors/foundation or rot in windows or floor; (2) whether the household reports issues with the dwelling being too dark; (3) whether the household has an issue with noise from neighbours or outdoors; and (4) whether the household has issues keeping the dwelling adequately warm. The four variables are described in more detail in Appendix Table B.1. A complete list of the latest EU-SILC variables, and in-depth information on how they were derived, can be found in the *Methodological Guidelines and Description of EU-SILC Target Variables* document (Eurostat 2017). For the statistical analysis, we also use further variables provided by the EU-SILC database, which include, for instance, information about the household (e.g. income, size) and general housing conditions (e.g. living in rural or urban area, single- or multi-family home). Numerous EU-SILC variables were of interest for the current study, examining the impact of poor indoor climate on children's health. Definitions and descriptions for these variables are provided in Table B.2.

3.1.3 Global Burden of Disease Database

The GBD is one of the most comprehensive data sources with regards to the collection of a range of factors (e.g. mortality and morbidity) associated with a large number of diseases. It is an open access dataset that quantifies the health burden associated with hundreds of diseases, injuries and risk factors globally (IHME 2019a). Importantly, GBD data includes information on both the prevalence of a risk factor and the relative harm caused by it, presented through estimates of the following outcomes for a given cause (e.g. asthma):

- All-cause mortality;
- Deaths by cause;
- Years of life lost due to premature mortality (YLLs);
- Years lived with disability (YLDs); and
- Disability adjusted life years (DALYs).

As explained by IHME (2019b), the GBD first provided estimates of premature death and disability from 107 diseases in 1990, across eight regions, broken down into five different age groups. The dataset has grown significantly since then, now providing annual estimates from more than 350 diseases and injuries across 195 countries, broken down by age (into five-year age categories) and gender. The latest estimates are for 2017, with annual estimates of all outcomes available back to 1990, and mortality and life expectancy estimates now date back to 1950. In order to examine the associations between poor indoor climate and the burden related to disease areas of child health, we extracted outcomes from the GBD dataset for the four health conditions that emerged from the review of the literature as potentially being associated with the exposure to damp or mould:[26]

[26] Note that we focus the analysis on the exposure to damp or mould because there were sufficient parameters for this poor indoor climate indicator in the literature on the relative risk to develop a health condition, such as asthma,

- Asthma;
- Atopic dermatitis;
- Lower respiratory infections (e.g. bronchitis); and
- Upper respiratory infections (e.g. rhinitis).

For each of these four conditions, we extracted the relevant information on the associated burden with regards to DALYs and other metrics from the GBD.

3.2 Statistical methods

3.2.1 Multivariate regression methods using EU-SILC data

In order to quantify the prevalence of poor indoor climate indicators across Europe and to examine the household characteristics associated with poor indoor climate indicators, such as damp or lack of daylight, and how these indicators are associated with children's health outcomes using the EU-SILC data, we use multivariate regression models. Specifically, we draw on two empirical estimation methods, the linear probability model (LPM) and ordinal logit models (OLM), as well as the general ordinal logit model (GOLM). Both regression methods are explained in more detail in Appendix C. In short, the LPM and the OLM have in common that they allow for an assessment of the association between an explanatory variable (e.g. a problem with damp in the dwelling) and a dependent variable of interest, when the dependent variable is either binary (e.g. child healthy, 'yes' or 'no') or ordinal scaled (e.g. self-reported health status of a child in different categories, such as 'poor', 'good', 'very good').

All statistical analyses were conducted in STATA 15. Results are reported at the 10 per cent significance level. That means that for statistical significance we expect the p-value to be less than ($p<0.1$).[27]

3.2.2 Health burden associated with poor indoor climate

We aimed to calculate the burden associated with the health implications of a change in indoor dampness exposure of children. In chapter 2, we outlined that damp may be associated with asthma, acute rhinitis, and upper and lower respiratory infections in children. For the purpose of this analysis, we draw on GBD data, which includes a rich set of information regarding diseases and captures both morbidity and mortality rates by disease for each specific gender and age group. This is measured through a metric called disability adjusted life years (DALYs). In essence, DALYs are calculated as follows:

$$DALYs = YLLs + YLDs \quad (1)$$

if exposed to the hazard, whereas for other indoor risk factors, such as radon exposure, the necessary parameters were available. See section 3.2.2 below for further explanation.

[27] Note that in some research areas, such as economics, it is relatively common to report estimates at least at the 10 per cent significance level. However, each estimate is reported on whether it passes the 1%, 5%, and 10% significance level, which is denoted in the report tables with different stars (e.g. three starts implying that it is statistically significant at the 1% level).

where YLLs refer to years of life lost (mortality) and YLDs refer to years lived with disability (morbidity). Years of life lost generally refers to the difference between general life expectancy at age and the age at time of death from a given cause. It is calculate as the sum of the number of death cases (N) and the life expectancy at the time of death (L): $\sum N \times L$. Years lived with disability refers to the time over the life that an individual has to spend in suboptimal health, which can be written as the sum of the number of disability incidences (I), the corresponding disability weight of the disease (DW) and the length of disability (LD): $\sum I \times DW \times LD$.

One challenging aspect of trying to assess the health burden is that many illnesses are associated with several factors simultaneously. For instance, the disease burden of asthma in a country is likely influenced by several factors, including inhaled allergens (e.g. dust mites, pollen, mould), inhaled irritants (e.g. tobacco smoke, cooking and heating fumes), medicines (e.g. aspirin), and genetic factors, among others (Global Asthma Network 2014). However, it is possible to attribute the total disease burden in a society from a disease to a specific health risk, such as damp or mould. In order to assess the risk factor-specific associations, we need the attributable or relative risk parameters from the medical or epidemiologic literature. In essence, the attributable or relative risk represents the percentage difference in observed morbidity between the exposed population (e.g. the population exposed to damp) and the unexposed population. In other words, it represents the share of the disease burden that would be reduced if the risk factor were to be eliminated.

Technically, the population attributable fraction (PAF) of a risk factor, such as damp, can be calculated as follows:

$$PAF = (P \times (RR-1))/(P \times (RR-1) + 1) \qquad (2)$$

where P represents the overall proportion of the population exposed (e.g. share of children exposed to mould) and RR represents the attributable risk, or relative risk, of the disease onset under exposure. Generally, it is important to highlight that the PAF may inflate the true values of the attributable risk, because in many cases, when the relative risks are assessed empirically in the scientific literature, not all possible risk factors have been able to be adjusted for.

For the purpose of this analysis, for the variable P in equation (2), we use data from the EU-SILC with regards to the overall share of children affected by damp exposure, which is based on the variable on the prevalence of 'a leaking roof, damp walls or rot in windows'. The RR in relation to damp for each disease area is taken from the literature review: asthma (RR = 1.3 (Quansah et al. 2012)); rhinitis (RR = 1.4 (McNally et al. 2001)); rhinitis/upper respiratory infection (RR = 1.6 (Jaakkola et al. 2013)); bronchitis/lower respiratory infection (RR = 1.5 (Urlaub & Grün 2016)).

3.2.3 Limitations to the analysis presented in this chapter

For the vast majority of the statistical analyses conducted in relation to children, we have only cross-sectional data available, and hence we cannot infer causal relationships in the data within the statistical analyses presented in this chapter. However, the dataset includes a large set of control variables that allows for the adjustment of some confounding factors, which allows us to examine the independent association between two variables. As the EU-SILC data are at the level of the country, we include country-fixed effects in each regression, adjusting for country-specific variables, such as size, economic strength, and legislation, as well as country-specific institutions (e.g. different health systems), among others.

Furthermore, it is important to highlight that the answers to many of the questions reported in the EU-SILC database depend on the subjective interpretation of the respondent. For instance, if the respondent answers that she is affected by noise in the dwelling, her answer most likely depends on her self-reported perception of noise. A more noise-sensitive person could answer this question differently from a less noise-sensitive person, even though the level of noise affecting the dwelling is equal. This also holds for the other variables that are used as indicators for poor indoor climate. For instance, the wording 'adequately warm' could be interpreted by a respondent as referring either to too warm or to too cold, depending on the respondent.

In addition, it is important to stress that the analysis with regards to the overall health burden (e.g. DALYs) associated with exposure to damp is based on parameter estimates (e.g. relative risks) from existing literature, which in most cases represent associations rather than causal relationships. This also applies to the existing estimates with regards to school days or working days missed associated with such health conditions as asthma, rhinitis, or dermatitis. This may likely lead to an overestimation of the true burden because often the different disease areas are not independent from each other. For instance, a child exposed to damp may be more likely develop asthma as well as rhinitis. In addition, one also needs to take into account the difference between relative risk and absolute risk. For instance, while exposure to damp increases the relative risk of developing asthma by about 30 per cent (e.g. a person exposed to damp has a 30 per cent higher likelihood to develop asthma than a person not exposed to damp), overall the exposure to damp in residential buildings across the EU-28 is between 13 and 15 per cent and asthma incidence rates in children have been declining over the past decades in most European countries.[28] That is, while the relative risk of exposure to damp or other poor indoor climate risks appears relative large, when examined in absolute terms, the risk exposure is more nuanced.[29]

3.3 Empirical results

In this section, we first report the prevalence of poor indoor climate indicators across the 28 EU member states. Then we present some further statistical analysis on the associations between poor indoor climate indicators and children's health.

3.3.1 Prevalence of poor indoor climate indicators across the EU

Table 3.1 reports the prevalence of reported leaking roofs, damp walls/foundations or rot in windows, as well as a lack of light across EU member states, based on EU-SILC data. For each poor indoor climate

[28] According to GBD data.

[29] To give an example, if the proportion of households exposed to damp or mould is 13 per cent and the relative risk for developing asthma while being exposed to the hazard is 30 per cent (relative higher risk compared with an individual not exposed), then the population-attributable factor of damp with regards to asthma is 3.75 per cent. In other words, about 3.75 per cent of cases of asthma are explained by exposure to damp or mould.

indicator, the proportion of households affected, as well as the proportion of children in total affected, is reported by country for the year 2017.[30]

Overall, about 13 per cent of EU households report issues with their dwellings of residence with regard to leaking roofs, damp or rot in windows, which affects about 15 per cent of all individuals aged 0 to 17 (which are labelled as children for the rest of this chapter). Also, about 13 per cent of EU households report that their dwelling has not enough light and hence that it is too dark, which roughly affects about 5 per cent of children in the EU. There is considerable variation across EU member states. For instance, the proportion of children affected by leaking roofs, damp and rot is substantially above EU average in Belgium, Cyprus, Hungary, Latvia, Portugal, Slovenia and the United Kingdom, whereas the proportion of children affected is below average in the Czech Republic, Finland, Slovakia and Sweden. With regard to children living in households reporting not enough light, countries with substantially above EU average proportions are Bulgaria, Hungary, Latvia, Luxembourg, Portugal, and the United Kingdom.

Table 3.2 reports the prevalence of noise in the dwelling and the lack of the ability to keep the home adequately warm across the EU-28 member states. Across the EU-28, about 18 per cent of households report having issues with noise in the dwelling from neighbours or from outside. This affects about 17 per cent of children.

[30] The year 2017 is the latest for which EU-SILC data are publicly available.

Table 3.1: Prevalence of leaking roofs, damp, rot and lack of light across EU-28, year 2017

	Leaking roof, damp walls/floors/foundations, or rot in window frames or floors (Damp)		Dwelling too dark, not enough light (Dark)	
	% Households	% Children	% Households	% Children
EU-28	13%	15%	13%	5%
Austria	11%	14%	6%	7%
Belgium	18%	22%	6%	7%
Bulgaria	12%	14%	6%	9%
Croatia	12%	10%	5%	4%
Cyprus	30%	28%	4%	4%
Czechia	8%	9%	3%	4%
Denmark	14%	19%	4%	4%
Estonia	14%	13%	4%	3%
Finland	4%	5%	4%	3%
France	11%	13%	7%	6%
Germany	12%	15%	4%	4%
Greece	14%	12%	5%	5%
Hungary	24%	30%	8%	11%
Ireland	12%	13%	6%	7%
Italy	16%	15%	4%	4%
Latvia	23%	22%	9%	10%
Lithuania	15%	18%	6%	6%
Luxembourg	17%	19%	7%	10%
Malta	9%	7%	7%	7%
Netherlands	13%	15%	4%	2%
Poland	12%	12%	5%	5%
Portugal	26%	26%	12%	11%
Romania	10%	14%	4%	7%
Slovakia	6%	8%	3%	3%
Slovenia	23%	20%	5%	4%
Spain	11%	12%	4%	4%
Sweden	7%	8%	6%	7%
UK	16%	21%	8%	9%

Notes: Based on EU-SILC 2017. Entries are weighted with appropriate cross-sectional weights.

The countries with significantly below EU average levels of reporting suffering of noise are Croatia, Estonia, Ireland, Hungary, Poland, Finland and Slovakia. Those with above EU average levels are Germany, Malta, Netherlands, Portugal and Denmark.

Table 3.2: Prevalence of noise in dwelling and lack of ability to keep home adequately warm across EU-28, year 2017

	Noise in dwelling from neighbours or from outside (Noise)		Lack of ability to keep home adequately warm (Not warm)	
	% Households	% Children	% Households	% Children
EU-28	18%	17%	8%	7%
Austria	18%	16%	2%	2%
Belgium	15%	17%	5%	7%
Bulgaria	10%	10%	37%	35%
Croatia	9%	7%	8%	6%
Cyprus	17%	16%	23%	23%
Czechia	14%	13%	3%	2%
Denmark	20%	15%	3%	3%
Estonia	8%	8%	3%	2%
Finland	13%	11%	2%	2%
France	16%	18%	5%	4%
Germany	26%	24%	3%	4%
Greece	20%	20%	26%	25%
Hungary	11%	13%	7%	7%
Ireland	8%	11%	4%	5%
Italy	13%	11%	15%	14%
Latvia	14%	13%	10%	9%
Lithuania	13%	16%	29%	26%
Luxembourg	22%	22%	2%	1%
Malta	25%	24%	7%	5%
Netherlands	26%	23%	3%	2%
Poland	13%	13%	7%	4%
Portugal	23%	24%	21%	17%
Romania	19%	20%	11%	11%
Slovakia	13%	14%	4%	5%
Slovenia	14%	11%	4%	3%
Spain	15%	15%	8%	9%
Sweden	17%	15%	2%	2%
UK	17%	18%	6%	7%

Notes: Based on EU-SILC 2017. Entries are weighted with appropriate cross-sectional weights. '

The ability to keep the home adequately warm may relate not just to an actual housing deficiency, but also to the general socio-economic situation of a household. On average, about 8 per cent of households across the EU report struggling to keep their dwelling adequately warm. This affects about 7 per cent of children. The countries with below EU average proportion of households struggling to keep the dwelling adequately warm are Austria, Czechia, Denmark, Estonia, Finland, France, the Netherlands, Slovenia. The countries above EU average proportion are Bulgaria, Cyprus, Greece, Lithuania, Portugal, and Italy.

Table 3.3 provides a summary on the total number of children by country that are exposed to at least one of the four poor indoor climate indicators as reported in the EU-SILC. On average, we find that about one third of children across the EU 28 are exposed to at least one of the four poor indoor climate indicators, representing about 26 million children.

Table 3.3: Proportion and number of children exposed to at least one poor indoor climate indicator across EU-28

		At least 1 poor indoor climate indicator	
	Number of children	Per cent	Absolute
EU-28	78,608,010	33.5	26,298,078
Austria	1,225,424	29.4	360,477
Belgium	1,919,418	40.7	780,920
Bulgaria	1,005,304	42.4	425,978
Croatia	628,114	20.9	131,420
Cyprus	196,152	49.8	97,705
Czechia	1,604,428	23.1	370,875
Denmark	958,156	31.3	300,354
Estonia	212,174	21.4	45,335
Finland	898,527	18.8	168,843
France	11,823,456	31.4	3,715,632
Germany	10,712,112	34.8	3,730,799
Greece	1,631,736	45.5	743,063
Hungary	1,412,902	37.7	532,950
Ireland	1,021,580	27.2	277,566
Italy	8,167,974	33.8	2,760,904
Latvia	301,508	37.0	111,562
Lithuania	427,947	47.6	203,499
Luxembourg	92,820	39.2	36,377
Malta	61,638	34.5	21,237
Netherlands	2,838,147	33.5	952,113
Poland	5,695,329	26.4	1,500,870
Portugal	1,466,593	50.6	742,324
Romania	3,064,321	36.1	1,107,716
Slovakia	831,322	21.6	179,177
Slovenia	305,198	30.9	94,229
Spain	6,916,924	29.1	2,012,512
Sweden	1,688,806	25.9	437,348
United Kingdom	11,500,005	38.8	4,456,294

Notes: Based on EU-SILC 2017. Entries are weighted with appropriate cross-sectional weights. Total number of children based on UN Population data.

3.3.2 Household and dwelling characteristics associated with poor indoor climate across the EU

Table 3.4 reports the parameter estimates from a regression analysis using as dependent variables the binary indicators of whether respondents in the EU-SILC data report to have issues with (1) leaking roofs, damp or rot; (2) a lack of light; (3) noise from indoors or outdoors; (4) a lack of ability to keep dwelling adequately warm; or (5) at least one of the four poor indoor climate indicators.[31]

The parameter estimates reported in column (1) of Table 3.4 suggest that if a household is reporting issues with a leaking roof, damp and rot (*Damp*), then this household is also more likely report issues with a lack of light (*Dark*); noise (*Noise*) and the ability to keep the house adequately warm (*Not warm*), all else equal.[32] For instance, if a household reports having a lack of daylight, this household will also report issues with a leaking roof, damp and rot with 25 percentage point higher likelihood than a household that has no issues with daylight. The findings thus suggest that these indicators of poor indoor climate tend to be clustered together. Furthermore, overcrowding is associated with the likelihood of reporting an issue with a leaking roof, damp or rot, and compared with households living in suburban areas, households in rural areas tend to report more likely this indicator of poor indoor climate. On average, we also find that compared with households living in multi-family dwellings, households in single-family dwellings are more likely to report issues with a leaking roof, damp or rot. When looking at the ownership status, we find that those renting (either as tenant or as having a reduced or free rent) also are more likely to report having issues with a leaking roof, damp or rot.

Similar associations can be found for the other poor indoor climate indicators, as reported in columns (2) to (4). Columns (2) to (4) confirm that the poor indoor climate indicators are associated with each other. We also find that, all else being equal, all of the indicators are associated with deprivation. Issues with a lack of light tend to be more likely reported in households living in urban areas. For instance, living in an urban area increases the probability to report having issues with a lack of light by 0.9 percentage points. With regards to single- and multi-household dwellings, we find that there is no statistically significant difference for a lack of light between the two dwelling types but that single-household dwellings are more likely tend to have an issue with noise. Furthermore, reporting issues with lack of light tends to be more likely in rented accommodation (e.g. as tenant, reduced or free rent), whereas on average an issue with noise, is more likely to be reported by households living rent-free.

Overall, if we look at household income, we find that all poor indoor climate indicators are associated with lower household incomes. That is, all else being equal, households in higher household income quintiles are less likely to report any of the four housing deficiencies. For instance, a household in the lowest income quintile is on average 25 percent less likely to have a problem with at least one of the four poor indoor climate indicators.[33]

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[31] The empirical analysis uses the LPM (see section 3.2.1 for a description and discussion) using the pooled EU-SILC data for the years 2011–2017 at the person level with added household information. Only responses from household heads have been taken into account.

[32] E.g. the parameter estimates are positively associated with damp and statistically significant.

[33] The average proportion of all households in the lowest household income quintile that report at least one of the four poor indoor climate indicators is 25.6 per cent. Hence we divide the 6.31 percentage point lower likelihood reported in Table 3.5 column 5 by the 25.6 per cent and find that the likelihood to report at least one of the poor indoor climate indicators reduces by about 25 per cent for a household in the highest quintile of the household income distribution, compared with a household in the lowest quintile.

Table 3.4: Household and dwelling characteristics associated with leaking roofs, damp, rot; lack of light, noise and inability to keep adequately warm across EU-28

Variable	(1) Damp	(2) Dark	(3) Noise	(4) Not warm	(5) At least 1
Damp		0.1135	0.0452	0.1124	
		(0.010)***	(0.004)***	(0.007)***	
Dark	0.2454		0.0309	0.1275	
	(0.023)***		(0.004)***	(0.011)***	
Not warm	0.0901	0.0285		0.0292	
	(0.011)***	(0.005)***		(0.005)***	
Noise	0.0887	0.0466	0.0116		
	(0.006)***	(0.005)***	(0.002)***		
Deprived	0.0979	0.0324	0.5547	0.0185	0.4295
	(0.017)***	(0.004)***	(0.040)***	(0.007)**	(0.021)***
Overcrowded	0.0399	0.0255	-0.0020	0.0011	0.0409
	(0.004)***	(0.002)***	(0.004)	(0.003)	(0.004)***
Rural (base: suburban)	0.0176	0.0036	-0.0067	-0.0373	-0.0127
	(0.004)***	(0.003)	(0.004)*	(0.003)***	(0.005)**
Urban (base: suburban)	-0.0029	0.0093	-0.0009	0.0411	0.0373
	(0.005)	(0.002)***	(0.003)	(0.007)***	(0.004)***
Single family	0.0516	0.0028	0.0121	-0.0766	0.0163
	(0.008)***	(0.003)	(0.004)**	(0.008)***	(0.009)*
Mortgage (base: full owner)	0.0056	0.0002	-0.0007	-0.0053	0.0012
	(0.005)	(0.001)	(0.002)	(0.004)	(0.008)
Rent (base: full owner)	0.0599	0.0169	0.0038	0.0444	0.0980
	(0.005)***	(0.002)***	(0.003)	(0.008)***	(0.011)***
Reduced (base: full owner)	0.0711	0.0143	0.0002	0.0609	0.1118
	(0.009)***	(0.005)***	(0.005)	(0.005)***	(0.006)***
Free (base: full owner)	0.0410	0.0232	0.0084	0.0051	0.0521
	(0.010)***	(0.006)***	(0.003)***	(0.008)	(0.013)***
HHI: 2nd quintile	-0.0067	-0.0074	-0.0129	0.0022	-0.0161
	(0.004)*	(0.001)***	(0.003)***	(0.003)	(0.003)***
HHI: 3rd quintile	-0.0111	-0.0131	-0.0196	0.0015	-0.0298
	(0.005)**	(0.002)***	(0.004)***	(0.006)	(0.005)***
HHI: 4rd quintile	-0.0235	-0.0145	-0.0281	-0.0056	-0.0552
	(0.005)***	(0.002)***	(0.005)***	(0.007)	(0.004)***
HHI: 5th quintile	-0.0351	-0.0178	-0.0387	-0.0110	-0.0631
	(0.005)***	(0.002)***	(0.006)***	(0.008)	(0.006)***
Observations	3,551,728	3,551,728	3,551,728	3,551,728	3,562,013
R-squared	0.2290	0.1896	0.4447	0.1927	0.2400

*Notes: Clustered standard errors (household identifier) in parentheses (*** p<0.01, ** p<0.05, *p<0.1). Based on pooled EU-SILC 2011–2017. The outcome variables include binary indicator variables taking the value 1 if any of the poor indoor climate indicators in Column (1 to 4) are prevalent. The coefficients are from LPM regressions using the control variables reported in the table in addition to year and country-fixed effects, as well as person-level variables from the household head, including highest level of education, gender and age. For entries where information on urban/rural/suburban or the single family or multi-household was not available, we added a category 'missing' in the analysis. HHI = .Household Income.*

3.3.3 The associations between poor indoor climate and children's health based on EU-SILC 2017

In the analysis presented in this section, we examine the association between different indicators of poor indoor climate and children's health, reported on a scale from 1 ('bad') to 4 ('very good'). We first report descriptively the overall health status of children as reported across the EU-28 member states. We then examine statistically the factors associated with a child's health using ordered and generalized ordered logit regression models. Finally, using the coefficients from these regressions, we conduct a counterfactual analysis in estimating how many children across the EU would have an improved health status if they had not been exposed to any of the four poor indoor climate indicators as reported in the EU-SILC data: (1) leaking roof, damp or rot; (2) lack of light; (3) noise; and (4) inability to keep dwelling adequately warm. Table 3.5 reports the overall distribution of the self-reported children's health variable across the 28 EU member states.

Table 3.5: Children's health status across the EU-28

	Child self-reported health status			
	1- poor	2- fair	3- good	4- very good
EU-28	0.76%	3.47%	31.09%	64.68%
Austria	0.85%	3.27%	16.97%	78.91%
Belgium	1.09%	3.30%	24.91%	70.70%
Bulgaria	0.94%	1.03%	24.29%	73.74%
Croatia	0.96%	1.41%	15.55%	82.08%
Cyprus	0.64%	1.61%	8.04%	89.70%
Czechia	0.91%	3.11%	22.51%	73.48%
Denmark	0.97%	4.44%	25.07%	69.52%
Estonia	1.17%	7.28%	46.22%	45.33%
Finland	0.50%	2.91%	28.82%	67.76%
France	0.57%	4.29%	21.36%	73.78%
Germany	0.76%	4.35%	29.71%	65.18%
Greece	0.85%	1.14%	3.76%	94.25%
Hungary	0.98%	4.37%	33.63%	61.02%
Ireland	0.97%	2.80%	17.61%	78.63%
Italy	0.39%	0.90%	51.54%	47.16%
Latvia	1.31%	8.62%	67.89%	22.18%
Lithuania	1.45%	3.31%	55.93%	39.31%
Luxembourg	1.40%	4.43%	25.90%	68.27%
Malta	0.30%	2.11%	42.06%	55.52%
Netherlands	0.54%	4.49%	44.92%	50.05%
Poland	1.32%	5.61%	37.60%	55.47%
Portugal	1.09%	8.96%	44.69%	45.26%
Romania	0.43%	0.25%	23.35%	75.96%
Slovakia	0.84%	2.85%	39.61%	56.69%
Slovenia	1.04%	5.20%	29.74%	64.02%
Spain	0.37%	1.54%	33.34%	64.76%
Sweden	0.79%	3.76%	28.25%	67.20%
United Kingdom	1.37%	4.96%	25.80%	67.87%

Notes: Based on EU-SILC 2017. Entries are weighted with appropriate cross-sectional weights.

Overall, we find that the majority of children across the EU have a 'very good' health status, with about one third reporting 'good' health. Only about 4.5 per cent of children across the EU report only 'fair' or 'poor' health. There is variation across countries, as, for instance, the proportion of children with 'poor' health is substantially above EU average in countries are the United Kingdom, Luxembourg, Lithuania, Latvia, and Estonia.

While Table 3.5 provides a picture of the current status of children's health across Europe, Table 3.6 reports the factors associated with children's health. Specifically, it reports the association with regards to poor indoor climate indicators, as well as household and individual characteristics (e.g. socio-economic status). The parameter estimates presented in Table 3.6 are based on OLM and GOLM (as the dependent variable is based on an ordinal scale).[34] Note that in Table 3.6 a negative coefficient suggests that the explanatory variable (e.g. leak, damp or rot) is decreasing the probability that the child reports a higher category of health (e.g. 'poor', 'fair', 'good' or 'very good' health).[35] A positive coefficient suggests that the explanatory variable increases the probability that the child reports a higher category of health.

The findings suggest that, all else being equal, all four indicators of poor indoor climate are statistically significantly associated with a child's health status.[36] For instance, a prevalent issue with a leaking roof, damp or rot is negatively associated with a child's health, with the OLM coefficient taking the value −0.1692, suggesting that this poor indoor climate indicator reduces the probability that the child reports a better health outcome.

The GOLM coefficients report the varying parameters for each of the possible thresholds of the outcome variable. We found that the association with damp varies somewhat in magnitude across the different thresholds but stay statistically significant from zero. For instance, the GOLM estimates suggest that the associations may be a bit larger in the case of children with lower health status (coefficient for threshold poor-fair 0.2501; coefficient for threshold fair-good -0.3368, compared with -0.1507 for threshold good-very good). A similar association applies for households that report that they are struggling to keep the house adequately warm, which is also negatively associated with a child's health. Living in a dwelling that lacks light is also associated with poorer child health on average. However, with regard to lack of light, the GOLM shows that the significant difference is only on the third threshold (good-very good), with a coefficient of −0.1355. This means that lack of light is associated with health status but that the effect only explains somewhat less serious health problems (e.g. between 'good' to 'very' good health) and does not explain more serious health problems (e.g. between 'poor' and 'fair' health). In contrast, all else being equal, noise pollution is also significantly negatively associated with a child's health status across all three child health status thresholds.

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[34] See Appendix B for a more detailed discussion on the statistical regression methods.

[35] In this analysis a higher category of health represents better self-reported health.

[36] However, living in a dwelling that is perceived to be too dark by the occupant is only statistically significant at the 10 per cent level.

Table 3.6: Associations between poor indoor climate indicators, household and individual characteristics and child health

	(1)	(2)	(3)	(4)
Estimation method	OLM	GOLM		
		poor-fair	fair-good	good-very good
Leak, damp, rot	-0.1692 (0.044)***	-0.2501 (0.139)*	-0.3368 (0.076)***	-0.1507 (0.045)***
Not adequately warm	-0.2267 (0.070)***	-0.3768 (0.202)*	-0.5402 (0.118)***	-0.1951 (0.071)***
Too dark	-0.1297 (0.072)*	0.0006 (0.231)	-0.0435 (0.119)	-0.1355 (0.074)*
Noise pollution	-0.1755 (0.043)***	-0.2840 (0.153)*	-0.4053 (0.075)***	-0.1485 (0.043)***
Age of respondent	-0.0283 (0.010)***	-0.0522 (0.050)	-0.0306 (0.024)	-0.0267 (0.010)***
Female	0.0525 (0.023)**	0.1921 (0.115)*	0.1563 (0.055)***	0.0434 (0.023)*
Migrant background	0.0359 (0.081)	0.4757 (0.411)	0.1560 (0.145)	0.0237 (0.086)
(Log) Household income	0.1319 (0.025)***	0.2458 (0.113)**	0.1394 (0.065)**	0.1507 (0.033)***
Deprived	-0.3036 (0.076)***	-0.6971 (0.210)***	-0.2856 (0.118)**	-0.3050 (0.078)***
Secondary education (base: primary only)	-0.0032 (0.054)	0.3609 (0.177)**	0.1930 (0.098)**	-0.0119 (0.056)
Tertiary education (base: primary only)	0.1717 (0.057)***	0.4738 (0.188)**	0.4555 (0.104)***	0.1572 (0.059)***
Overcrowded	0.0022 (0.040)	-0.1725 (0.159)	-0.0559 (0.076)	0.0083 (0.041)
Owner paying mortgage (base: outright owner)	0.0339 (0.038)	0.0405 (0.175)	0.0430 (0.082)	0.0323 (0.040)
Tenant paying rent (base: outright owner)	-0.0302 (0.048)	0.0459 (0.228)	-0.0626 (0.090)	-0.0282 (0.051)
Rented at reduced rate (base: outright owner)	-0.1813 (0.076)**	-0.2788 (0.250)	-0.4345 (0.125)***	-0.1377 (0.075)*
Accommodation provided free (base: outright owner)	-0.1323 (0.063)**	-0.3024 (0.246)	-0.0879 (0.131)	-0.1392 (0.067)**
Interviewed: 2nd quarter (base: 1st quarter)	0.1387 (0.041)***	0.2090 (0.164)	0.0977 (0.075)	0.1393 (0.042)***
Interviewed: 3rd quarter (base: 1st quarter)	0.1941 (0.055)***	-0.1429 (0.223)	0.0808 (0.116)	0.2039 (0.056)***
Interviewed: 4rd quarter (base: 1st quarter)	-0.0487 (0.075)	-0.0667 (0.333)	0.1486 (0.160)	-0.0577 (0.076)

Notes: *Clustered standard errors (household identifier) in parentheses (*** p<0.01, ** p<0.05, *p<0.1). Based on EU-SILC 2017 sample for child responses only. Entries are weighted with appropriate cross-sectional weights. Based on ordered logit models (OLM) and generalised ordered logit models (GOLM) regressions using the variables reported in the table in addition to country-fixed effects.*

The findings further suggest that a household's socio-economic status is positively associated with a child's health status. For instance, we find that household income is positively associated with reporting a better health status of a child, as well as a better education level. Households that have been classified as suffering from economic deprivation report on average a lower health status for the child. Interestingly, after controlling for a variety of control variables, we find no statistically significant association between a child's migrant status and its health. The findings suggest that female children tend to be healthier, which specifically applies for less severe health problems (e.g. thresholds fair-good and good-very good), whereas there is no difference in reported health status between female and male children with regard to more serious health problems (e.g. threshold poor-fair). All else equal, in line with the negative association found for socio-economic status, we find a negative association between social housing (e.g. reduced rent or accommodation provided for free) and health problems, but we do not find a statistically significant association for overcrowding. Interestingly, as well, we observe some seasonal effects when we adjust for the quarter in which the interview took place. For instance, for interviews conducted in spring and summer, we found, all else being equal, a positive association with a child's health status, compared with interviews conducted in the colder months, and the GOLM estimates suggest it is only related to smaller health problems (e.g. threshold good-very good health), suggesting seasonal flu or cold outbreaks may play a role in the reporting and, hence, that it is important to adjust for these potential seasonal effects.

We use the parameter coefficients reported in Table 3.6 to run a counterfactual analysis. That is, we predict how the distribution of reported child health would change if we were to reduce the prevalence of (or exposure of children to) the four poor indoor climate indicators across Europe. To that end, we first predict the frequencies of each of the four health categories (1 poor; 2 fair; 3 good; 4 very good) using the GOLM parameters from columns (2) to (4), for the EU as a whole and for each country. We then use these parameters to predict the proportion of children who would report a better health status than they currently do if the counterfactual values for each of the poor indoor climate indicators are set to zero. The findings of the counterfactual analysis are presented in Table 3.7.

We predict, using the counterfactual analysis described above across the EU-28 member states, that about 1.2 million children could improve their health status by reducing their exposure to the four poor indoor climate indicators. This corresponds to about 1.5 per cent of all children or about 4.3 per cent of children who have not reported a very good health status initially. There is variation across the different countries, ranging from 1.6 per cent of children without very good health status initially (Latvia) to 5.47 per cent (France).

Table 3.7: Predicted number of children improving their health status if exposure to damp, lack of daylight, noise pollution and the inability to keep the dwelling adequately warm is set to zero

Estimated number of children improving health status			
	Total improved	% total number of children	% children not in very good health
EU-28	1,195,672	1.52%	4.31%
Austria	14,084	1.15%	5.45%
Belgium	28,050	1.46%	4.99%
Bulgaria	10,307	1.03%	3.90%
Croatia	5,452	0.87%	4.84%
Cyprus	1,101	0.56%	5.45%
Czechia	20,331	1.27%	4.78%
Denmark	14,286	1.49%	4.89%
Estonia	3,624	1.71%	3.12%
Finland	13,680	1.52%	4.72%
France	169,519	1.44%	5.47%
Germany	181,373	1.69%	4.86%
Greece	4,791	0.29%	5.11%
Hungary	20,940	1.48%	3.80%
Ireland	11,669	1.14%	5.34%
Italy	150,291	1.84%	3.48%
Latvia	3,824	1.27%	1.63%
Lithuania	7,238	1.69%	2.79%
Luxembourg	1,429	1.54%	4.85%
Malta	1,050	1.70%	3.83%
Netherlands	48,530	1.71%	3.42%
Poland	105,716	1.86%	4.17%
Portugal	25,213	1.72%	3.14%
Romania	29,435	0.96%	4.00%
Slovakia	13,708	1.65%	3.81%
Slovenia	4,707	1.54%	4.29%
Spain	115,768	1.67%	4.75%
Sweden	26,428	1.56%	4.77%
United Kingdom	163,129	1.42%	4.41%

Notes: Entries calculated using the coefficients in Table 3.6. Based on a counterfactual analysis setting the prevalence of the four poor indoor climate indicators to zero and predicting the proportions of children who would hypothetically report a better health status in the absence of the exposure to these indicators.

3.3.4 The health burden and the educational burden associated with damp related to children across Europe

We now turn to the analysis to examine the potential healthy life years lost in association with exposure to damp, as well as an estimation of the potential school days lost associated with children's exposure to damp. Table 3.8 reports the burden of disease related to exposure to damp that is associated with four disease areas (asthma, atopic dermatitis, lower and upper respiratory infections) based on GBD data.

Table 3.8: Burden of disease from indoor damp exposure in children aged 0 to 15 (asthma, atopic dermatitis, lower and upper respiratory infections), estimated DALYs total

	(1)	(2)	(3)	(4)	(5)	(6)
	Asthma	Atopic dermatitis	Lower respiratory infections	Upper respiratory infections	Sum (1) to (4)	Total incidence (%)
EU-28	7,284.0	14,603.7	7,710.0	7,979.8	37,577.5	4.6
Austria	94.4	158.3	31.3	130.2	414.1	3.8
Belgium	208.0	460.2	123.1	301.7	1,093.0	4.0
Bulgaria	52.2	82.0	436.6	50.7	621.5	12.1
Croatia	27.9	40.9	21.0	23.4	113.1	4.5
Cyprus	28.3	50.5	8.2	38.4	125.4	3.8
Czechia	52.8	113.1	87.6	56.5	310.0	5.2
Denmark	108.0	268.1	44.1	127.9	548.0	4.0
Estonia	9.3	31.0	31.0	10.7	82.1	5.9
Finland	26.8	71.2	3.5	32.3	133.7	3.8
France	891.3	2,238.3	304.4	1,142.4	4,576.4	4.0
Germany	681.2	1,750.8	388.6	1,160.9	3,981.5	3.9
Greece	101.9	149.2	113.7	142.2	507.0	4.4
Hungary	141.7	344.6	341.2	148.0	975.5	5.8
Ireland	112.0	186.5	28.7	99.6	426.8	3.9
Italy	447.7	1,375.6	317.6	918.6	3,059.4	3.9
Latvia	31.5	48.6	77.9	24.1	182.0	6.2
Lithuania	31.0	32.2	122.1	29.1	214.3	7.8
Luxembourg	12.8	29.5	4.2	12.8	59.2	4.0
Malta	2.6	4.1	3.2	3.3	13.2	4.7
Netherlands	253.6	584.0	85.3	307.8	1,230.6	4.0
Poland	400.1	623.6	481.0	251.7	1,756.5	5.2
Portugal	330.5	366.1	177.8	254.1	1,128.5	4.3
Romania	205.1	293.6	2,919.7	149.2	3,567.6	20.0
Slovakia	23.4	53.4	122.5	25.5	224.9	8.0
Slovenia	28.5	37.6	13.3	20.7	100.1	4.2
Spain	448.2	692.8	210.5	624.4	1,975.9	3.9
Sweden	103.9	272.5	29.8	102.1	508.3	4.0
United Kingdom	2,429.4	4,245.5	1,182.3	1,791.5	9,648.7	4.3

Notes: Based on GBD data, based on DALYs on year 2017 calculated using the population-attributable fractions using damp exposure data from the EU-SILC and relative risk measures for each of the disease areas based on the existing literature.

Section 3.2.2 explains in more detail how we calculate the DALYs associated across the four disease areas that can be attributed to exposure to damp. We use the PAF and the overall prevalence and DALYs of asthma, atopic dermatitis, and upper and lower respiratory infections (e.g. rhinitis, cough and bronchitis).

Table 3.8 reports that across the EU-28 member states exposure to damp has been associated with about 7,300 DALYs related to asthma (column 1), more than 14,600 related to atopic dermatitis (column 2), and more than 15,000 related to lower and upper respiratory infections combined. This results in more than 37,000 DALYs across the EU-28 member states. If we divide that by the total number of incidences across the four disease areas, we find that damp is associated with about 4.6 per cent of cases.[37]

In addition to the morbidity and mortality burden represented in DALYs, we also estimated the number of school days missed per year due to the child's exposure to indoor damp. Again, using the PAF of each of the diseases and the average number of school days missed by disease area, we estimate the total number of school days missed in 2017 associated with the exposure to damp. We assume that children suffering from asthma lose on average about 2.5 school days per year due to the illness,[38] children suffering from atopic dermatitis, about 4 school days,[39] and children suffering from upper and lower respiratory infections, about 1 school day.[40]

Based on the findings reported in Table 3.9, it is estimated that annually across the 28 EU member states about 0.3 million school days are missed by pupils due to asthma, 1 million due to atopic dermatitis, and 0.3 million due to lower and upper respiratory infections associated with exposure to damp.[41] Overall, across the EU-28 member states about 1.7 million school days are missed per year due to diseases associated with damp in residential buildings. #

We used the annual number of school days per year across the EU (about 180 days on average)[42] and the total number of school-age children to calculate the total annual school days by country. Then we calculated the share of school days missed in association with exposure to damp (column 6). On average, across the EU-28 member states about 0.014 per cent of school days are lost across all school days.

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[37] It is important to highlight that the reported figures likely present an overestimate of the true figures, as the four disease areas are likely correlated with each other, meaning that, for instance, a child with asthma may also have atopic dermatitis.

[38] This is based on Ferrante & La Grutta (2018), who report that children with asthma lose on average about 3 to 5 school days. In order to be conservative, we take the middle point of 4 days.

[39] This is based on Filanovsky et al. (2016), who report that about 40 per cent of caregivers lose on average about 20.5 hours per month of working time.

[40] This is not based on a specific study; rather, it reflects an assumption made by the authors. We believe it is a conservative estimation as, for instance, in the case of bronchitis, the length of the illness can last from 8 to 10 days.

[41] However, the evidence that missed school days lead to lower educational outcomes is ambiguous.

[42]For a member state-specific distribution of annual school day information, see Commission/EACEA/Eurydice (2018).

Table 3.9: Burden of disease from indoor damp exposure in school age children (asthma, atopic dermatitis, lower and upper respiratory infections), estimated missed school days

	(1) Asthma	(2) Atopic dermatitis	(3) Lower respiratory infections	(4) Upper respiratory infections	(5) Sum (1) to (4)	(6) Total school days (%)
EU-28	365,453	1,075,907	2,507	255,714	1,699,580	0.014
Austria	4,793	11,644	27	4,176	20,639	0.011
Belgium	10,485	33,871	55	9,648	54,058	0.019
Bulgaria	2,662	6,050	81	1,578	10,371	0.007
Croatia	1,420	3,010	20	757	5,207	0.006
Cyprus	1,440	3,716	5	1,250	6,410	0.023
Czechia	2,676	8,335	63	1,719	12,793	0.005
Denmark	5,475	19,762	18	4,138	29,393	0.019
Estonia	475	2,290	45	346	3,156	0.010
Finland	1,360	5,250	5	1,049	7,665	0.005
France	45,034	164,665	137	36,260	246,095	0.016
Germany	34,343	128,876	182	37,522	200,924	0.012
Greece	5,177	10,991	20	4,597	20,785	0.009
Hungary	7,169	25,435	258	4,435	37,296	0.018
Ireland	5,665	13,731	13	3,238	22,647	0.015
Italy	22,657	101,106	137	29,638	153,538	0.011
Latvia	1,603	3,581	113	781	6,078	0.014
Lithuania	1,574	2,374	137	925	5,010	0.008
Luxembourg	644	2,171	2	415	3,231	0.024
Malta	132	304	1	103	540	0.006
Netherlands	12,885	42,965	31	9,705	65,587	0.015
Poland	20,377	46,025	313	8,142	74,857	0.008
Portugal	16,841	26,986	36	8,252	52,115	0.024
Romania	10,519	21,770	303	4,791	37,384	0.009
Slovakia	1,185	3,941	39	817	5,982	0.005
Slovenia	1,457	2,771	27	671	4,925	0.010
Spain	22,554	51,025	66	20,183	93,828	0.009
Sweden	5,287	20,084	19	3,296	28,686	0.012
United Kingdom	119,567	313,179	352	57,282	490,379	0.027

Notes: Calculated using the population-attributable fractions using exposure data from the EU-SILC and relative risk measures for each of the disease areas based on the existing literature. Assumed average school days per year lost by disease area: asthma (2.5 days); atopic dermatitis (4 days); upper and lower respiratory infections (1 day).

3.4 The potential burden associated with poor indoor climate

This chapter aimed to examine some of the potential burden associated with exposure to poor indoor climate risks, including overall self-reported child health, as well as the burden with regards to healthy life years lost or missing school days associated with exposure to a damp environment at home. The findings suggest that, indeed, exposure to poor indoor climate risk could lead to negative health consequences for children. In the next chapter, we aim to quantify the potential economic implications at the macroeconomic level of some of the health burden with regards to exposure to indoor climate risk, including the exposure to a damp environment at home and poor ventilation rates in schools.

4. The potential economic implications associated with exposure to poor indoor climate at home and in schools across EU countries

In this chapter we estimate the economic effects associated with the exposure of children to damp/mould in residential buildings and its impact on their health. Furthermore, we estimate the potential economic benefits associated with improved ventilation rates in schools. The analysis covers all 28 EU member states. To estimate the economic effects of a reduction in the exposure to damp and the improvement of ventilation rates, we use a macroeconomic model similar to the WHO's EPIC (Economic Cost of Ill-Health) model,[43] but which is more detailed and comprehensive in how it models the economic interactions between different agents in an economy, such as households, firms or the government.

The key findings of this chapter can be summarised as follows:

Box 4.1: The potential economic implications associated with exposure to poor indoor climate at home and in schools across EU countries (summary)

- **Macroeconomic cost associated with children's exposure to damp and mould:** It is estimated that, if the current cohorts of children would not be exposed to damp, the associated economic benefit across the EU-28 over the next 40 years would be about US$60 billion.
- **Benefit per affected dwelling/household:** Breaking down the net present value of the future economic benefits of a complete reduction in exposure to damp at EU level is estimated to create an economic benefit per dwelling by 2040 by about US$2,523.
- **Better air quality in schools could lead to better educational outcomes:** There is emerging empirical evidence associating improvements in indoor air quality in schools and universities with improved test scores and other educational outcomes.
- **Improving ventilation rates in European schools could lead to economic benefits:** It is estimated that an improvement in ventilation rates of 0.5 l/s per person in European schools is associated with a cumulative total increase in EU-28 GDP by 2050 of US$24.4 billion, and by 2060 of US$57 billion. The associated annual average benefits are US$813.4 million by 2050 and US$1,425.1 by 2060 million per year, respectively. Across European schools, this would be associated with an increase in cumulative EU-28 GDP of US$120.5 billion by 2050 and US$281.4 billion by 2060, with average annual increases in GDP of US$4 billion by 2050 and US$7 billion by 2060.

We start the chapter with a brief description of the macroeconomic model in non-technical terms. A more detailed description of the model can be found in the Appendix C. Then, we describe how we model the

[43] See, for instance, Bloom et al. (2017) for a more detailed description of the model.

potential economic benefits. The following sections explain in more detail the analytical approach and the corresponding research findings.

4.1 The macroeconomic model

In order to assess the economic implications of children's exposure to damp and mould and the improvement of ventilation rates in schools, we use a multi-country computable general equilibrium (CGE) model. Such a model simultaneously solves multiple equations that relate to production from firms and household demand, within a country, and between countries through trade linkages. This type of modelling approach has gained ground in health economics applications, such as anti-microbial resistance (AMR), pandemic influenza and non-communicable disease (see e.g. Rutten & Reed 2009; Smith et al. 2005; Taylor et al. 2014), among others.

Within a CGE modelling framework, the current economic projection for each country is computed using the current underlying economic factors (e.g. so-called 'status quo' or 'baseline scenario') and subsequently compared against a 'what-if' scenario in which various parameters are changed. For instance, for the purpose of this analysis, we compare and analyse in the long term how various outcomes (e.g. economic output of a country) would change (e.g. compared with status quo) if we hypothetically completely eradicated children's exposure to damp and mould (e.g. improving the health of children and reducing work absence days of their carers) or improved ventilation rates (e.g. improving grades and educational attainment and subsequent life-time earnings). In the baseline scenario, the underlying assumption is that the country's economy grows under a long-term growth rate, and in the counterfactual, or 'what-if', scenario, we compare by how much this long-term growth is affected if the underlying parameter change (e.g. people become healthier).

Specifically in the field of health economics, the application of CGE models has recently become more common due to its advantages over more traditional approaches, such as cost of illness (COI) methods (e.g. Bloom et al. 2018). COI is an easy-to-understand method that summarises the direct and indirect cost associated with ill health, taking into account, for instance, the sum of all direct personal medical cost, as well as the indirect cost (e.g. income loss due to absenteeism or premature death). While the approach is relatively straightforward, it does not take into account the potential spillover effects on other agents or markets in an economy. For instance, in reality, many adjustment mechanisms play out, such as the substitution between labour and capital should the labour supply be negatively affected due to ill health or caregiver responsibilities. In contrast, a general equilibrium model, such as CGE, takes into account these ripple effects on other parts of the economy by reporting how overall economic output is affected. A more detailed description of the model and the underlying economic data used can be found in Appendix C.

The application of a CGE modelling framework to assess the different economic implications of potential changes in the exposure of children to damp and mould or changes in ventilation rates in schools has several strengths, as outlined above, including the ability to directly take into account simultaneously the costs and benefits associated with a scenario and assessing the overall net effects. However, there are some limitations to the modelling approach taken. First, the CGE model applied for the economic analysis is not intended to provide an exact forecast of the economy at a given point in time in the future. The deterministic model does not take into account transitory (stochastic) short-term changes to the overall economic growth path. The aim of the applied modelling framework is to examine the effects of changes across different modelling parameters representing different scenarios and then compare how the economy of a country would evolve in the medium to long term in the counterfactual scenario compared with the baseline, holding all other factors constant. This is a simplification of how events would affect the economy in reality; however, it allows for the analysis of specific factors (such as changes in the health of children) in isolation. Second, the scenarios examined within the economic modelling framework depend heavily on input data and parameters based on empirical evidence from other studies. In many instances, the estimated parameters drawn from other studies do not represent causal effects but, rather, associations between two variables (e.g. improvement of grades due to improvements in ventilation rates). Furthermore, sometimes data are incomplete. For instance, the prevalence of ventilation rates (see in section 4.3) is only available for a cluster of countries, and hence any country-specific outputs represent crude estimates and should always be treated with a degree of caution.

In what follows, we describe the approach and results using the macroeconomic model to assess the economic implications of a reduction in children's exposure to damp and mould at home and an improvement in ventilation rates in schools.

4.2 The economic implications associated with reducing children's exposure to residential damp

4.2.1 How a reduction in the exposure of children to damp and mould affects the economy in the model

There are potentially many channels through which the exposure to damp could impact individuals in the society and hence have an effect on the economy more generally, but for the purpose of this analysis we focus on the effect on the labour supply, that is, the macroeconomic model uses the effective labour supply as one of the inputs into production. The effective labour supply is represented by function of the overall number of workers (physical labour) and their corresponding productivity (efficiency).[44]

In the model, the reduction in effective labour supply is manifested through **three** potential channels:

- **Increased mortality (child) –** Such health conditions as asthma or pneumonia are associated with an increased mortality risk for children. Deaths potentially attributable to these conditions permanently reduce the population size, and the effect of increased mortality on economic output is a future decrease in the working-age population. This could have especially negative consequences in ageing societies, such as those in Europe.
  We model increased mortality rates of children over the future supply of physical labour. To that end, we use data on the deaths per year for each of the four disease areas associated with exposure to damp (asthma, atopic dermatitis and upper and lower respiratory infection) and

[44] For instance, one worker with full productivity would provide the same number of effective labour units to the economy as two workers who with only half the productivity of the worker with full productivity.

the associated deaths per 100,000 of the population[45] together with the corresponding PAF to calculate how many more children (and hence future working-age population) would be alive if the exposure to damp and the associated mortality were to be reduced.

- **Reduced labour productivity (caregiver) –** Prolonged periods of sickness of children temporarily reduce the country's workforce if parents have to stay at home and look after an ill child, with can manifest itself in higher levels of absenteeism and/or presenteeism of the current workforce.
  We model the higher levels of working days lost of parents or caregivers through the efficiency parameter of the effective labour units. We assume that parents of a child with asthma lose on average 2.5 working days a year, parents of a child with atopic dermatitis lose on average about 4 working days, and parents of a child with upper and lower respiratory infections (e.g. rhinitis or bronchitis) lose on average 1 working day.[46] This reflects the estimated time children affected by any of these disease areas are missing school.
- **Reduced labour productivity (adult) –** While some who had issues with asthma as a child will not have issues later on in life, the scientific evidence suggests that health conditions, such as asthma, acquired as a child could last with some probability also into adulthood, with potentially negative consequences for a person's work productivity, i.e. due to increased levels of health-related absenteeism and presenteeism.
  We assume that a person who suffered from asthma as a child has a 40 per cent probability of also suffering from asthma as an adult. Furthermore, we assume that a person who suffers from asthma loses on average about 2 working days per year due to absenteeism or presenteeism.[47]

In the analysis, as the baseline scenario, we project how the economy of each of the countries included in the analysis would evolve assuming no changes to current levels of children's exposure to damp. For the counterfactual scenario, we estimate how much more of economic output (e.g. measured as GDP) could be produced in the future if we eradicated the exposure to damp completely. In essence, in this analysis we compare how the economy of a country today (baseline) would evolve over time if the negative health factors associated with damp and mould, such as lower productivity and mortality, were to be removed completely (counterfactual scenario).

[45] Provided by GBD data by country and gender and age group.

[46] For more detail on how the efficiency of labour is calculated, see Appendix A. Overall, it is assumed that the 'normal' efficiency of a unit of physical labour is 1. The efficiency unit of each unit of labour is calculated as the actual working days divided by the total number of working days. So if a person loses 20 days a year (e.g. because of absenteeism or presenteeism) and we assume 200 working days per year, then the efficiency for this unit of physical labour is 0.9 (instead of 1), calculated as (200−20)/200.

[47] This is based on findings related to the average working time lost of adults in the working population who have been diagnosed with asthma, as reported in Hafner et al. (2019).

4.2.2 The macroeconomic cost associated with children's exposure to damp and mould: model results

Table 4.1 reports the cumulative economic gains associated with reducing the exposure to damp and mould for children, from now up to 40 years in the future. In other words, we look at how much an economy of a country could produce more, from now into the future, if we were to stop today's children now and all future generations from being exposed to damp and mould.

Table 4.1: Estimated cumulative economic gains associated with the reduction of children's exposure to damp and mould, by country (2018 prices, US$ billion)

Estimated cumulative economic gains (net present value)									
	Year								
	0	*5*	*10*	*15*	*20*	*25*	*30*	*35*	*40*
Austria	0.000	0.054	0.170	0.302	0.452	0.622	0.812	1.027	1.268
Belgium	0.000	0.062	0.196	0.348	0.521	0.716	0.936	1.184	1.461
Bulgaria	0.000	0.005	0.017	0.033	0.052	0.076	0.106	0.143	0.191
Croatia	0.000	0.004	0.013	0.024	0.038	0.055	0.076	0.104	0.138
Cyprus	0.000	0.003	0.011	0.019	0.029	0.039	0.052	0.065	0.080
Czechia	0.000	0.013	0.044	0.083	0.131	0.191	0.266	0.361	0.481
Denmark	0.000	0.065	0.205	0.363	0.544	0.747	0.972	1.218	1.488
Estonia	0.000	0.001	0.005	0.009	0.015	0.021	0.030	0.040	0.054
Finland	0.000	0.016	0.050	0.090	0.138	0.194	0.259	0.336	0.425
France	0.000	0.418	1.323	2.371	3.578	4.966	6.550	8.345	10.366
Germany	0.000	0.357	1.133	2.043	3.095	4.291	5.638	7.164	8.906
Greece	0.000	0.038	0.119	0.211	0.316	0.434	0.567	0.717	0.885
Hungary	0.000	0.010	0.032	0.061	0.096	0.140	0.195	0.264	0.352
Ireland	0.000	0.034	0.106	0.189	0.282	0.388	0.507	0.641	0.791
Italy	0.000	0.167	0.510	0.874	1.264	1.688	2.147	2.640	3.164
Latvia	0.000	0.002	0.006	0.012	0.019	0.028	0.039	0.053	0.070
Lithuania	0.000	0.003	0.011	0.020	0.032	0.046	0.064	0.087	0.116
Luxembourg	0.000	0.005	0.016	0.029	0.044	0.060	0.078	0.099	0.122
Malta	0.000	0.001	0.004	0.007	0.010	0.014	0.019	0.023	0.029
Netherlands	0.000	0.113	0.355	0.631	0.944	1.298	1.696	2.145	2.647
Poland	0.000	0.041	0.135	0.254	0.402	0.587	0.817	1.108	1.476
Portugal	0.000	0.039	0.123	0.219	0.327	0.449	0.587	0.742	0.917
Romania	0.000	0.017	0.057	0.107	0.169	0.247	0.344	0.466	0.621
Slovakia	0.000	0.006	0.019	0.036	0.058	0.084	0.117	0.159	0.212
Slovenia	0.000	0.002	0.008	0.015	0.025	0.036	0.050	0.068	0.090
Spain	0.000	0.100	0.306	0.520	0.745	0.989	1.257	1.553	1.873
Sweden	0.000	0.073	0.242	0.457	0.726	1.057	1.462	1.961	2.577
United Kingdom	0.000	0.797	2.566	4.681	7.144	9.979	13.229	16.963	21.247
EU-28	0.000	2.449	7.781	14.009	21.197	29.441	38.874	49.676	62.047

Notes: Entries represent the net present value of the cumulative economic effects in terms of GDP from now up to 2060 in five-year increments. Analysis assumes that cases across four disease areas (asthma, atopic dermatitis, upper and lower respiratory infections) associated with damp and mould exposure in the child population from now into the future are set to zero.

Table 4.2: Estimated cumulative economic gains by affected dwelling, by country (2018 prices, US$ billion)

	Estimated cumulative economic gains per dwelling (net present value)								
	Number of households affected	***5***	***10***	***15***	***20***	***25***	***30***	***35***	***40***
Austria	97,153	557	1,751	3,113	4,656	6,399	8,363	10,573	13,053
Belgium	221,460	282	885	1,573	2,353	3,234	4,227	5,344	6,597
Bulgaria	85,650	62	203	383	607	885	1,233	1,672	2,226
Croatia	54,365	70	232	437	693	1,010	1,407	1,908	2,541
Cyprus	26,169	131	412	733	1,096	1,507	1,969	2,490	3,073
Czech Republic	103,491	129	424	800	1,267	1,847	2,573	3,489	4,647
Denmark	85,542	760	2,391	4,248	6,358	8,734	11,364	14,244	17,401
Estonia	21,559	69	227	428	677	987	1,376	1,866	2,485
Finland	26,046	600	1,904	3,452	5,291	7,446	9,956	12,888	16,319
France	995,390	420	1,329	2,382	3,595	4,989	6,581	8,384	10,414
Germany	1,032,410	346	1,098	1,979	2,998	4,156	5,461	6,939	8,627
Greece	169,809	222	699	1,242	1,858	2,554	3,338	4,220	5,210
Hungary	264,292	37	121	229	363	529	737	999	1,330
Ireland	88,042	384	1,205	2,142	3,204	4,403	5,755	7,277	8,983
Italy	1,331,409	125	383	656	950	1,268	1,613	1,983	2,376
Latvia	50,342	39	127	239	379	553	770	1,044	1,391
Lithuania	62,517	51	169	320	506	738	1,028	1,394	1,856
Luxembourg	12,544	415	1,306	2,320	3,471	4,770	6,235	7,883	9,731
Malta	5,429	228	715	1,272	1,902	2,614	3,416	4,319	5,332
Netherlands	304,122	372	1,168	2,076	3,105	4,267	5,578	7,052	8,705
Poland	504,896	81	267	503	797	1,162	1,619	2,195	2,923
Portugal	371,122	105	331	589	881	1,211	1,582	2,001	2,470
Romania	277,397	62	204	385	610	890	1,240	1,681	2,239
Slovakia	37,762	155	512	966	1,531	2,231	3,109	4,215	5,614
Slovenia	60,082	41	137	258	408	595	829	1,124	1,496
Spain	792,639	127	386	656	941	1,248	1,586	1,959	2,363
Sweden	83,689	873	2,887	5,466	8,678	12,627	17,472	23,432	30,791
United Kingdom	1,237,590	644	2,073	3,782	5,773	8,063	10,690	13,707	17,168
EU-LEVEL	8,402,918	291	926	1,667	2,523	3,504	4,626	5,912	7,384

Notes: Entries represent the net present value of the cumulative economic effects in terms of GDP from now up to 2060 in five-year increments. Analysis assumes that cases across three disease area (asthma, atopic dermatitis, upper and lower respiratory infections) associated with damp and mould exposure in the child population from now into the future are set to zero. The number of dwellings with at least one child has been taken from the EU-SILC database, counting the number of households that report to have at least one child.

As reported in Table 4.1, across the EU-28 member states, the cumulative economic gain by 2040 would be US$21.2 billion, by 2050 US$38.9 billion and by 2060 about US$62 billion. The cumulative gain represents the total GDP that could be produced more over the 40 years if children were not exposed to damp and mould at home. The reason for the increase over time is that the more future child generations profit from a damp- and mould-free environment, the larger will be the associated health and economic gains in the future. Or in other words, the economic gains occur not only directly, with a reduced mortality and less absenteeism and presenteeism of carers, but also in the future, when more children have profited from a damp-free environment. There is variation across the EU member states in terms of the cumulative economic gains, which are a function of the size of a country's underlying economic structure and size but also of the initial level of exposure to damp and mould. Note that year 0 in Table 4.1 reflects the year 2019 and that there are no economic gains recorded between the baseline scenario and the counterfactual damp-free scenario because the current year is the starting point of the economic projections.

While Table 4.1 reports the cumulative economic gains over time, Table 4.2 reports these gains by the number of dwellings affected by damp and mould where a child lives, which is provided by the EU-SILC database.

At the EU level, we estimate that, by 2040, the benefit per dwelling is about US$2,523; by 2050 US$4,626 and by 2060 US$7,384. In other words, if the cost of making a dwelling damp-free is less than US$7,384, that investment would outweigh its cost. Again, it is important to take into account that, in reality, the full benefits only occur over time, as more children benefit from a damp-free environment. Again, there is considerable variation across EU member states, mainly as a function of the overall size and nature of the economy and the initial number of children/households affected by damp and mould, which varies across EU countries.

4.3 The economic implications associated with improving ventilation rates in schools

The review of the literature presented in Chapter 2 focussed on the residential environment in children's homes. The evidence on the association between poor indoor climate and educational outcomes is relatively sparse, and the empirical literature on days' absence from school because of such health conditions as asthma is ambiguous. However, the residential or home environment is only one area where children could be exposed to indoor climate hazards. Children spend more time in school than in any other place other than their home. Hence, the indoor environment in schools constitutes a particularly critical one with regards to exposure to a variety of different indoor air risk factors as well, with potentially negative consequences for children's health and school performance. And in fact, there is abundant evidence regarding the potential detrimental effect on health of a variety of indoor pollutants that can be found in school environments, either originating from the ambient air or produced indoors from building materials, products or activities (EC 2014).

Overall, a large number of studies investigate the link between ambient air pollution and health and educational outcomes (Roth 2017), but the literature on the associations between indoor air pollution and educational outcomes in particular is more sparse. The European Commission-funded project SINPHONIE provides a comprehensive summary of the evidence regarding school indoor pollution in Europe and health (EC 2014). The report covers a variety of different indoor air pollutants, including, among others, chemical parameters (e.g. formaldehyde, benzene, PM, radon, carbon monoxide (CO)), physical and comfort parameters (e.g. temperature, relative humidity), and microbiological agents and allergens (e.g. endotoxins, fungal and bacterial DNA, cats, dogs, house mites, dust mites). The project aimed to collect detailed data on the prevalence for these indoor pollutants across schools in Europe. The report concludes that most of the guidelines with respect to indoor air pollution in schools are not met. For instance, almost half of children in Europe have been exposed to radon levels above the level of 100 Bq/m3.[48] Furthermore, the majority of children were exposed to formaldehyde in schools with concentrations above 10 μg/m3 (guideline value to protect from negative impacts on lung function and excess lifetime cancer risks). With regard to carbon dioxide concentration, the study found that the levels of CO_2 in European schools were higher than the generally acceptable 1,000 ppm in most schools and kindergartens. While CO_2 concentration was lowest in northern European countries and some western European countries, a significant share of classrooms in eastern and southern European countries had CO_2 levels above 1,500 ppm, a level which has been shown the impair the quality of the learning performance of children. Directly related to the high CO_2 concentration, the report also found that the majority (86 per cent) of values for ventilation rates were lower than the desirable value of 4 l/s.

Generally, a large part of the empirical literature with regards to the association between poor indoor air quality and school performance focused on the concentration of CO_2 or the ventilation rates in classrooms. For instance, Fisk (2017) provides a summary of the existing evidence of the effects of a lack of ventilation in schools. Based on reviewed literature, the author concludes that ventilation rates in classrooms across the globe often are below the recommended guidelines, associated with high levels of CO_2 concentration. Furthermore, the existing evidence suggests that a lack of ventilation is associated with respiratory health issues in children and hence may lead to higher student absenteeism rates. Furthermore, Fisk (2017) concludes that there is relatively robust evidence on the associations between ventilation rates and student performance. A previous review paper by Mendell & Heath (2005) came to similar conclusions, suggesting that high indoor concentration of nitrogen dioxide (NO_2) are associated with lower school attendance. Furthermore, the authors found evidence for the association between low ventilation rates and academic performance. Furthermore, indoor dampness could be associated with the exacerbation of asthma symptoms and respiratory infections. Other studies have investigated the association between ventilation rates and academic performance of children. For instance, Haverinen-Shaughnessy & Shaughnessy (2015) estimated the effects of classroom ventilation rate and temperature on academic achievement in US elementary schools. The authors found positive associations between ventilation rates and test scores in maths, reading and science. On average, test scores increased by about 0.5 per cent per each litre per second per person linear increase in ventilation rates, from 0.9 to 7.1 l/s per person; however, the evidence regarding effects above that level seem to suggest that the effect flattens after this threshold. A similar threshold of 7.1 l/s per person was found by the same authors in a previous study (Haverinen-Shaughnessy et al. 2011). Beyond ventilation rates, Roth (2016) examined the associations between indoor air pollution and cognitive performance for schools in the United Kingdom. The study exploits unique data on readings of indoor pollution related to particulate matter with more than 10 micrometre (PM10), in combination with test scores from students at a UK university. The study, while focussed on older students, finds that increased exposure to PM10 substantially decreases test scores, especially among male students. Another study focussing on elementary schools in Texas, by

[48] This is proposed by the WHO in order to manage the excess of lifetime risk of radon-induced lung cancer.

Stafford (2015), looked at the effects of large renovation projects to improve indoor air pollution (e.g. projects on improving mould, ventilation, roof). The findings suggest that such renovations have positive effects on standardised test scores, but no effect on student attendance. However, as the study does not use actual readings related to indoor air quality, but just the volume and cost of the renovation project, it is more difficult to conclude whether the improvement in test scores is solely due to an improvement in air quality or just to improved material or aesthetic conditions.

4.4 Modelling the economic effects of improved indoor air quality in schools

As the previous section outlined, there is some evidence for positive associations between better indoor air quality and children's health and academic outcomes. While the vast majority of the empirical evidence on health effects investigating the link between exposure to indoor air quality risk factors, such as damp and mould, focuses on exposure at home (where children usually spends most of their time) and we already modelled these health effects in the previous section, we focus here solely on the effects associated with better indoor air quality and academic performance. Specifically, based on the quality of the existing empirical estimates from the literature where we have a valid research basis for their quantification, we model improvements in indoor air quality as improvements in ventilation rates. A similar approach was taken by a previous Danish study conducted by Slotsholm (2012), which found that increasing the ventilation rates in Danish schools from 6 l/s per person to 8.4l/s per person (which is the level in Sweden) would return an increase of GDP in the magnitude of 173 million euros per year up to the year 2050.[49] The study estimated the effects of better ventilation rates on student test scores (productivity effect of 106 million euros), fewer students staying longer in school if they do not have to (increase in GDP by 67 million euros) and lower teacher sickness rates.

In this analysis, we model the economic effects, over a horizon of up to 40 years, from an increase of ventilation rates in European schools. Specifically, in different sub-counterfactual scenarios, we model hypothetical increases in ventilation rates in 0.5 l/s person incremental steps, from 0.5 to 3 l/s person (six sub-scenarios), compared with a baseline world where ventilation rates are not changed. In our analysis, we draw on three different sources of data or relevant modelling parameters.

First, we use the findings provided by Haverinen-Shaughnessy & Shaughnessy (2015), which found that up to the threshold of 7.1 l/s, an increase in ventilation rate by 1 l/s increases math test scores by 0.5 per cent and reading scores by about 0.15 per cent.

Second, we use data on the distribution of ventilation rates across Europe provided by the SINPHONIE report (EC 2014) across four clusters of countries (see Table 4.3).

[49] Using an exchange rate of US$1.11 for 1 euro, this corresponds to about US$192 million per year.

Table 4.3: Distribution of ventilation rates by cluster of countries

	Mean	Min.	Max.
Cluster 1: Northern Europe	3.39	0.35	11.2
Cluster 2: Western Europe	0.87	0.17	2.87
Cluster 3: Central Eastern Europe	1.82	0.14	13.33
Cluster 4: Southern Europe	1.42	0.12	11.08
All	1.8	0.12	13.33

Source: EC (2014).

It is evident from Table 4.3 that average ventilation rates tend to be higher in northern European countries compared with the rest of Europe. However, even within the northern cluster of countries, the rates vary substantially (from 0.35 to 11.2). The lowest ventilation average rate was found in western Europe, with an average of just 0.87 (range from 0.17 to 2.87). The average ventilation rates in central and eastern European schools is 1.82 (range 0.14 to 13.33), and for southern European schools the average is 1.42 (range from 0.12 to 11.08). In our analysis, we want to be conservative in the estimation of the cost, and hence we assume that children in schools with ventilation rates above 7.1 l/s per person would not profit from an increase in ventilation rates in terms of better educational performance, based on the findings by Haverinen-Shaugnessy and Shaughnessy (2015).[50] Therefore, within each of the eight sub-scenarios of ventilation rate increases, we calculate an adjustment parameter to take into account that not all children will be affected by the increase in ventilation rates, but only those up to a ventilation rate of 7.1 l/s. A detailed description on the assumptions made for this analysis can be found in Appendix A (section A.2).

Finally, we translate improved test scores into increased life-time earnings using parameter estimates provided by Crawford & Cribb (2013). Their findings suggest that a one standard deviation increase in math test scores at age 10 is associated with a 7.1 per cent increase in gross weekly earnings at age 38 and that a one standard deviation increase in reading test scores is associated with a 2.1 per cent increase at age 38.[51] We translate these findings of higher wages into the macroeconomic model as a general productivity or efficiency increase (affecting the effective labour supply), feeding this back into the labour efficiency part of the demographics model. The increase in human capital associated with the increase in test scores has a positive productivity-enhancing effect in the CGE model. The effect of increased efficiency is phased in over a 10-year period, as the first cohort of children benefitting from better ventilation rates would enter the labour market in 10 years' time, so in 2030 in our model. Note that, due to fact that the

[50] This may be too restrictive, as Slotsholm (2014) de-facto modelled the corresponding educational gains from an increase of ventilation rates from 6 L/s per person (Danish Building Code requirement) to 8.4 l/s per person (Swedish requirement), whereas in our analysis we assume students in schools with ventilation rates above 7.1 l/s would not profit from better ventilation rates. However, if educational performance still increases after this threshold, for the purpose of this analysis the findings would have to be seen as a lower bound estimate of the true economic benefits.

[51] Note that these are the independent effects of each (math and reading scores), as both have been included in the empirical specification. And the authors also show that the findings are robust for using hourly wages instead of weekly earnings. Furthermore, the authors find no significant differences in the effect sizes at ages 30, 34 and 38, with the returns to the test scores estimated at one point likely to be representative of those of other ages.

underlying ventilation rate data across school is only available across country clusters, for the economic analysis we aggregate the 28 EU member states into these clusters and run the analysis. The breakdown across countries is then conducted by calculating the share of each of the countries' cluster contribution in total GDP.

4.5 The economic implications associated with higher ventilation rates across schools: results

Table 4.4 and Table 4.5 report the cumulative economic effects in GDP of increases in ventilation rates under six different sub-scenarios for the aggregate of the EU-28 member states, as well as separately for each country. The effects are reported for up to the years 2040, 2050 and 2060. The effects increase over time because, if ventilation rates were to improve from now into the future, then more children would benefit from improved grades and hence higher earnings once they entered the labour market. Instead of the total cumulative effects by year, Tables 4.6 and 4.7 report the average annual effects in terms of GDP.

We find that in cumulative terms, the overall economic benefit at EU-28 level from improving ventilation rates by 0.5 l/s per person by 2050 is US$24.4 billion, which increases to US$57 billion by 2060. The associated annual average benefits are US$813.4 million (2050) and US$1,425.1 million (2060) per year, respectively. However, 0.5 l/s per person would be a relatively small improvement, and the corresponding economic benefits would be bigger from improving ventilation rates by a larger increase. For instance, an increase in ventilation rates by 2.5 l/s per person (an increase similar to that estimated by Slotsholm (2014)) would lead to a larger cumulative GDP across the EU-28 member states, of US$120.5 billion by 2050 and US$281.4 billion by 2060, with average annual increases of GDP by US$4 billion by 2050 and US$7 billion by 2060. Interestingly, we estimated a very similar effect as did Slotsholm (2014) for Denmark, even though the data input parameters and the economic model likely differ. For instance, Slotsholm (2014) finds a positive effect from improving ventilation rates from 6 l/s per person to 8.4 l/s per person of 106 million euros per year. Over roughly the same time horizon of 40 years, we find an average increase in Denmark's GDP by about US$118.8 million per year.

Table 4.4: Cumulative economic GDP effects of improving ventilation rates by 0.5, 1, 1.5 litre per second (l/s) per person in European schools (2018 prices, US$ billion)

	Improvements in ventilation rates								
	0.5 l/s			1.0 l/s			1.5 l/s		
Year	2040	2050	2060	2040	2050	2060	2040	2050	2060
EU-28	6.599	24.403	57.002	13.183	48.706	113.763	19.094	72.207	169.494
Austria	0.132	0.468	1.06	0.262	0.934	2.114	0.392	1.397	3.161
Belgium	0.152	0.54	1.221	0.302	1.076	2.435	0.452	1.609	3.642
Bulgaria	0.035	0.142	0.368	0.069	0.283	0.734	0.072	0.392	1.067
Croatia	0.025	0.103	0.266	0.05	0.205	0.532	0.052	0.284	0.773
Cyprus	0.008	0.03	0.067	0.017	0.059	0.134	0.025	0.089	0.201
Czechia	0.087	0.358	0.927	0.173	0.713	1.851	0.182	0.989	2.69
Denmark	0.116	0.427	0.973	0.232	0.853	1.94	0.346	1.271	2.892
Estonia	0.01	0.04	0.103	0.019	0.079	0.206	0.02	0.11	0.3
Finland	0.116	0.45	1.089	0.232	0.894	2.168	0.345	1.332	3.234
France	1.18	4.284	9.833	2.359	8.557	19.64	3.517	12.794	29.371
Germany	1.263	4.727	11.017	2.525	9.423	21.968	3.773	14.087	32.85
Greece	0.092	0.327	0.739	0.183	0.652	1.475	0.274	0.974	2.205
Hungary	0.064	0.262	0.678	0.127	0.521	1.354	0.133	0.723	1.967
Ireland	0.082	0.292	0.661	0.163	0.582	1.318	0.245	0.871	1.972
Italy	0.485	1.665	3.619	0.971	3.335	7.232	1.45	4.984	10.818
Latvia	0.013	0.052	0.135	0.025	0.104	0.27	0.027	0.144	0.392
Lithuania	0.021	0.086	0.224	0.042	0.172	0.447	0.044	0.239	0.649
Luxembourg	0.013	0.045	0.102	0.025	0.09	0.203	0.038	0.134	0.304
Malta	0.003	0.011	0.024	0.006	0.021	0.048	0.009	0.032	0.072
Netherlands	0.275	0.978	2.213	0.547	1.95	4.413	0.819	2.916	6.6
Poland	0.267	1.098	2.844	0.531	2.188	5.682	0.559	3.035	8.255
Portugal	0.095	0.339	0.766	0.189	0.675	1.528	0.284	1.009	2.285
Romania	0.112	0.462	1.197	0.224	0.921	2.391	0.235	1.277	3.474
Slovakia	0.038	0.158	0.409	0.076	0.314	0.816	0.08	0.436	1.186

	Improvements in ventilation rates								
	0.5 l/s			1.0 l/s			1.5 l/s		
Year	***2040***	***2050***	***2060***	***2040***	***2050***	***2060***	***2040***	***2050***	***2060***
Slovenia	0.016	0.067	0.173	0.032	0.133	0.346	0.034	0.185	0.503
Spain	0.383	1.274	2.718	0.762	2.535	5.416	1.145	3.803	8.117
Sweden	0.318	1.32	3.398	0.633	2.624	6.754	0.948	3.916	10.087
United Kingdom	1.198	4.401	10.176	2.406	8.812	20.348	3.593	13.175	30.428

Notes: Entries represent the net present value of the cumulative economic effects in terms of GDP from now up to 2040, 2050 and 2060. Values are reported for three scenarios of ventilation rate increases (0.5, 1, 1.5 l/s per person) compared with a baseline scenario of no change in ventilation rates.

Table 4.5: Cumulative economic GDP effects of improving ventilation rates by 2, 2.5, 3 litre per second (l/s) per person in European schools (2018 prices, US$ billion)

	Improvements in ventilation rates								
	2.0 l/s			2.5 l/s			3.0 l/s		
Year	***2040***	***2050***	***2060***	***2040***	***2050***	***2060***	***2040***	***2050***	***2060***
EU-28	26.201	96.804	226.085	32.611	120.495	281.433	38.934	143.869	336.027
Austria	0.521	1.856	4.201	0.649	2.313	5.236	0.775	2.763	6.257
Belgium	0.601	2.139	4.84	0.748	2.665	6.033	0.893	3.184	7.209
Bulgaria	0.136	0.561	1.458	0.17	0.699	1.814	0.202	0.834	2.165
Croatia	0.099	0.407	1.056	0.123	0.506	1.314	0.147	0.604	1.568
Cyprus	0.033	0.118	0.266	0.041	0.147	0.332	0.049	0.175	0.397
Czechia	0.344	1.416	3.677	0.428	1.762	4.574	0.511	2.103	5.46
Denmark	0.459	1.685	3.833	0.569	2.09	4.751	0.676	2.484	5.648
Estonia	0.038	0.158	0.41	0.048	0.196	0.51	0.057	0.234	0.608
Finland	0.458	1.766	4.285	0.567	2.19	5.313	0.674	2.602	6.314
France	4.685	17.018	39.046	5.832	21.184	48.62	6.957	25.303	58.08
Germany	5.021	18.75	43.696	6.254	23.351	54.425	7.472	27.873	64.987
Greece	0.364	1.295	2.931	0.453	1.613	3.653	0.541	1.928	4.365
Hungary	0.252	1.035	2.688	0.313	1.288	3.345	0.373	1.538	3.992

	Improvements in ventilation rates								
	2.0 l/s			2.5 l/s			3.0 l/s		
Year	***2040***	***2050***	***2060***	***2040***	***2050***	***2060***	***2040***	***2050***	***2060***
Ireland	0.325	1.158	2.62	0.405	1.442	3.265	0.483	1.723	3.902
Italy	1.93	6.637	14.403	2.41	8.274	17.949	2.883	9.899	21.472
Latvia	0.05	0.206	0.535	0.062	0.256	0.666	0.074	0.306	0.795
Lithuania	0.083	0.342	0.887	0.103	0.425	1.104	0.123	0.508	1.318
Luxembourg	0.05	0.179	0.404	0.062	0.223	0.504	0.075	0.266	0.602
Malta	0.012	0.042	0.096	0.015	0.053	0.12	0.018	0.063	0.143
Netherlands	1.089	3.875	8.771	1.355	4.828	10.931	1.618	5.769	13.062
Poland	1.056	4.344	11.282	1.315	5.406	14.038	1.567	6.454	16.755
Portugal	0.377	1.342	3.037	0.469	1.672	3.784	0.56	1.997	4.522
Romania	0.445	1.828	4.747	0.553	2.275	5.907	0.659	2.716	7.05
Slovakia	0.152	0.624	1.621	0.189	0.777	2.016	0.225	0.927	2.407
Slovenia	0.064	0.265	0.687	0.08	0.329	0.855	0.095	0.393	1.021
Spain	1.519	5.055	10.793	1.894	6.303	13.452	2.263	7.533	16.089
Sweden	1.258	5.191	13.361	1.561	6.439	16.575	1.852	7.647	19.686
United Kingdom	4.78	17.513	40.454	5.944	21.791	50.347	7.108	26.042	60.153

Notes: Entries represent the net present value of the cumulative economic effects in terms of GDP from now up to 2040, 2050 and 2060. Values are reported for three scenarios of ventilation rate increases (2, 2.5, 3 l/s per person) compared with a baseline scenario of no change in ventilation rates.

Table 4.6: Average annual economic GDP effects of improving ventilation rates by 0.5,1, 1.5 l/s per person in European schools (2018 prices, US$ million)

	Improvements in ventilation rates								
	0.5 l/s			1.0 l/s			1.5 l/s		
	2040	***2050***	***2060***	***2040***	***2050***	***2060***	***2040***	***2050***	***2060***
EU-28	329.9	813.4	1,425.10	659.2	1,623.50	2,844.10	954.7	2,406.90	4,237.30
Austria	6.6	15.6	26.5	13.1	31.1	52.8	19.6	46.6	79
Belgium	7.6	18	30.5	15.1	35.9	60.9	22.6	53.6	91.1
Bulgaria	1.7	4.7	9.2	3.4	9.4	18.4	3.6	13.1	26.7
Croatia	1.3	3.4	6.7	2.5	6.8	13.3	2.6	9.5	19.3
Cyprus	0.4	1	1.7	0.8	2	3.4	1.2	3	5
Czechia	4.4	11.9	23.2	8.7	23.8	46.3	9.1	33	67.3
Denmark	5.8	14.2	24.3	11.6	28.4	48.5	17.3	42.4	72.3
Estonia	0.5	1.3	2.6	1	2.6	5.2	1	3.7	7.5
Finland	5.8	15	27.2	11.6	29.8	54.2	17.2	44.4	80.8
France	59	142.8	245.8	118	285.2	491	175.9	426.5	734.3
Germany	63.1	157.6	275.4	126.2	314.1	549.2	188.7	469.6	821.3
Greece	4.6	10.9	18.5	9.1	21.7	36.9	13.7	32.5	55.1
Hungary	3.2	8.7	16.9	6.3	17.4	33.8	6.7	24.1	49.2
Ireland	4.1	9.7	16.5	8.2	19.4	33	12.2	29	49.3
Italy	24.3	55.5	90.5	48.5	111.2	180.8	72.5	166.1	270.4
Latvia	0.6	1.7	3.4	1.3	3.5	6.7	1.3	4.8	9.8
Lithuania	1.1	2.9	5.6	2.1	5.7	11.2	2.2	8	16.2
Luxembourg	0.6	1.5	2.6	1.3	3	5.1	1.9	4.5	7.6
Malta	0.2	0.4	0.6	0.3	0.7	1.2	0.4	1.1	1.8
Netherlands	13.8	32.6	55.3	27.4	65	110.3	41	97.2	165
Poland	13.4	36.6	71.1	26.6	72.9	142	27.9	101.2	206.4
Portugal	4.8	11.3	19.2	9.5	22.5	38.2	14.2	33.6	57.1
Romania	5.6	15.4	29.9	11.2	30.7	59.8	11.8	42.6	86.8
Slovakia	1.9	5.3	10.2	3.8	10.5	20.4	4	14.5	29.6

	Improvements in ventilation rates								
	0.5 l/s			1.0 l/s			1.5 l/s		
	2040	***2050***	***2060***	***2040***	***2050***	***2060***	***2040***	***2050***	***2060***
Slovenia	0.8	2.2	4.3	1.6	4.4	8.7	1.7	6.2	12.6
Spain	19.2	42.5	68	38.1	84.5	135.4	57.2	126.8	202.9
Sweden	15.9	44	84.9	31.7	87.5	168.9	47.4	130.5	252.2
United Kingdom	59.9	146.7	254.4	120.3	293.7	508.7	179.6	439.2	760.7

Notes: All values are reported in 2018 US$ million. Entries represent the net present value of the average annual economic effects in terms of GDP from now up to 2040, 2050 and 2060. Values are reported for three scenarios of ventilation rate increases (0.5, 1, 1.5 l/s per person) compared with a baseline scenario of no change in ventilation rates.

Table 4.7: Average annual economic GDP effects of improving ventilation rates by 2, 2.5, 3 l/s per person in European schools (2018 prices, US$ million)

	Improvements in ventilation rates								
	2.0 l/s			2.5 l/s			3.0 l/s		
	2040	***2050***	***2060***	***2040***	***2050***	***2060***	***2040***	***2050***	***2060***
EU-28	1,310.00	3,226.80	5,652.10	1,630.60	4,016.50	7,035.80	1,946.70	4,795.60	8,400.70
Austria	26.1	61.9	105	32.4	77.1	130.9	38.8	92.1	156.4
Belgium	30	71.3	121	37.4	88.8	150.8	44.7	106.1	180.2
Bulgaria	6.8	18.7	36.4	8.5	23.3	45.3	10.1	27.8	54.1
Croatia	4.9	13.6	26.4	6.2	16.9	32.8	7.3	20.1	39.2
Cyprus	1.7	3.9	6.7	2.1	4.9	8.3	2.5	5.8	9.9
Czechia	17.2	47.2	91.9	21.4	58.7	114.4	25.5	70.1	136.5
Denmark	22.9	56.2	95.8	28.4	69.7	118.8	33.8	82.8	141.2
Estonia	1.9	5.3	10.2	2.4	6.5	12.7	2.8	7.8	15.2
Finland	22.9	58.9	107.1	28.4	73	132.8	33.7	86.7	157.9
France	234.3	567.3	976.1	291.6	706.1	1,215.50	347.9	843.4	1,452.00
Germany	251	625	1,092.40	312.7	778.4	1,360.60	373.6	929.1	1,624.70
Greece	18.2	43.2	73.3	22.6	53.8	91.3	27	64.3	109.1
Hungary	12.6	34.5	67.2	15.7	42.9	83.6	18.7	51.3	99.8

Ireland	16.3	38.6	65.5	20.2	48.1	81.6	24.2	57.4	97.6
Italy	96.5	221.2	360.1	120.5	275.8	448.7	144.2	330	536.8
Latvia	2.5	6.9	13.4	3.1	8.5	16.6	3.7	10.2	19.9
Lithuania	4.2	11.4	22.2	5.2	14.2	27.6	6.2	16.9	32.9
Luxembourg	2.5	6	10.1	3.1	7.4	12.6	3.7	8.9	15.1
Malta	0.6	1.4	2.4	0.7	1.8	3	0.9	2.1	3.6
Netherlands	54.4	129.2	219.3	67.7	160.9	273.3	80.9	192.3	326.6
Poland	52.8	144.8	282.1	65.7	180.2	350.9	78.4	215.1	418.9
Portugal	18.8	44.7	75.9	23.5	55.7	94.6	28	66.6	113.1
Romania	22.2	60.9	118.7	27.7	75.8	147.7	33	90.5	176.3
Slovakia	7.6	20.8	40.5	9.4	25.9	50.4	11.3	30.9	60.2
Slovenia	3.2	8.8	17.2	4	11	21.4	4.8	13.1	25.5
Spain	76	168.5	269.8	94.7	210.1	336.3	113.2	251.1	402.2
Sweden	62.9	173	334	78	214.6	414.4	92.6	254.9	492.1
United Kingdom	239	583.8	1,011.40	297.2	726.4	1,258.70	355.4	868.1	1,503.80

Notes: All values are reported in 2018 US$ million. Entries represent the net present value of the average annual economic effects in terms of GDP from now up to 2040, 2050 and 2060. Values are reported for three scenarios of ventilation rate increases (2, 2.5, 3 l/s per person) compared with a baseline scenario of no change in ventilation rates.

5. Summary and implications for key stakeholders

5.1 Summary of key findings

Our study has found that a significant proportion of children in the EU-28 are exposed to one or several indoor climate hazards. Notably, in 2017, 15 per cent of European children lived in houses with a leaking roof; damp in walls, floors and/or foundations; or rot in window frames or floors. In certain countries, this number is even significantly higher, reaching 30 per cent in Hungary, for example. Exposure to several of the other hazards we looked at is also high. For example, 17 per cent of children are exposed to significant levels of noise. Exposure to lack of daylight and excess cold are below 10 per cent for Europe as a whole, but nonetheless worryingly high in individual countries, such as Bulgaria, where 35 per cent of children are exposed to excess cold. All in all, we found that 30 per cent of children in the EU-28 are exposed to one or several of these four deficiencies, which equals 26 million children aged 0 to 15.

Our study has, furthermore, found that exposure to each of these four housing deficiencies is correlated with a higher risk of certain health issues. Starting with damp, there is some evidence that it has a negative effect on health, albeit indirectly. Damp promotes the growth of all kinds of microorganisms, such as mould, other fungi and bacteria, which in turn increase the risk of developing asthma as well as other respiratory diseases, atopic conditions and allergies. With regard to noise, our REA has found that exposure to it is statistically significantly associated with annoyance, emotional problems, cognitive dysfunction, behavioural dysfunction and abnormal growth hormone release. With regard to lack of daylight as well as excess cold, our study has identified a statistically significant association with increased health risks. In addition to these four hazards, we also looked at indoor air pollution as well as radiation through radon. While no data or estimates concerning the prevalence data could be found, our REA identified several papers that showed a significant health risk related to indoor pollution. Radiation through radon is the only hazard we looked at for which the results in terms of health risk were inconclusive.

Because of the strong evidence base and good availability of data, our subsequent quantitative analysis and modelling task has focused on the impact of damp and mould. Its results can be summarised as follows:

Box 5.1: Health, educational and socioeconomic impact of children's exposure to damp and mould in the EU-28 (summary):

- If in all dwellings reporting damp, noise, excess cold and/or lack of daylight those respective deficiencies were removed, the health of more than 1 million children (aged 0–15) in the EU could be improved.
- The burden of disease from indoor damp and mould exposure of children in relation to asthma, atopic dermatitis, as well as respiratory infections is 37,500 disability adjusted life years (DALYs) for the EU as a whole, or 276 DALYs per 100,000 children.
- The total number of school days missed by children across the EU that is attributable to the prevalence of damp and mould in their homes is 1.7 million.
- The macroeconomic costs associated with children's exposure to damp and mould can be estimated to be US$62 billion over the next 40 years. The same sum would be saved if all European dwellings with children were made damp-free. Breaking it down to household level, dividing it by the number of damp-affected households with children, our calculation comes to the following results: By 2040, the estimated benefit per affected dwelling would be US$2523. By 2050, it would be US$4626, and by 2060, it would be US$7384.

In addition to all the above analyses concerning children's exposure to damp and mould in their homes, we carried out an economic analysis related to the economic effects associated with improving ventilation rates in European primary and secondary schools. Based on our calculations, it can be stated that improving ventilation rates in European schools could lead to substantial economic benefits: We estimate that even a small improvement in ventilation rates, of 0.5 l/s per person, in European schools would be associated with a cumulative total increase in EU-28 GDP by 2050 of US$24.4 billion, which would increase to US$57 billion by 2060. The estimated economic benefits more substantial improvements in ventilation rates would be even larger. For instance, a 2.5 l/s improvement across European schools would be associated with an increase in cumulative EU-28 GDP of US$120.5 billion by 2050 and US$281.4 billion by 2060.

5.2 Implications for key stakeholders

Housing deficiencies constitute a very important health risk for children across Europe. While there are important differences between countries, types of dwellings and settlements, as well as socio-economic status, it is noteworthy that 30 per cent of children in the EU-28 are living in dwellings featuring one of the following four housing deficiencies for which the EU-SILC database provides data: (1) leaking roof, damp in walls, floors and/or foundations or rot in window frames or floors; (2) lack of daylight; (3) noise; and (4) inability to keep the house comfortably warm. Our study has found evidence that all those four types of hazards constitute a risk for children who are exposed to them. We have, furthermore, demonstrated that economic benefits could be realised if fewer children in the EU were exposed to these housing deficiencies.

These findings should be taken into account by a wide variety of stakeholders. First, these findings have important implications for house owners, tenants and landlords. **The good condition of dwellings should not only be seen as an issue of comfort, but as an essential basic requirement for good health of the residents**, and even more so when they are families with children. Second, all kinds of private sector agents, in particular in the construction, renovation and property management domains, should also take these findings into account and design and maintain buildings in such a way that decreases the likelihood of any of these deficiencies occurring. Third, there is also a task for policy-makers. The study has shown that the condition of dwellings often correlates with socioeconomic status. Less well-off householders, who cannot afford to improve the condition of their dwellings or who may simply have to prioritise other things, may need the support of public authorities in order to improve the condition of their dwellings. This support could take very different forms. For house owners, direct or indirect (i.e. tax-benefits-based) financial support but also awareness raising (e.g. through specific information campaigns) seem like recommendable options. In order to support tenants living in not well-maintained apartments, legal obligations for landlords and/or building managers may be required.

The results of our analysis show that **there is a strong case for improving the air quality in schools**. In addition to the positive impact this will have on the health of the children, it may have a positive effect in terms of educational outcomes. These findings have bearings in particular for policy-makers and administrations in the field of education. They show that not only the quality of education and the equipment of schools, but also air quality in schools are important for educational outcomes.

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Appendix A. The REA search protocol and the inclusion/exclusion criteria

A.1. The search protocol

As specified in section 2, the REA aimed primarily to explore research question 1:

- What is the evidence in terms of existing studies and literature concerning the impact of poor indoor climate on human and in particular on children's health? More specifically, what is the impact of the following hazards: damp, mould, indoor air pollution, noise, radiation through radon, excess cold, and lack of daylight?

In addition, however, the REA also had the objective of supporting the estimation of the health burden &&and the educational burden as well as macroeconomic modelling by identifying attributable risks. In this way, it was also linked to research questions 4 and 5:

- Following on all the above, what is the health and educational burden of poor indoor climate?
- What would be the economic benefits associated with reduction in children's exposure to poor indoor climate, e.g. in terms of decreased learning abilities for children, salary losses of parents due to necessary leave days and salary losses of affected children in their later adult life due to the persistence of the disease?

The search strategy and inclusion/exclusion criteria were developed with these key questions in mind. In line with this, we developed two search strings, one addressing research question 1 and one addressing research questions 4 and 5. We then combined both search strings into one overarching search string:

Search terms	**Element addressed**	**Research question addressed**
((Child OR children OR kid OR kids OR baby OR babies OR infant OR infants OR newborn OR newborns OR teen OR teens OR adolescen* OR preteen* OR pre-teen* OR minor OR minors OR juvenile* OR youngster* OR Toddler OR Toddlers OR pediatric*[tiab] OR paediatric*[tiab])))	Under-18-year-olds	Research question 1: 'What is the evidence in terms of existing studies and literature concerning the impact of poor indoor climate on human and in particular on children's health? More specifically, what is the impact of the following
AND		
(((“indoor environment*”[tiab] OR “indoor pollution”[tiab] OR “indoor air pollution”[tiab] OR “indoor pollutant*”[tiab] OR “indoor air	Indoor environment and its various hazards	

quality"[tiab] OR "ambient air pollution"[tiab] OR "residential air pollution"[tiab] OR "indoor climate"[tiab] OR air pollution, indoor[mh]) OR ((Indoor*[tiab] OR house[tiab] OR houses[tiab] OR home[tiab] OR homes[tiab]) AND ("air pollution"[tiab] OR "air pollutant*"[tiab] OR "air quality"[tiab] OR "air qualities"[tiab] OR mold[tiab] OR mould[tiab] OR "carbon monoxide"[tiab] OR radiation[tiab] OR damp[tiab] OR dampness[tiab] OR temperature[tiab] OR temperatures[tiab] OR heat[tiab] OR hot[tiab] OR cold[tiab] OR noise[tiab] OR noisy[tiab] OR ((light[tiab] OR sun[tiab]) AND (exposure[tiab] OR exposed[tiab])) OR daylight[tiab] OR "thermal conditions"[tiab] OR "thermal condition"[tiab] OR radon[tiab]))		hazards: damp, mould, indoor air pollution, noise, radiation through radon, excess cold, and lack of daylight?'
AND		
(Health*[tiab] OR sick[tiab] OR sickness[tiab] OR sickly[tiab] OR unwell[tiab] OR ill[tiab] OR illness[tiab] OR breath*[tiab] OR respiratory[tiab] OR asthma*[tiab] OR allerg*[tiab] OR infect*[tiab] OR headache*[tiab] OR fatigue[tiab] OR malaise[tiab] OR tiredness[tiab] OR disease*[tiab] OR disorder[tiab] OR chronic*[tiab] OR morbidity[tiab] OR death*[tiab] OR dead*[tiab] OR mortal*[tiab] OR cancer[tiab] OR (co[tiab] AND poison*[tiab]) OR ("carbon monoxide"[tiab] AND poison*[tiab]) OR neurological[tiab] OR "physical health"[tiab] OR wheeze[tiab] OR "nasal patency"[tiab] OR "nasal obstruction"[tiab] OR flu[tiab] OR influenza[tiab] OR eczema[tiab] OR alveolitis[tiab] OR cough[tiab] OR building related illness*[tiab] OR dermatitis[tiab] OR "humidifier fever"[tiab] OR "tight building syndrome"[tiab] OR pneumonia[tiab] OR "heat edema"[tiab] OR heat rash*[tiab] OR heat cramp*[tiab] OR "heat exhaustion"[tiab] OR "heat syncope"[tiab] OR "heat stroke"[tiab] OR "hearing loss"[tiab] OR	Health in general and various specific diseases and health conditions	

tinnitus[tiab] OR stress[tiab] OR annoyance[tiab] OR sleep disturbance*[tiab] OR hearing impairment*[tiab] OR Vitamin D deficien*[tiab] OR cardiovascular[tiab])		

OR

((Child OR children OR kid OR kids OR baby OR babies OR infant OR infants OR newborn OR newborns OR teen OR teens OR adolescen* OR preteen* OR pre-teen* OR minor OR minors OR juvenile* OR youngster* OR Toddler OR Toddlers OR pediatric*[tiab] OR paediatric*[tiab])))	Under-18-year-olds	Research question 4: 'Following on all the above, what is the health and educational burden of poor indoor climate?' & Research question 5: 'What would be the economic benefits associated with reduction in children's exposure to poor indoor climate, e.g. in terms of decreased learning abilities for children, salary losses of parents due to necessary leave days and salary losses of affected children in their later adult life due to the persistence of the disease?'
AND		
((breath*[tiab] OR respiratory[tiab] OR asthma*[tiab] OR headache*[tiab] OR fatigue[tiab] OR (co[tiab] AND poison*[tiab]) OR ("carbon monoxide"[tiab] AND poison*[tiab]) OR wheeze[tiab] OR "nasal patency"[tiab] OR "nasal obstruction"[tiab] OR flu[tiab] OR influenza[tiab] OR eczema[tiab] OR alveolitis[tiab] OR cough[tiab] OR building related illness*[tiab] OR dermatitis[tiab] OR "humidifier fever"[tiab] OR "tight building syndrome"[tiab] OR pneumonia[tiab] OR "heat edema"[tiab] OR heat rash*[tiab] OR heat cramp*[tiab] OR "heat exhaustion"[tiab] OR "heat syncope"[tiab] OR "heat stroke"[tiab] OR "hearing loss"[tiab] OR tinnitus[tiab] OR stress[tiab] OR annoyance[tiab] OR sleep disturbance*[tiab] OR hearing impairment *[tiab] OR Vitamin D deficien*[tiab] OR cardiovascular[tiab]))	Various specific diseases and health conditions	
AND		
((("educational achievement"[tiab] OR "educational attainment"[tiab] OR "school performance" OR "academic achievement"[tiab] OR "academic performance"[tiab] OR academic success*[tiab]) OR ("Work productivity"[tiab] OR employ[tiab] OR employment[tiab] OR	Impact on education or work productivity	

employs[tiab] OR employed[tiab] employer*[tiab] OR employee*[tiab] OR employable[tiab] OR employability[tiab])OR "work productivity"[tiab] OR (economic*[tiab] AND productivity[tiab]) OR "loss of productivity"[tiab] OR "decreased productivity"[tiab] OR "productivity losses"[tiab] OR "labor productivity"[tiab] OR "labour productivity"[tiab] OR income[tiab] OR earnings[tiab]) OR "sick leave"[tiab] OR "labor efficiency"[tiab] OR "labour efficiency"[tiab] OR absenteeism[tiab] OR presenteeism[tiab] OR WPAI[tiab] OR "work productivity and activity impairment"[tiab] OR wage[tiab] OR wages[tiab] OR "school days lost"[tiab] OR "school missed"[tiab] OR "missed school"[tiab] OR (school[tiab] AND "low attendance"[tiab]) OR "workdays lost"[tiab] OR "lost workdays"[tiab] OR "work days lost"[tiab] OR "lost work days"[tiab] OR "work missed"[tiab] OR "missed work"[tiab]))		
NOT		
Pregnancy[tiab] OR pregnant[tiab] OR prenatal[tiab] OR ambient[tiab] OR obesity[tiab] OR vaccine*[tiab] OR HIV[tiab] OR "posttraumatic stress"[tiab] OR "post-traumatic stress"[tiab] OR violence[tiab]	Specific terms not in the interest of this study	

A.2. Inclusion and exclusion criteria

Table: Inclusion and exclusion criteria of the rapid evidence assessment

Criteria	Inclusion criteria	Exclusion criteria	Rationale
Publication date	2014–present	Pre-2014	Due to the large number of articles we identified during the initial search when applying a 10-year period, it was deemed necessary to reduce the period to 5 years. This also helps us to identify as much of the relevant evidence as possible while ensuring this is up-to-date.
Geography	Europe and North America	All other countries	Evidence from low- and middle-income countries is unlikely to be relevant to a high-income context (e.g. likelihood of different types of indoor climate problems).
Language	English	Non-English languages	It was determined that much of the available literature would be available in English, as the focus of the REA is on academic literature.
Study types	Peer-reviewed publications, including literature/systematic reviews	Autobiography; Bibliography; Biography; Books and Documents; Clinical Trial, Veterinary; Comment; Editorial; Electronic Supplementary Materials; Festschrift; Historical Article; Lecture; Legal Case; Letter; News; Newspaper Article; Observational Study, Veterinary; Patient Education Handout; Periodical Index; Personal Narrative; Portrait; Practice Guideline; Retracted Publication; Retraction of Publication; Scientific Integrity Review; Twin Study; Validation Studies; Video-Audio Media	Evidence from peer-reviewed journals is most likely to contain high-quality and robust evidence from a trustworthy source. Some of the excluded sources of evidence are likely to contain irrelevant literature.
Population	Children (0 to 18 years)	Adults aged 18 and over and foetuses	The focus of this piece of research is specifically on adults and children after they have been born, rather than during pregnancy.

Study participants	Human studies	Animal studies	This research focuses on the health impacts of humans only.
Study location	Homes	Workplaces, schools and other locations	This REA is specifically focused on the health and economic impacts of children living in homes with poor indoor climate.
Topic	Indoor sources of pollution	Outdoor sources of pollution	This research focuses on the health effects of indoor climate factors, and so our focus for pollution/air quality is on that produced by indoor sources.
	Pollution arising from the structural aspects of a home	Pollution arising from other sources, not related to the structure of the building, including smoking, cooking/burning fuel, candles/incense, cleaning, pets, dust/dust mites, furniture, renovations	This research focuses on the impacts of factors directly relating to the structure of the home. These specific exclusion criteria were put in place after the initial screening, as they were deemed to be irrelevant to the research.
Health condition	Any physical or mental health condition a study links to poor indoor climate	Health conditions not directly linked to poor indoor climate	The scope of the REA is not restricted by type of health outcome; however, for inclusion, the evidence has to be directly linked to a source of poor indoor climate.

Appendix B. Details on the statistical methods

This Appendix aims to provide further detail on the statistical approach taken in analysing the EU-SILC data. Specifically, it discusses the difference between the LPM and the OLM estimators used for the regression analysis.

Depending on the analysis, the outcome variable is binary in nature (e.g. taking the value 1 if a household resides in a dwelling with a problem with regard to rot or damp, or 0 otherwise) or ordinal in nature (e.g. individuals rate their health status according to an ascending scale, from 1 (very poor) to 5 (very good). When the dependent variable is binary, we apply ordinary least squares (OLS) regression analysis, and using OLS for binary outcome variables leads automatically to the LPM. One issue that may arise with LPM is that it may predict values for the probability of reporting, for instance, rot or damp that lie outside the probability interval between 0 and 1. A Probit or Logit response estimator would take this into account but needs assumptions about the error terms using maximum-likelihood techniques. However, as long as the relative proportion of LPM predicted values that fall outside the unit interval is small, the LPM estimator is expected to be unbiased (Angrist & Pischke 2010). That is, the LPM is our preferred estimator, as for further interpretational practicality the LPM directly delivers the marginal effects of our variables of interest, without the need for conversion of odds ratios into meaningful metrics.

When the dependent variable is ordinal in nature, we apply OLM. In non-technical terms, in contrast to the case when one is estimating regression models with a continuous dependent variable Y, and an explanatory variable X; when Y is ordinal, for instance meaning that it represents different categories that respondents can answer, then the actual continuous Y is a collapsed version of an underlying unobserved variable Z, or so-called 'latent' variable (Long & Freese 2014). As respondents cross the different thresholds on the latent variable Z, their values on the observed ordinal variable Y change. For example, consider a variable 'household income' in a questionnaire that is coded into 4 categories, as follows: 1 (£1 to £10,000); 2 (£10,001 to £40,000); 3 (£40,001 to £70,000); 4 (£70,001 plus). Presumably, household income could take any given value on a continuous scale, but respondents decide which option best reflects the range of their true income. For such variables, we know the interval that the underlying latent variable Z falls in, but not its exact value. OLM allows us to estimate the effects of the Xs on the Z. In essence, for each X, OLM can provide us with the estimated probability that a respondent would answer a specific category of Y. For instance, assume X represents a variable education (e.g. higher education degree vs non-higher-education degree), then using OLM would provide the estimated probability (or odds) that a respondent with a higher education degree would report a higher income, all else being equal, where we would expect a priori the coefficient to be positive (e.g. more education leads to higher income). One limitation of the standard OLM is that the estimated probabilities are constant across the different thresholds of the ordinal dependent variable Y, which is referred to as the 'parallel regression assumption' and the standard OLM often called the 'proportional odds' model. However, in reality one would assume that at least some explanatory variables would predict different probabilities for each of the thresholds, and hence we apply the generalised OLM (GOLM), which allows different parameter estimates for the various threshold categories of Y. A more technical description and discussion of the OLM and GOLM can be found in Winkelmann and Boes (2009).

Appendix C. The macroeconomic model

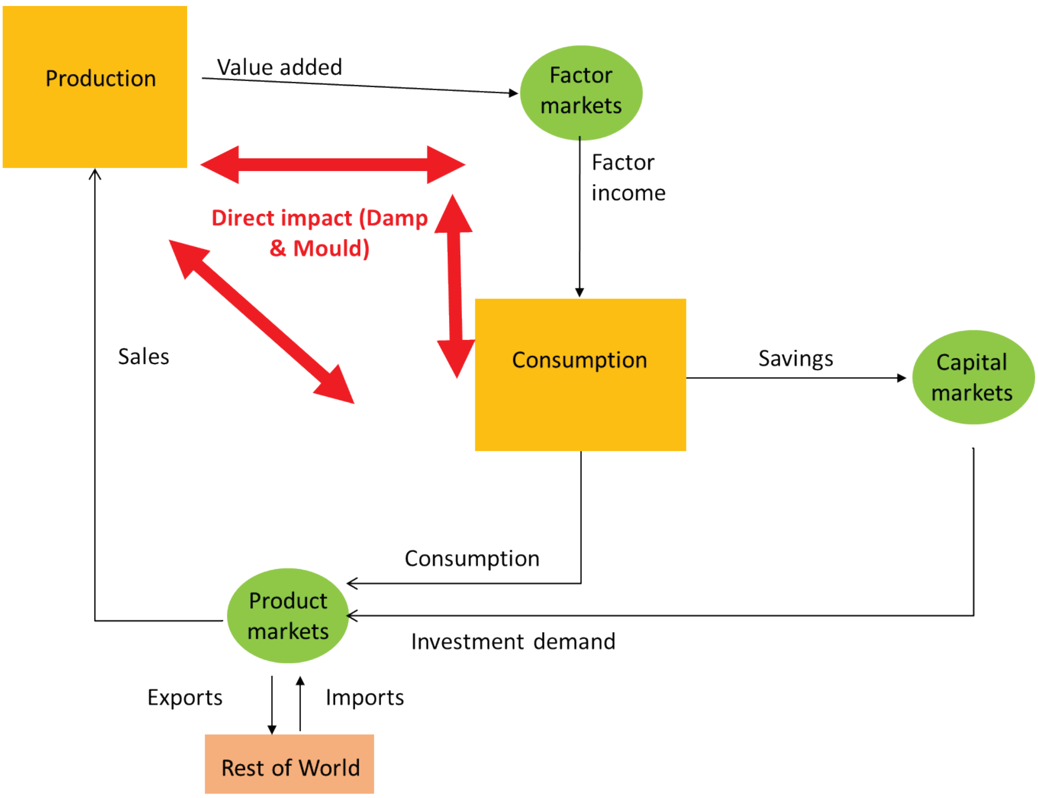
The CGE model is a multi-regional model whereby each region has bilateral trade with all other regions, simultaneously. World prices are, therefore, determined globally by the model, and each country/region has an effect on all the other regions. Larger regions will have larger effects compared with smaller regions. This is different from the small-open economy health models, in which countries cannot affect world prices but, rather, take them as given (e.g. Smith et al. 2005). In each country or region, firms produce a single good using a multi-level, differentiable, constant return to scale production function that combines factor inputs (i.e. capital and labour) with intermediate goods. The model uses a constant elasticity of transformation function to split production into domestic production and exports. Then, domestic production is combined with imports to form the final Armington good (Armington 1969). The representative agent in each country/region is assumed to be rational with a locally, non-satiated preference and demand for final Armington goods. Thus, subject to disposable income, the representative agent in each country/region maximizes a continuous, multi-level utility function. First, we assume a Ramsey-type utility function, which imposes a fixed share between savings and a consumption bundle (Ramsey 1928). This is an appropriate function for a recursive dynamic model, because agents are assumed to be myopic and do not alter their consumption-savings behaviour in anticipation of future. Multi-level functions mean that they are a combination of different functions stacked together to form a more complex function. Breaking them into levels makes it simpler to analyse and describe. The Armington assumption allows for cross-hauling, thus allowing for product differentiation between import and exports of similar goods. Second, subject to the net-savings disposable income, the representative agent maximizes a typical Cobb-Douglas utility function (Cobb & Douglas 1928). As previously discussed, the government has no active role in the model because of our assumption that the government maintains its current methods (i.e. policies) towards providing the public good. Therefore, the public and private sectors are aggregated together, which simplifies the model, reduces the number of assumptions necessary and increases transparency. Finally, a virtual investment firm 'builds' new capital stock for the next period by demanding some Armington final-inputs in fixed proportion. Capital is accumulated under the assumption of a competitive capital market. This means that the purchase price of one unit of new capital is equal to the rental earnings of that unit, plus the value of the remaining capital sold in the subsequent period (net of depreciation).

C.1. How improvements in health or educational outcomes affect the model economy

Figure A.1 starts with a schematic depiction of how a reduction in children's exposure to damp and mould affects the economy. In the model, just as in reality, production sectors (e.g. different agricultural, industrial and services sectors) require capital and labour inputs, which they access through the factor markets. Firms hire labour and rent capital from households, which allows households to obtain income. Goods are then sold in product markets, which households pay for, given their available income. The framework depicted does not include the government, which in our model collects taxes and demands final goods. Finally, households and the governments save/borrow in the capital markets. The economy also trades with the rest of the world through a complex set of international linkages.

Specifically, in the first analysis we consider the health effects of damp and mould on children. The existing evidence suggests that children exposed to damp and mould are more likely to develop such health conditions as asthma, acute rhinitis, atopic dermatitis (eczema), pneumonia, bronchitis, or even just more a common cold. Some of these conditions, such as pneumonia and asthma, are associated with a higher mortality risk, but also with higher rates of school absence and a loss in work productivity for the adult carers, who have to take time off work to care for the ill child. Furthermore, if a child develops asthma or acute dermatitis, there is a relatively high probability that the child will also suffer from the condition in adulthood and hence further experience potential work impairment due to the health condition as an adult. Within this modelling framework, the exposure to damp and mould as a child hence can directly reduce the supply of effective labour, which is viewed as a key resource in the economy. Hence, one element of the model is the focus on the effective are larger of labour supply, which is the physical amount of labour (e.g. number of employed people at any given time) augmented by their productivity level (e.g. depending on their health or skill). In a country *r*, output in sector *i* consists of goods and services Y_{ir}, that are produced by capital K_{ir}, other inputs N_{ijr} (e.g. intermediate inputs from sector *j*), and effective labour L_{ir} (i.e. a labour input adjusted for efficiency units). Thus, production is modelled as a function of $Y = F(K, N, L)$, where subscripts *i* and *r* are omitted for simplicity.

Figure A.1: The economic interaction between different agents in the economy



Similar to the method used by Taylor et al. (2014) and Hafner et al. (2016) in a different context for the study of AMR and sleep, for each time period *t*, the model assumes that effective labour supply is adjusted for efficiency units by $L_{r,t} = \bar{L}_{r,t} \cdot E_{r,t}$, with the physical supply of labour input $\bar{L}_{r,t}$, and efficiency of labour $E_{r,t}$.

In the model, the reduction in effective labour supply is manifested through **three** potential channels:

- **Increased mortality (child) –** Such health conditions as asthma or pneumonia are associated with an increased mortality risk for children. Potential deaths attributable to these conditions permanently reduce the population size, and the effect of increased mortality on economic output is a future decrease in the working-age population. This could have especially negative consequences in ageing societies, such as those in Europe.
- **Reduced labour productivity (caregiver) –** Prolonged periods of sickness of children temporarily reduce the country's workforce if parents have to stay at home and look after an ill child, with can manifest itself in higher levels of absenteeism and/or presenteeism.
- **Reduced labour productivity (adult) –** The scientific evidence suggests that such health conditions as asthma or atopic dermatitis acquired as a child will last with a certain probability also into adulthood, with potentially negative consequences for a person's work productivity, i.e. due to increased levels of health-related absenteeism and presenteeism.

In essence, in this economic analysis we compare how the economy of a country today (baseline) would evolve over time if the negative health factors associated with damp and mould, such as lower productivity and mortality, were to be removed completely (counterfactual scenario).

In a second analysis, we analyse the effects of improving ventilation rates in schools. The existing empirical evidence suggests that improving ventilation rates could increase, all else being equal, grades of students. Improved grades have a positive effect on individuals' earnings in the future. In our model, we capture this effect through increased labour productivity as an adult, as there is a high correlation between productivity and wages.

C.1.1. Model input data

The base underlying economic data used for the purpose of this analysis is from the Global Trade Analysis Project (GTAP) database. This database has been developed by the Center for Global Trade Analysis at Purdue University since 1993. Overall, GTAP covers 140 countries for 57 GTAP commodities and includes all bilateral trade patterns, production, consumption and intermediate inputs of commodities and services. We use the latest version, GTAP 9, which has a reference year of 2011. From the GTAP database, we extract a Social Accounting Matrix (SAM) for the specific countries and regions included in the analysis. The SAM is a complex table expressed in terms of incomes and expenditures, i.e. a double-entry accounting method. GTAP includes SAMs for individual countries, which are based on national accounts data (e.g. use-supply tables, input-output tables) and information from household survey data and trade data. Because of the sheer amount of work involved, GTAP collects and coordinates country SAMs from researchers across the world and cleans and standardizes the data. For the purpose of this analysis, we extracted the SAMs for all the EU-28 member states as well as for the United States of America and Canada and the rest of the world (RoW). In order to make the model tractable, we aggregate the different sectors into three industries: agriculture, manufacturing and services. The data for the underlying population data come from the United Nations' UN Population Database (2019). We divide a country's population into the working-age population and the non-working-age population, whereby the working-age population is defined as the part of the population between age 15 and age 65. Furthermore, we use data from the International Labour Organization on the distribution of educational attainment across countries to divide the working-age population further, into skilled and unskilled labour. The UN Population Database also provides the current mortality rates by age and gender, which we apply to calculate the counterfactual working-age population in the absence of damp-/mould-related mortality.

To calculate the excess deaths due to damp-/mould-related health conditions, such as asthma and pneumonia, we calculate the population attributable fraction (PAF) related to damp and mould in combination with information on deaths provided by the Global Burden of Disease (GBD) database.[52]

The share of children exposed to damp and mould is taken from the EU-SILC database.

We then use this information to predict the population of each of the countries included in the analysis into the future using a cohort component model. In essence, we base the growth of physical labour and its efficiency on demographic projections for a variety of possible future scenarios. We generate the demographic projections using input data from the UN[53] and an adapted version of Chapin's cohort-component model, which we implement as five-year projections using Stata.[54]

The cohort-component model starts with the current base population and is categorized for each country region by age, gender and skill level. The base population subsequently evolves by applying assumptions on mortality, fertility and migration. The outcome of the model is a projection of the population by (five-year) age, gender and skill groups up to 40 years, In essence, the cohort-component model characterizes population change according to a 'natural' increase (births minus deaths) and net-migration (in-migration less out-migration). More formally, the population by age cohort a and gender s at time t can be written as:

$$P(a,s,t_1) = P(a,s,t_o) + B(a,s) - D(a,s) + IM(a,s) - OM(a,s)$$

where *B(a,s)* represents the total births, *D(a,s)* total deaths and *IM(a,s)* and *OM(a,s)* represent inward and outward migration, respectively. The total births in a given period depends on the size of the population, the age structure and the age-specific fertility rates, which vary across countries. It is important to stress that we assume in our projections that fertility rates will follow in each country a similar trend within each country as they have during the last decade.

Similarly, the number of deaths in any given period depends on the population size, the age distribution and the age- and gender-specific mortality rates. We apply the abridged life tables

[52] See IHME (2019c).

[53] See United Nations (2019) for more information.

[54] See UC Berkeley (2019) for more information.

provided by the UN[55] to calculate age- and gender-specific probabilities of surviving from one age group to the next. Specifically, we draw on country-specific data for the demographic model input based on the initial population, net migration, age- and gender-specific fertility and mortality rates, as well as net-migration rates. Within these demographic projections, we define the potential working population as all individuals in the age range from 15 to 65. Furthermore, for each country, we divide the working population into high- and low-skilled according to their educational attainment.

To calculate the related efficiency units of labour (labour productivity) associated with health, we draw mainly on data collected from existing literature on the morbidity effects of asthma and other health issue associated with damp or mould. For instance, we know that a child suffering from asthma loses on average about 2.5 days from school, for which at least one of the parents most likely would have to take a day off work. Thus, in our model, labour efficiency is based on subtracting a number of days (normalized to a year) from the baseline yearly efficiency level; attributable lost days is for a combination of the adult workers and child population. Simply put, the yearly efficiency of a worker is:

$$E = 1 - Number\ of\ lost\ days\ normalised\ to\ a\ year$$

So, for instance, the efficiency unit E for a worker who loses 20 working days a year, based on 200 working days per year in total, is calculated as *(200−20)/200* or *1–(20/200).*

C.2. Parameter and distributional assumption on how to model the economic effects of improvements in ventilation rates across schools

In order to calculate the country cluster-specific adjustment parameter $\beta_c \in (0,1)$, we assume that the ventilation rates across European schools as provided in Table 1.1 follow a Pareto distribution and, with the adjustment parameter, can be written as follows:

$$\beta_c = F_c(x) = 1 - \left(\frac{x_{c,m}}{7.1 - \rho}\right)^{\alpha}$$

where $F_c(x)$ represents the cumulative Pareto distribution, $x_{c,m}$ represents the minimum level of ventilation rate in country cluster *c*, and ρ represents the modelled increase in ventilation rates for each sub-scenario, with $\rho \in [0.5, 3]$. For the analysis, we assume $\alpha = 1$. In other words, if, for instance, we model an increase in the ventilation rates across schools of 1 l/s per person, we assume that the percentage of students who lie on the interval of this distribution between $F_c(7.1)$ and $F_c(6.1)$ will not profit from better ventilation and have corresponding better grades or test scores.

[55] See United Nations (2019) for more information.

C.3. Analytical limitations

The application of a DCGE modelling framework to assess the different economic implications of a reduction in children's exposure to damp and the potential economic implications of improving ventilation rates in schools has several strengths, such as the ability to model the long-term economic benefits taking into account all potential spillovers on other agents in an economy that could occur from such changes. However, there are some limitations to the modelling approach taken.

First, the DCGE model applied for the economic analysis is not intended to provide an exact forecast of the economy at a given point in time in the future. The deterministic model does not take into account transitory (stochastic) short-term changes to the overall economic growth path. The aim of the applied modelling framework is to examine the effects of changes across different modelling parameters representing different scenarios and then compare how the economy of a country would evolve in the medium to long term in the counterfactual scenario compared with the baseline, holding all other factors constant. This is a simplification of how events would affect the economy in reality; however, it allows for the analysis of specific factors in isolation. So, for instance, the model inherently assumes that any transitory shocks to an economy, for instance, to take a recent example, shocks introduced by international trade wars, would affect the baseline and the counterfactual scenario in the same way. And as we calculate the difference between the counterfactual and the baseline scenario, the transitory effect of the trade war on the economy would cancel out in the difference.

Second, the scenarios examined within the economic modelling framework depend heavily on assumptions made on how, for instance, damp and mould or increased ventilation rates affect children's health and educational outcomes. We aimed, whenever possible, to use robust empirical evidence provided by the existing literature to support the modelling assumptions made. Where there was a lack of existing evidence, we aimed to apply conservative estimates on assumed parameters where possible. Furthermore, the assumptions made during the modelling of this study were made based on the best available evidence from the existing literature or additional economic modelling at the time of the analysis. In the future, it may be possible to amend some assumptions based on better empirical evidence that may emerge.

Finally, the modelling framework is based on a microfoundation of the underlying equations that determine the economic behaviour of the various economic agents. However, some of the microeconomic parameters are fixed and are hence invariant across different scenarios. Such fixed input parameters include, among others, different demand, substitution and income elasticities, as well as parameters relevant to the production technology, such as the relative importance of each of the production inputs. Potentially, any changes in the counterfactual scenario, such as making individuals healthier in the future, could change their economic behaviour. For instance, a healthier person may change their consumption behaviour and become more price sensitive to changes in prices for specific goods (e.g. healthy vs unhealthy foods). However, it is not straightforward to make an ultimate judgment call on whether these changes would really occur in the setting of reducing children's exposure to damp today, and hence we keep the underlying behavioural parameters fixed in the counterfactual scenarios.