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# Impacts of the Indoor Environment in Our Homes and Schools on Child Health

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## ABSTRACT

*Today, more than 26 million European children are living in unhealthy homes putting them at higher risk of experiencing health problems. Good air quality, sufficient access to daylight and adequate ventilation are important for creating a healthy indoor environment in any home, with the effects reaching far beyond childhood. Our research is based on analysis of the Eurostat microdata from the EU-wide survey "Income and Living Conditions in Europe" (EU-SILC). The results show that mould and dampness, as well as poor ventilation, can take a child from good health to poor health with links to higher levels of asthma, allergies, eczema, and lower and upper respiratory conditions. A growing number of children are burdened with ailments that challenge their ability to be present and fully engaged at school. Across Europe, the prevalence of children affected by asthma has become an increasing problem in the last few decades. It is not just childhood health that is affected by poor indoor climate. Unhealthy home environments can result in higher absence from school and work, putting a greater strain on both children, parents and the economy. Tackling the unhealthy homes in which a third of European children live and the many unhealthy schools and day-care centres they attend, is an opportunity to improve the health and quality of life of the most vulnerable Europeans. Furthermore, it is also an opportunity to improve societies, deliver on our energy and climate commitments and address inequalities, while saving money and valuable resources at the same time.*

## INTRODUCTION

Today, we know that our homes have a huge impact on our health and wellbeing. We live 90 % of our lives inside buildings; in our homes 2/3 of this time, with the remaining third spent in workplaces, schools, and other public spaces (WHO 2014). Within Europe, residential buildings cover about 75% of the building stock, with 60% of European households living in single-family homes and 40% in multi-family homes (Eurostat 2012). One of the challenges is Europe's old building stock. Many of Europe's buildings are energy inefficient, as well as in need for improvements, so that the residential building stock support residents' health and quality of life, which is emphasized by the UN Sustainable Development Goal (SDG) 3. The SDG 3 underlines the importance of ensuring good health and well-being. And 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

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- Light environment

Many, if not all of these aspects, are directly influenced by the condition and structure of buildings. For the purpose of this paper, we adopt the term indoor climate to cover all these aspects. According to the EU Statistics on Income and Living Conditions (EU-SILC) database, the housing inadequacies have a negative impact on the indoor climate and it have an effect on people's health of a significant number of EU citizens, including the children. And taking the health risks of unhealthy homes and schools seriously, by assessing the need for improvements to buildings across Europe, is essential to achieving both UN SDGs as well as WHOs initiatives. Furthermore, 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 (Ahrendt et al. 2016). This paper is based on a yearly initiative, funded by the VELUX Group, under the overall headline, the Healthy Homes Barometer. The Healthy Homes Barometer intends to investigate European citizens' health and well-being and the impact of the building's state.

## 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?
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 based on four distinct tasks, which partially build upon each other. For extended details of the analysis, ss well as the assessment model, our statistical analysis and macroeconomic model, see the complete report (RAND 2019).

**Table 1. Overview of the hazards covered by each study task**

| Hazard | REA | Multi-variate regression analysis (EU-SILC) | Estimation of health and educational burden | Macro-economic |
|---|---|---|---|---|
| Damp and mould | ✓ | ✓ | ✓ | ✓ |
| Indoor air pollution | ✓ | | | |
| Noise | ✓ | ✓ | | |
| Radiation | ✓ | | | |
| Excess cold | ✓ | ✓ | | |
| Lack of Daylight | ✓ | ✓ | | |
| Ventilation | | | | ✓ |

**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, by identifying quantified information with regard to attributable risks. Hence, it was also related to research questions 4 and 5. A REA is a systematic approach to searching literature (e.g. PubMed) 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, a REA constitutes a robust, systematic and replicable method providing a reliable indication of the evidence available in a particular domain. A total of 122 articles were taken forward for full-text extraction, but 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.

**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, provided by Eurostat, was identified as a data source that provides annual statistics at microdata (i.e. household) level. 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. 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. This analysis focus on the Health and Children's Health ad-hoc module (Eurostat 2019) 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. All EU-SILC data are self-reported. 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).

In order to determine the overall health burden related to specific diseases associated with poor indoor climate, we use data from the Global Burden of Disease (GBD) database. 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 (IHME 2019). 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). In order to examine the associations between poor indoor climate and the burden related to disease areas of child health, the educational burden and for the macroeconomic modelling, we extracted outcomes from the GBD dataset for the four health conditions that emerged from REA. We focussed 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.

**Regression analysis.** Using the EU-SILC microdata provided to us by Eurostat, we then carried out a multivariate regression analysis, the linear probability model (LPM) and ordinal logit models (OLM), as well as the general ordinal logit model (GOLM). 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, and results are statistical significance if $p<0.1$. The statistical analysis addres 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. For the vast majority of the statistical analyses conducted in relation to children, we have only crosssectional 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.

**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.

**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 multicountry 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.

## OUR HOMES AND ITS HEALTH EFFECTS ON CHILDREN

This section provides a short summary of the rapid evidence assessment (REA). 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.

In addition, it examines the associations between different indicators of poor indoor climate and corresponding health of European children based on EU-SILC data. For that purpose, we use the prevalence of poor indoor climate indicators of damp, noise, lack of daylight and the inability to keep the house adequately warm and self-reported child's health. We then investigate empirically the associations between poor indoor climate indicators and children's health and educational outcomes. Specifically, we analyse the following:

1) Rapid evidence assessment (REA)
2) 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.
3) The health burden on children associated with damp and mould, including the calculation of disability adjusted life years; and overall school days missed associated with damp and mould in residential buildings in Europe.

### Rapid evidence assessment (REA)

This section provides a summary 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. In-depth details of the REA are found in the RAND report (RAND 2019).

**Damp and mould.** 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.

**Indoor air pollution.** Multiple studies we reviewed explored the impact of indoor pollution on a range of health outcomes. Some types of indoor air pollution are linked to significant increases in poor respiratory health, as well as eczema and sleep disturbances. Children are more at risk of developing respiratory conditions appear to be more susceptible to these negative health impacts.

**Noise.** Noise exposure is significantly associated with annoyance, emotional problems, cognitive dysfunction, behaviour dysfunction and abnormal growth hormone release in children.

**Radiation (through radon).** 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.

**Excess cold.** Studies exploring the effects of excess indoor temperatures on children's health indicate mixed results.

**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.

**Indoor climate hazards on parents' economic outcomes.** 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.

**Indoor climate hazards on children's academic achievement.** 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.

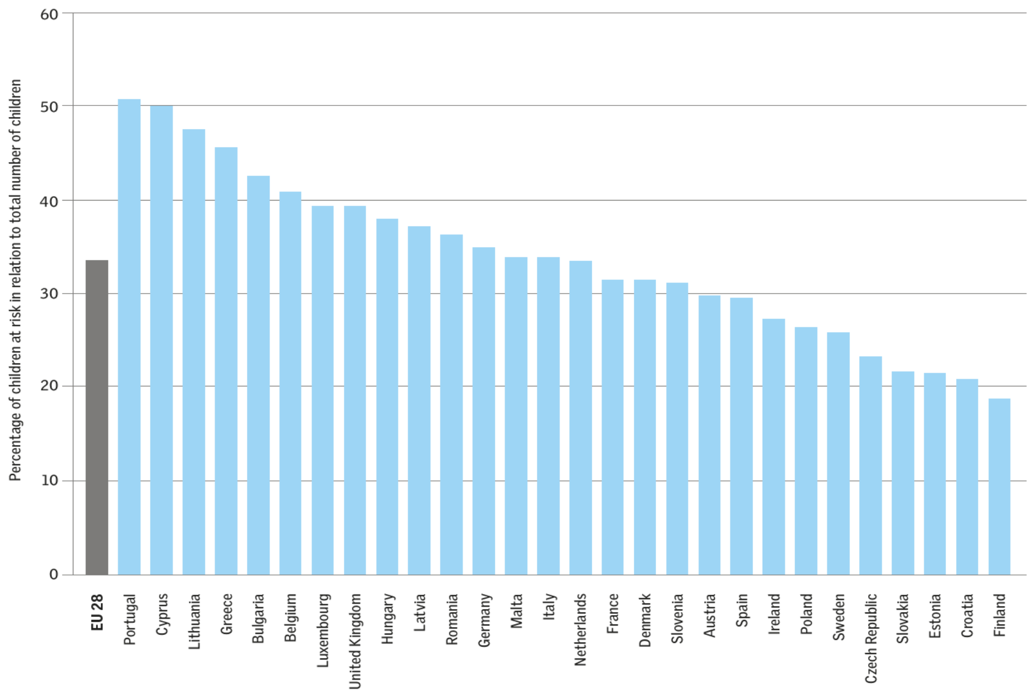


**Figure 1** The proportion, in percentage, of children across EU-28, exposed to at least one poor indoor climate. The entries in percentage are weighted with appropriate cross-sectional weights. Total number of children (N=78,608,010) is based on UN Population data.

## Association between building deficiencies and health

Living in unhealthy homes puts children indicator, the proportion of households affected, as well as the proportion of children in total affected, is reported by country for the year 2017. Overall, about 13% of EU households report issues with their dwellings of residence regarding leaking roofs, damp or rot in windows, which affects about 15% of all individuals aged 0 to 15 (which are labelled as children for the rest of this section). Also, about 13% report that their dwelling has not enough light and hence that it is too dark, which roughly affects about 5% of the children. A total of 18% of the households' report having issues with noise in the dwelling from neighbours or from outside, which affects about 17% of children. 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% of households report struggling to keep their dwelling adequately warm. This affects about 7% of children. Overall, for each indicator of poor indoor climate, there is considerable variation across the EU member states. Figure 1 show the total number of children, in percentage, 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. Further analysis 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, suggest that these indicators of poor indoor climate tend to be clustered together. 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.

The association between different indicators of poor indoor climate and children's health is reported on a scale from 1 ('bad') to 4 ('very good'). The overall health status of children as reported across the EU-28 member states have a 'very good' health status, with about one third reporting 'good' health. Only about 4.5% of children report only 'fair' or 'poor' health. The statistically factors associated with a child's health using ordered and generalized ordered logit regression models (as the dependent variable is based on an ordinal scale) suggest that, all else being equal, all four indicators of poor indoor climate are statistically significantly associated with a child's health status. The findings further suggest that a household's socio-economic status is positively associated with a child's health status(see table 2). Table 2 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 2 are based on OLM and GOLM (as the dependent variable is based on an ordinal scale). Note that in Table 2 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). A positive coefficient suggests that the explanatory variable increases the probability that the child reports a higher category of health. 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. 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. The analysis suggests 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% of all children or about 4.3% of children who have not reported a very good health status initially.

**Table 2. Associations between poor indoor climate indicators, household and individual characteristics and child health.**

| Estimation method | (1) OLM | (2) GOLM Poor-Fair | (3) GOLM Fair-Good | (4) GOLM Good-Very Good |
|---|---|---|---|---|
| (1) Leaking roofs, damp or rot | -0.1692 | -0.2501 | -0.0435 | -0.1507 |
| | (0.044)*** | (0.139)* | (0.119) | (0.045)*** |
| (2) Lack of light | -0.1297 | 0.0006 | 0,0309 | -0.1355 |
| | (0.072)* | (0.231) | (0,004)*** | (0.074)* |
| (3) Noise from indoors or outdoors | -0.1755 | -0.2840 | -0.4053 | -0.1485 |
| | (0.043)*** | (0.153)* | (0.075)*** | (0.043)*** |
| (4) Lack of ability to keep dwelling adequately warm | -0.2267 | -0.3768 | -0.5402 | -0.1951 |
| | (0.070)*** | (0.202)* | (0.118)*** | (0.071)*** |
| (Log) Household income | 0.1319 | 0.2458 | 0.1394 | 0.1507 |
| | (0.025)*** | (0.113)** | (0.065)** | (0.033)*** |
| Deprived | -0.3036 | -0.6971 | -0.2856 | -0.3050 |
| | (0.076)*** | (0.210)*** | (0.118)** | (0.078)*** |

**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.

Finally, using the coefficients from these regressions (Table 2), 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. The analysis suggests 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% of all children or about 4.3 % of children who have not reported a very good health status initially. There is variation across the different countries, ranging from 1.63 per cent of children without very good health status initially (Latvia) to 5.47 per cent (France).

## Association of health and educational burden associated with damp and mould

We have examined the potential healthy life years lost (e.g. DALY) in association with exposure to damp and mould associated with four disease areas (asthma, atopic dermatitis, lower and upper respiratory infections) based on GBD data. Today, about 10-15 percent of new cases of childhood asthma in Europe can be attributed to indoor exposure to dampness and mould. This exposure can be linked to healthy life lost. The analysis suggests that, across the EU-28 member states, exposure to dampness and mould has been associated with about 7,300 DALYs related to asthma, more than 14,600 DALYs related to atopic dermatitis, and more than 15,000 DALYs related to lower and upper respiratory infections combined. This results in more than 37,000 DALYs across the EU-28 member states and divided by the total number of incidences across the four disease areas, we find that damp and mould is associated with about 4.6 per cent of cases. 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.

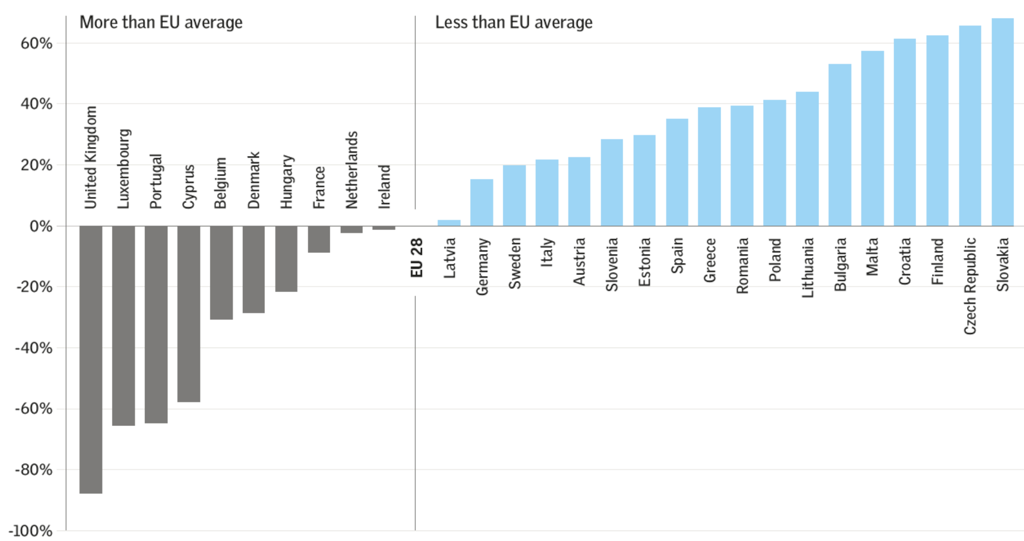


**Figure 2** Estimated missed school days, of total school days, due to burden of disease from estimated dampness in EU housing stock in school age children (asthma, atopic dermatitis, lower and upper respiratory infections). Variation in missed school days across the EU member states is shown by percentage difference from EU average.

In Europe, more than 65 million students and almost 4.5 million teachers spend between 170 and 190 days annually at school (European Commission (EACEA/Eurydice) 2018), and up to 70 percent of that time is spent inside the classroom. If we then consider how this will affect overall school days missed associated with dampness and mould in residential buildings. By using a population attributable fraction (PAF) of a risk factor of each of the diseases and the average number of school days (e.g. about 180 days on average) missed by disease area, we can estimate the total number of school days missed in 2017 associated with the exposure to damp and mould. Assuming that children suffering from asthma lose on average about 2.5 school days per year due to the illness (Ferrante and La Grutta 2018), children suffering from atopic dermatitis, about 4 school days (Filanovsky et al. 2016), and children suffering from upper and lower respiratory infections, about 1 school day (i.e. conservative assumption made by the authors). Estimating annually across the 28 EU member states suggest that 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. Overall, about 1.7 million school days are missed per year due to diseases associated with dampness and mould in residential buildings. On average, this means about 2.5 missed school days per sick child per year because of illnesses that frequently correlate with an unhealthy indoor climate alone in residential buildings.

## POTENTIAL ECONOMIC IMPLICATIONS ASSOCIATED WITH EXPOSURE TO POOR INDOOR CLIMATE AT HOME AND IN SCHOOLS

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).

In this section, 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. For further details about the macroeconomic model (RAND 2019). If 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, we can get an estimated cumulative economic gains by 2040 to 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. 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. These gains can also be estimated 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, the cost of making a dwelling damp-free is less than US$7,384 by 2060. 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.

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, Fisk (2017) concludes that there is relatively robust evidence on the associations between ventilation rates and student performance. Other studies have investigated the association between ventilation rates and academic performance of children. For instance, Haverinen-Shaughnessy and 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.

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 l/s person (incremental steps), 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 and 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. 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). A detailed description on the assumptions made for this analysis can be found in RAND, Finally, we translate improved test scores into increased life-time earnings using parameter estimates provided by Crawford and 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. 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. In cumulative terms, the overall economic benefit at EU-28 level from improving ventilation rates by 2.5 l/s per person 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.

## CONCLUSION

Our study has found that a significant proportion of children in the EU-28 are exposed to one or several indoor climate hazards. Exposure to each of these four housing deficiencies is correlated with a higher risk of certain health issues. 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. In 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. 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. 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.

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