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. Our study is based on the Eurostat microdata from the EU-wide survey "Income and Living Conditions in Europe" (EU-SILC). The overall objective looked 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:

- 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? How prevalent are problems related to non-optimal indoor climate in European homes?
- Which correlations can be observed between the prevalence of non-optimal indoor climate and the health status of affected children?
- What are 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?

The results show that mould and dampness, as well as poor ventilation, can take a child from good to poor health with links to higher levels of asthma, allergies, eczema, and lower and upper respiratory conditions. About 1.2 million European children, aged 0 to 15 years, are burdened with ailments, by self-reporting poor health, that challenge their ability to be present and/or fully engaged at school, resulting in an estimated 1.7 million missed school days. Across Europe, the prevalence of children affected by asthma has become an increasing problem in the last few decades. Unhealthy home environments can result in higher absence from school and work, putting a greater strain on both children, parents and the economy.

Tackling unhealthy homes, schools and day-care centres is an opportunity to improve the health and quality of life of European children. 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. It also points towards a key area for action: Europe's old building stock. Three-quarters of Europe's buildings are energy inefficient and responsible for about 40 % of Europe's energy consumption and CO_2 emissions (EU Commission 2019). European-wide energy renovations are a win-win for achieving climate neutrality while at the same time creating healthier and more sustainable buildings and boosting our economy post-COVID in the recovery plans. The recent Renovation Wave, the upcoming Fit for 55 Package and the rollout of (green) national recovery plans, represents a real opportunity to fundamentally transform the European building stock and help the EU achieve its climate and sustainability goals. National Long-term Renovation Strategies (LTRS) have to take a holistic approach towards buildings. The Energy Performance of Buildings Directive (EPBD) tasks the Member States with establishing such strategies to boost building renovations by setting clear targets and recommendations on energy efficiency as well as indoor air quality, comfort and health

– a process which has been significantly delayed by Member States and overall shown a lack of ambition. If properly implemented, the LTRS could offer a great, cost-efficient opportunity to achieve major improvements in health, comfort and energy efficiency.

This link between the energy efficiency agenda and a healthy indoor climate is clearly recognized in the recent European Parliament Report on Maximizing the energy efficiency potential of the EU building stock (2020/2070 (INI)) and is acknowledged several times in both the European Green Deal and the Renovation Wave Strategy, however, it is not yet reflected sufficiently in European legislation. The upcoming EPBD revision as part of the Fit for 55 Package and the implementation of the Renovation Wave Strategy is a unique opportunity to tackle these shortcomings.

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, ⅔ 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. Three-quarters of Europe's buildings are energy inefficient, as well as in need of improvements (EU Commission 2018, European Parliament 2016, BPIE 2017), 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. 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.

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, housing inadequacies have a negative impact on the indoor climate and consequently people's health, including children. Hence, to achieve both UN SDGs as well as WHOs guidelines, it is essential to take the health risks of unhealthy homes and schools seriously. 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 (Eurofund, 2012). Other studies (not included in this study), like the IEA Multiple Benefits of Energy Efficiency (2019) could inspire investment in energy efficiency and other benefits. 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 take a holistic approach to buildings, investigating European citizens' health and wellbeing and the impact of the buildings 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 are the health and educational burden of poor indoor climate?
5. What would be the economic benefits associated with reductions in children's exposure to poor indoor climate?

THE DESIGN OF THE STUDY

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 several 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 the 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, a REA constitutes a robust, systematic and replicable method providing a reliable indication of the evidence available in a particular domain (Petticrew & Roberts, 2006). 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 that were reviewed and had data extracted (see reference list in RAND 2018).

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 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. All EU-SILC data are self-reported.

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 2019a). 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). 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 statistically significant if $p<0.1$. Details on the statistical methods used in this study are described in appendix B of the report by RAND (2018). The statistical analysis address research question 3, to identify 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 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.

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 dampness 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 the 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 focuses 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.

Our homes and its health effects on children

This section 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. 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, including the calculation of disability-adjusted life years; and overall school days missed associated with damp and mould in residential buildings in Europe.

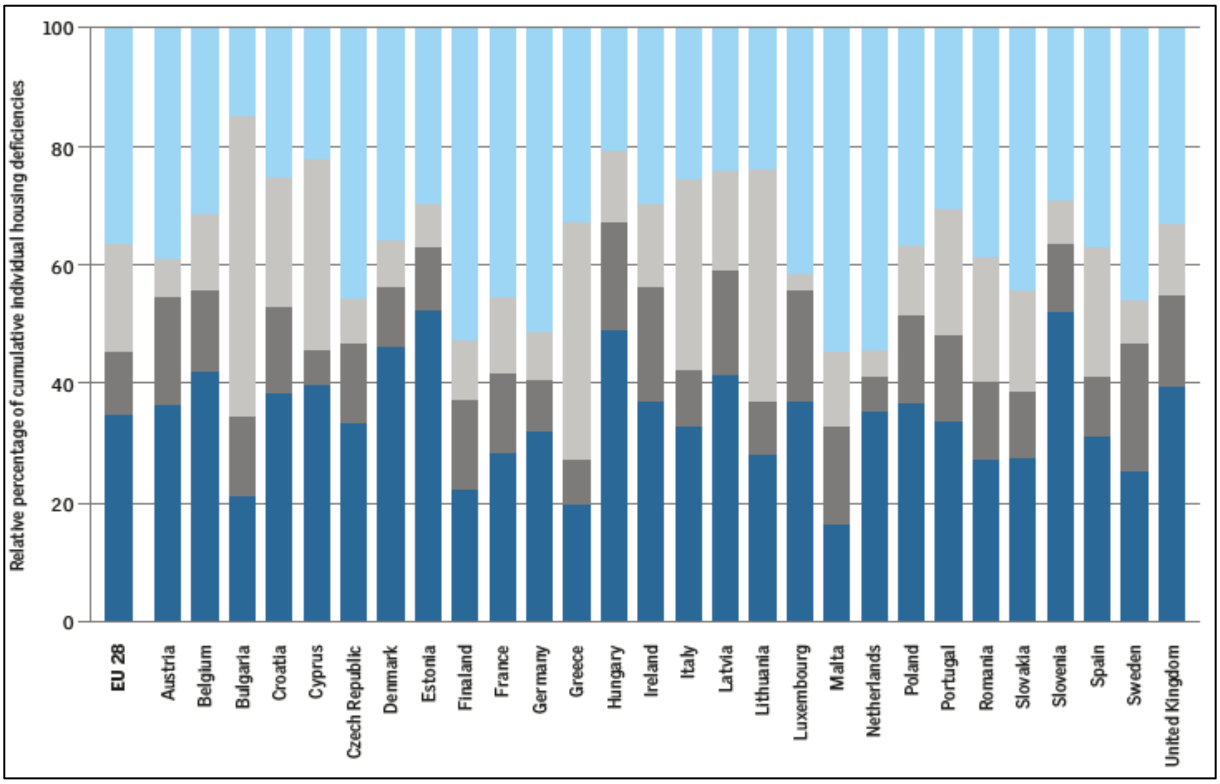

Figure 1. The building deficiencies and the distribution of dampness (■), darkness (■), cold temperatures (■) and excess noise (■), proportion, in percentage, of children across EU-28, exposed to at least one poor indoor climate. Note that these building deficiencies are not mutually exclusive. Dwellings with several deficiencies are therefore counted more than once.

ASSOCIATION BETWEEN BUILDING DEFICIENCIES AND HEALTH

This section associate the prevalence of the poor indoor climate indicators, reported in Figure 1, across the 28 EU member states and the associations between building deficiencies and children's health. The prevalence of these indicators is reported by leaking roofs, damp walls/foundations or rot in windows, as well as a lack of light, excess noise and temperatures across the EU member states, based on EU-SILC data, but, there is considerable variation across EU member states. 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. For instance, the proportion of children affected by leaking roofs, damp and rot is substantially above the 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. About children living in households reporting not enough daylight, countries with substantially above EU average proportions are Bulgaria, Hungary, Latvia, Luxembourg, Portugal, and the United Kingdom. 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 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. 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. The countries with below EU average proportion of households struggling to keep the dwelling adequately warm are Bulgaria, Cyprus, Greece, Lithuania, Portugal, and Italy. The countries above the EU average proportion are Austria, Czechia, Denmark, Estonia, Finland, France, the Netherlands and Slovenia.

Overall, for each indicator of poor indoor climate, there is considerable variation across the EU member states. Figure 1 shows the total number of children, in percentage, by the country that is 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 (see Table 1) 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.

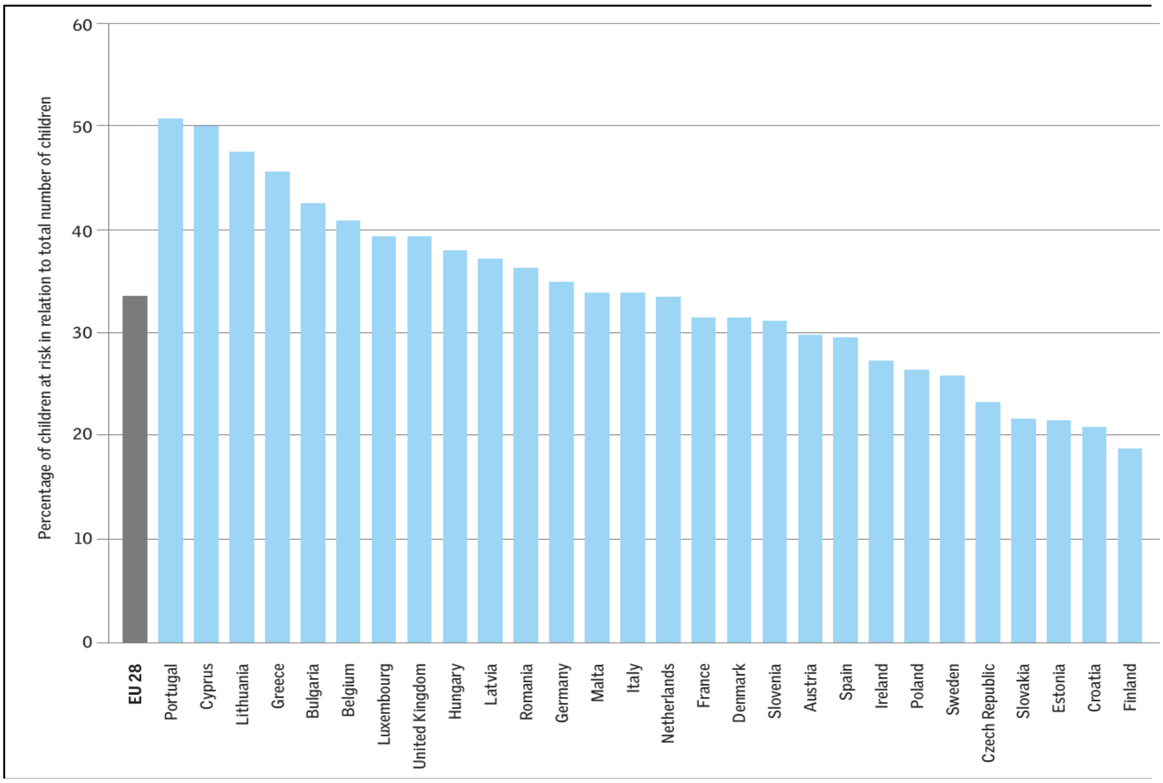

Figure 2. The proportion, in percentage, of children across EU-28, exposed to at least one poor indoor climate. In absolute numbers, the EU28 is 26,298,078 children which are equal to 33.5 %. The entries in percentage are weighted with appropriate cross-sectional weights. The total number of children (N=78,608,010) is based on UN Population data.

Table 1. Household and dwelling characteristics associated with leaking roofs, dampness, rot; lack of light, noise and inability to keep adequately warm across EU-28.

Variable	(1) Leaking roofs, damp or rot	(2) Lack of light	(3) Noise from indoors or outdoors	(4) Lack of ability to keep dwelling adequately warm	(5) At least 1
(1) Leaking roofs, damp or rot		0.1135 (0.010)***	0.0452 (0.004)***	0.1124 (0.007)***	
(2) Lack of light	0.2454 (0.023)***		0.0309 (0.004)***	0.1275 (0.005)***	
(3) Noise from indoors or outdoors	0.0901 (0.011)***	0.0285 (0.005)***		0.0292 (0.005)***	
(4) Lack of ability to keep dwelling adequately warm	0.0887 (0.006)***	0.0466 (0.005)***	0.0116 (0.002)***		
Single family	0.0516 (0.008)***	0.0028 (0.0003)	0.0121 (0.004)**	-0.0766 (0.008)***	0.0163 (0.0009)*
HHI: 2nd quintile	-0.0067 (0.004)*	-0.0074 (0.001)***	-0.0129 (0.003)***	0.0022 (0.003)	-0.0161 (0.003)***
HHI: 3rd quintile	-0.0111 (0.005)**	-0.0131 (0.002)***	-0.0196 (0.004)***	0.0015 (0.006)	-0.0298 (0.005)***
HHI: 4th quintile	-0.0235 (0.005)***	-0.0145 (0.002)***	-0.0281 (0.005)***	-0.0056 (0.007)	-0.0552 (0.004)***
HHI: 5th quintile	-0.0351 (0.005)***	-0.0178 (0.002)***	-0.0387 (0.006)***	-0.0110 (0.008)	-0.0631 (0.006)***
Observations R-squared	3,551,728 0.2290	3,551,728 0.1896	3,551,728 0.4447	3,551,728 0.1927	3,562,013 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 the year and country fixed effects, as well as to person-level variables from the household head, including the highest level of education, gender and age. HHI = Household Income.*

Table 2. 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
(1) Leaking roofs, damp or rot	-0.1692 (0.044)***	-0.2501 (0.139)*	-0.0435 (0.119)	-0.1507 (0.045)***
(2) Lack of light	-0.1297 (0.072)*	0.0006 (0.231)	0,0309 (0,004)***	-0.1355 (0.074)*
(3) Noise from indoors or outdoors	-0.1755 (0.043)***	-0.2840 (0.153)*	-0.4053 (0.075)***	-0.1485 (0.043)***
(4) Lack of ability to keep dwelling adequately warm	-0.2267 (0.070)***	-0.3768 (0.202)*	-0.5402 (0.118)***	-0.1951 (0.071)***
(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)***

*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 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 statistical 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 (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. The findings further suggest that a household's socioeconomic 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.

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 % of children without very good health status initially (Latvia) to 5.47 % (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 % of new cases of childhood asthma in Europe can be attributed to indoor exposure to dampness and mould (WHO Europe 2011). 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 % 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.

In Europe, more than 65 million students and almost 4.5 million teachers spend between 170 and 190 days annually at school (see European Commission, 2018 for member state-specific distribution of annual school day "The Organisation of School Time in Europe. Primary and General Secondary Education – 2018/19), and up to 70 % 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 & 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 dampness. 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

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, see the RAND report (RAND, 2018). 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 gain 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 dampness 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,

Table 3. The burden of disease from indoor damp exposure in school-age children (asthma, atopic dermatitis, lower and upper respiratory infections), estimated DALYs total and missed school days.

	(1) Asthma	(2) Atopic dermatitis	(3) Lower Respiratory infections	(4) Upper Respiratory infections	Sum (1) to (4)	Total Incidence (%)
DALY, EU 28	7,284	14,604	7,710	7,980	37,578	4.6
Missed School days, EU 28	365,453	1,075,907	2,507	255,714	1,699,580	0.014

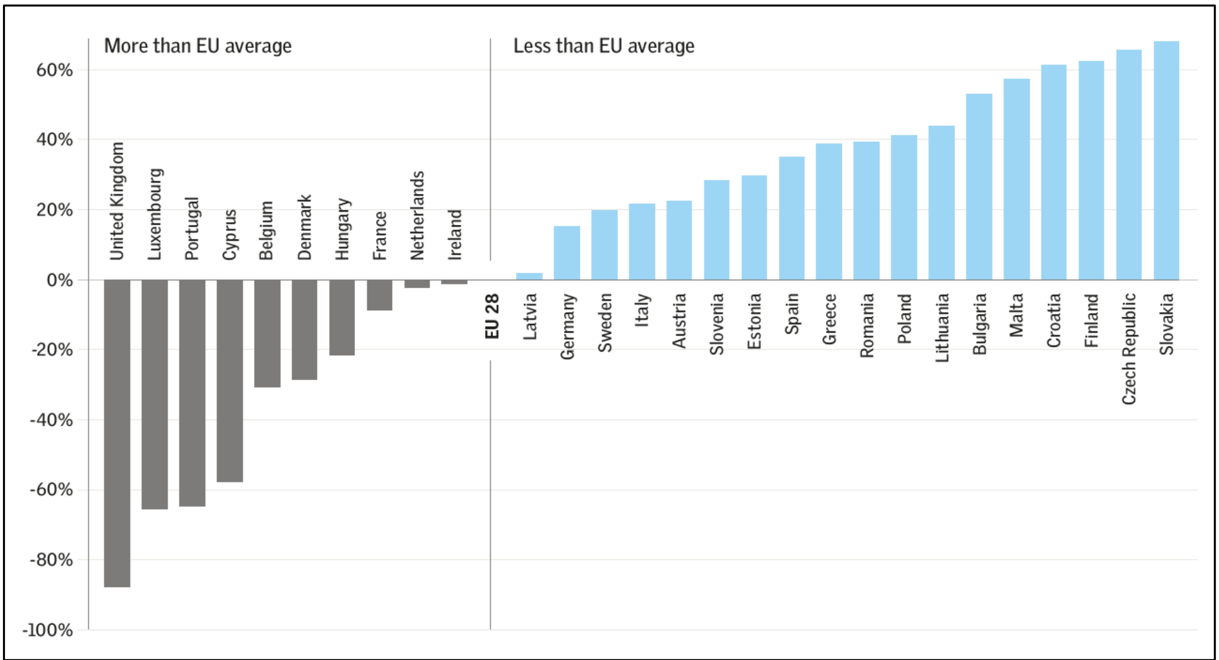

Figure 3. Estimated missed school days, of total school days, due to burden of disease from estimated dampness in EU housing stock in school-age children (asthma, atopic dermatitis, lower and upper respiratory infections). Variation in missed school days across the EU member states is shown by percentage difference from the EU average.

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 the 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 the 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 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 & 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 % and reading scores by about 0.15 %. 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 of the assumptions made for this analysis can be found in RAND, Finally, we translate improved test scores into increased lifetime 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 % 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 % 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 EU28 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.

Discussion

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 % 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 considered by a wide variety of stakeholders. First, these findings have important implications for house owners, tenants and landlords but also public authorities. The good condition of dwellings should not only be seen as an issue of comfort but as an essential basic requirement for the good health of the residents. Second, all kinds of private sector agents, in particular in the construction, renovation and property management domains, should 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 policymakers and public authorities to take action. 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 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. To support tenants living in not well-maintained apartments, legal obligations for landlords and/or building managers may be required as well as split incentive barriers overcome.

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 policymakers 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. The focus in the Renovation Wave on using the public buildings sector, including schools as a role model and reference point to scale up renovations is an important starting point. This ambition also has to be reflected in the upcoming revision of the

Energy Efficiency Directive (EED) and EPBD. For example, the depth and scope of Article 5 in the EED should be widened to cover all buildings serving the public's interest and public buildings beyond central government buildings, i.e. at a regional and local level. As part of the EPBD revision, a stronger focus on minimum requirements for Indoor Environmental Quality (IEQ) should be introduced to address health and comfort aspects to reflect the EU's ambition to move towards a sustainable building stock, as indicated in the Renovation Wave. The recent European Parliament Report on Maximising the energy efficiency potential of the EU building stock (2020/2070(INI)) also clearly articulates the link between the energy efficiency agenda and a healthy indoor climate, demanding a holistic approach towards buildings and renovation policies to ensure energy-efficient, healthy, affordable and sustainable buildings.

We acknowledge several limitations to our study presented, and we recommend that additional studies focusing on energy efficiency measures and how multiple benefits should gain attention to expand the perspective of energy efficiency beyond the traditional measures of reduced energy demand and lower greenhouse gas (GHG) emissions by identifying and measuring its impacts across many different spheres (IEA 2019). Although the present investigation is necessary to highlight an indication to improve existing building stocks and our school buildings, we also recognize the importance to consider studies on a smaller scale. One important topic is to ensure a better indoor environment in our schools. As we have highlighted indications towards good recommendations to higher ventilation rates and the health benefits of school children, we also recommend additional investigations is needed to explore ventilation improvements and energy efficiency, so we still meet the intended targets for reduced overall energy demands. Depending on the ventilation system and school building strategy, an energy-neutral ventilation concept combining both mechanical and natural sensor-driven systems could be recommended to meet future requirements for CO_2 levels, energy demands and resilient solutions towards climate change and eventually new pandemics. Another important task is clear national ambitions and targets for our existing building stock. Renovation requirements must focus on multiple benefits for homeowners, like the quality of a better indoor environment, both with focus on energy savings, as well as a more holistic approach, which includes the benefits with improved daylight conditions, higher indoor comfort etc. when our existing building stock undergo major renovations.

Conclusion

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 % 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. Exposure to several of the other hazards we looked at is also high. For example, 17 % of children are exposed to significant levels of noise. Exposure to lack of daylight and excess cold is below 10 % for Europe as a whole, but nonetheless worryingly high in individual countries. Overall, 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 dampness 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 dampness 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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