Housing Quality and Health Inequalities:

the case of home thermal efficiency in London

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Statement of Originality

I hereby declare that the work in this thesis is my own original research and that I have appropriately cited any work that is not my own.

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Abstract

Home thermal efficiency is a key component of housing quality that is increasingly put under pressure by global environmental challenges such as climate change. Thus, it is important to characterise home thermal efficiency at the city-level using epidemiological evidence to develop evidence-based housing policy. The overall aim of my MPhil is to develop a home thermal efficiency metric and estimate its associations with health, at the small-area level in London (i.e., Lower Super Output Area (LSOA)).

No single agreed-upon definition of housing quality exists. In the first part of this thesis, I summarised housing quality literature and tools to identify recurring themes. Using this insight, I developed a housing quality and health framework which is composed of 13 housing domains, meta-characteristics and interacting factors. In the second half of this thesis, I conducted a case study based on one housing quality domain, i.e., thermal comfort, in London. I first developed a mean LSOA home thermal efficiency metric using the Battese-Harter-Fuller model and then estimated the association between this metric and selected health outcomes.

My framework allows cities to comprehensively understand areas of housing quality that are relevant for their populations and also identify appropriate data sources to measure housing quality. The development of the thermal efficiency metric highlighted that mean thermal efficiency score is higher (i.e., better) in LSOAs near central London and generally decreases with distance from the city centre. Overall, there was an increased risk for all hospital admissions, all cardiovascular admissions, and all respiratory admissions with decreasing LSOA home thermal efficiency scores. Similar but weaker associations were observed when adjusting for income instead of smoking.

My thesis highlights the need for robust and accessible housing quality data, as well as the importance of taking health outcomes into consideration when building, renovating and retrofitting homes.

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1 Introduction

In the mid-1800s, Florence Nightingale stated that "the connection between the health and the dwelling of the population is one of the most important that exists" (Kopf, 1916). The Universal Declaration of Human Rights postulates that housing is a fundamental human need and a basic human right (Office of the United Nations High Commissioner for Human Rights/UN-Habitat, 2009). International organizations, including the United Nations, national and local governments, as well as urban planners and architects, have long recognised the importance of housing for human well-being, for example, as part of the Sustainable Development Goals. Globally, challenges posed by high and rising cost of housing, insufficient and inadequate housing stock, and weakened neighbourhood resilience and sustainability are escalating due to increased urbanisation, climate change and changing population demographics.

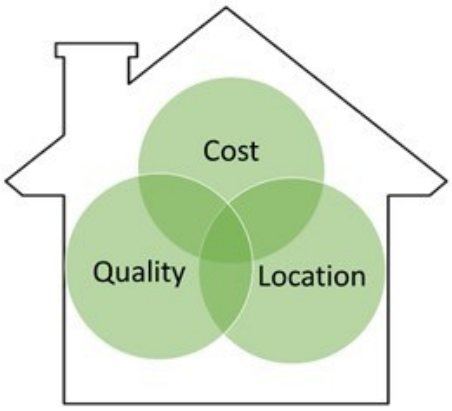


Figure 1.1. Components of housing

The impacts of housing, which encompasses cost/affordability, neighbourhood/location, and quality (Figure 1.1), on health are wide-ranging. The cost of housing, for example, determines what residual household income remains for other health-relevant needs such as food, transportation, and utilisation of medical services (Pollack et al., 2010, Bentley et al., 2011, Meltzer and Schwartz, 2015). Literature reviews have shown that experiencing foreclosure (Tsai, 2015, Downing, 2016) and lack of housing stability (Vasquez-Vera et al., 2017) are associated with both poor physical and mental health.

The neighbourhood and community surrounding a home also affect residents' health, both positively and negatively (Bird et al., 2018, Gibson et al., 2011, Diez Roux and Mair, 2010). Empirical evidence links ambient noise and air pollution to increased risk of cardiovascular disease (CVD) (Pershagen, 2017, Lee, 2014), raised blood pressure (Stansfeld and Matheson, 2003) and pregnancy complications (Yorifuji et al., 2015); availability of greenspace has been shown to improve health outcomes (Twohig-Bennett and Jones, 2018), including a reduction in CVD-related mortality (Gascon et al., 2016); and perceived neighbourhood safety has been suggested to be associated with psychological wellbeing and mental health (Berglund et al., 2017, Lorenc et al., 2013). It is also important to note that the availability of and distance to healthcare facilities near a home may impact health outcomes as individuals may be less likely to seek care if healthcare facilities are not available or accessible.

Housing quality has been determined to be a key socio-economic determinant of health (Philippa Howden-Chapman and Penelope Carroll, Housing & health : research, policy and innovation, World Health Organization, 2018) due to its role in improving or deteriorating the physical and mental health and wellbeing of its residents (Shaw, 2004, Swope and Hernandez, 2019, Palacios et al., 2020, D'Alessandro and Appolloni, 2020). The association between housing quality and health is complex but well established (Rolfe et al., 2020, Holding et al., 2020, Swope and Hernandez, 2019, Palacios et al., 2020, D'Alessandro and Appolloni, 2020, Philippa Howden-Chapman and Penelope Carroll, 2004, World Health Organization, 2018, Krieger and Higgins, 2002, Natalie Slopen et al., 2018, Gibson et al., 2011, Ferguson et al., 2013, Shaw, 2004, Bonnefoy, 2007, World Health Organization Europe, 2011).

Links between specific aspects of housing quality and specific health outcomes vary widely and include the impact of structural disrepair on injuries (Rolfe et al., 2020, Holding et al., 2020, Swope and Hernandez, 2019, Palacios et al., 2020, D'Alessandro and Appolloni, 2020); lead exposure on child development (Canfield RL, 2005); indoor temperature on mortality (Keall et al., 2008, Phelan KJ, 2005, DiGuiseppi et al., 2010); indoor air pollution on children's respiratory health (Padhi and Padhy, 2008, Smith et al., 2000) and high blood pressure/hypertension (Aylin et al., 2000, Wilkinson, 2001, Madrigano et al., 2013). Additionally, crowding (Padhi and Padhy, 2008, Smith et al., 2000); temperature (Walker et al., 2009), mould/dampness (Zock et al., 2002), biofuel use (Torres-Duque et al., 2008, Bruce et al., 2015) and second-hand smoke exposure (Dayal HH; Khuder, 1994 , Öberg et al., 2011) have all been associated with a range of respiratory conditions. According to the World Health Organization (WHO), the health burden attributable to inadequate housing is significant (World Health Organization, 2018). For instance, it is estimated that 15% of asthma deaths are attributable to damp conditions in the home (World Health Organization Europe, 2011).The WHO Large Analysis and Review of European housing and health Status (LARES) project affirmed housing-health links without prior strong evidence to inform an upcoming Environment and Health Ministerial Conference (Bonnefoy et al., 2003). LARES was conducted in eight European cities from 2002 to 2003 and collected housing data on variables such as thermal comfort, noise, infestations, lighting, indoor air quality, dampness and mould, access to water, sanitation and hygiene (WASH) equipment, green and play spaces, and accessibility for those with limited mobility. LARES found associations between these housing conditions and an array of health outcomes including: respiratory conditions (asthma, allergies, etc.), mental health (anxiety, depression, etc.), sleep disturbance, injuries and self-reported health status (WHO Regional Office for Europe, 2007).

1.1 Rationale

Despite the strong evidence for the association between housing quality and health outcomes, public health evidence is rarely incorporated into housing policy (Carmichael et al., 2020). Most existing studies linking housing quality to health measure specific housing quality-related exposures in a small number of individual homes (e.g., measurements of lead or mould concentrations in a home). This is costly and time-consuming to conduct at large-scale over an extended period of time. Additionally, there is a disconnect between the existing research and policy makers. Often, housing-related polices are informed by urban planners, building regulators or architects (Bonnefoy, 2007) and not the public health evidence.

To inform housing policy and improve housing quality effectively, housing quality needs to be characterised at a granular level across cities. Thus, there is a need to integrate epidemiological knowledge to conceptually define the association between housing quality and health and then develop a metric to measure housing quality and estimate associations with health outcomes and investigate health inequalities at the small-area level in a city. Such findings can provide a strong basis for developing strategic housing policy that incorporates public health evidence (Moore et al., 2003, Galea and Vlahov, 2005).

This thesis uses a case study to develop a metric for a housing quality domain at the granular level for a single city: home thermal efficiency in the city of London. Home thermal efficiency is a key component of the thermal comfort domain of housing quality that is increasingly put under pressure by global environmental challenges such as climate change as well as rising living costs. Both hot and cold temperatures in the home impact health. Low indoor temperatures and related housing interventions (e.g., retrofitting in homes with inadequate warmth) have been associated increased risk of cardiovascular and respiratory conditions, depression, mortality in infants and increased hospital admissions (Ormandy and Ezratty, 2012, World Health Organization, 2018, World Health Organization Europe, 2011). High indoor temperatures have been associated with heatstroke, dehydration, hyperthermia, and mortality (Ormandy and Ezratty, 2012, World Health Organization, 2018, World Health Organization Europe, 2011), as well as respiratory health (Sun et al., 2021), diabetes management and schizophrenia and dementia symptoms (Tham et al., 2020).

As the global capital of the world that features diverse demographic, socioeconomic, and environmental conditions that shape the experiences of its residents, London is an ideal geography to explore the associations between home thermal efficiency and health outcomes. Additionally, London's current

housing crisis reflects challenges unique to its residents but also shared with similar cities including an ever-evolving urban fabric (i.e., rising population coupled with changing demographics), climate change and economic hardship – all which affect housing.

1.2 Aims and objectives

The overall aim of my MPhil is to develop a metric to measure the home thermal efficiency housing quality domain and estimate its associations with health, at the small-area level in London.
In order to achieve this aim, I have been:

1. Reviewing housing quality literature and assessment tools to provide a detailed underpinning of the existing research and evidence base;
2. Developing a conceptual framework which links housing quality domains via specific indicators to health outcomes;
3. Identifying and integrating data sources on housing quality indicators to quantify home thermal efficiency;
4. Developing a metric to measure and map home thermal efficiency at the small-area level in London using data from Objective 3; and
5. Conducting a Bayesian small-area analysis, using R-INLA, to estimate associations between home thermal efficiency and relevant health outcomes and assess how these differ across the socioeconomic spectrum.

1.3 Thesis structure

The structure of this MPhil thesis is outlined below.

- Chapter 2 presents a review of the literature on housing quality definitions, frameworks, and assessment tools in order to understand the current state of knowledge in this area and lay the foundation for the thesis. This chapter also presents an overview of the London context, including its demography and housing stock, to set the scene for the case study.

- Chapter 3 discusses the development of a conceptual framework visualising the complex relationship between housing quality and health. Based on this framework, I provide an in-depth introduction to the identified 13 housing quality domains.
- Chapter 4 provides an overview of different potential data sources to characterise home thermal efficiency in London. The key data source, Energy Performance Certificates (EPCs), is discussed in detail.
- Chapter 5 outlines the development of a home thermal efficiency metric for London at the small-area level.
- Chapter 6 presents the findings of a small area health analysis on home thermal efficiency and selected health outcomes.
- Chapter 7 summarises my findings and discusses implications of their public health implications as well as areas of future work.

2 Background

In this chapter, I present my scoping review of quality definitions, as well as an overview of existing housing quality (and health) frameworks and assessment tools. These three sections highlight the existing evidence and gaps in the current literature relating to how housing quality is defined and characterised. In the final section of this chapter, I present an overview of the London context, including its demography and housing stock, to set the scene for the case study.

2.1 Defining housing quality

In 1966, the WHO stated that it is "necessary to develop a methodology to evaluate the hygienic quality of dwellings and their environment" for multiple reasons, including evaluating the effect of housing on the health of the population (World Health Organization, 1967). Yet, there is still no agreed-upon single definition of housing quality (Aliu and Adebayo, 2012, Bonnefoy, 2007, Asian Development Bank (ADB), 2019), especially in relation to health (Nriagu et al., 2011).

Housing quality is influenced by factors related to the location of the home, the physical building, and its residents (Adamkiewicz et al., 2014, Brkanić, 2017) and, as such, is multidimensional (John F. Kain and Quigley, 1970, Sandra Newman and Holupka, 2018, Sinha et al., 2017, Bonnefoy, 2007, Mandic and Cirman, 2011, Adair et al., 2014). Various conceptualisations of housing quality exist, though they are heterogenous with respect to the dimensions of housing quality that are included (Nightingale, 1860, Le et al., 2016, Mandic and Cirman, 2011, Clair et al., 2018, Gary W. Evans et al., 2001, Statistics New Zealand, 2015, Eurofound, 2016, Gary W. Evans, 2003, Hick et al., 2022).

The durability of the internal and external structure of the home, as well as the safety and security of the internal environment, are very frequently considered dimensions of housing quality (Statistics New Zealand, 2015, Aliu and Adebayo, 2012). Broader definitions sometimes also include other relevant dimensions (Hick et al., 2022), such as residents' satisfaction with housing (Brkanić, 2017), neighbourhood features and housing affordability (Eurofound, 2016, Gary W. Evans, 2003). Bonnefoy (2007) defines a healthy home as one that protects privacy, contributes to physical and psychological well-being, and supports the development and social integration of its inhabitants – in line with the UN definition of an adequate home (Office of the United Nations High Commissioner for Human Rights, 2009). The Asian Development Bank outlined that basic criteria for an adequate home, irrespective of different contexts, are: a finished roof, sufficient living space (i.e., not more than 3 residents in a bedroom), access to clean

water, and improved sanitation (i.e., flush toilet or ventilated pit latrine for one or two households) (Asian Development Bank (ADB), 2019). These definitions, nonetheless, are not comprehensive, especially from a public health lens. Additionally, housing quality definitions may be tailored to the study's outcome of interest. For instance, Evans (2001) explored the relationship between housing quality and children's socioemotional health, and thus included children's resources as one of the six subscales in his definition of housing quality. Nonetheless, to keep housing quality definitions generalizable and applicable to different settings, it has been suggested that the focus should be on the dwelling itself and not its residents (Adair et al., 2014) or their behaviours.

2.1.1 Scoping review

2.1.1.1 Methodology

I conducted a scoping review to identify definitions of housing quality used in the literature and how these definitions have been conceptualised. I searched MEDLINE, Embase, and grey literature from inception to 19 February 2023 using a search strategy compromised of keywords relating to housing quality (e.g., healthy housing, housing deprivation, housing conditions), terms for a definition or framework (e.g., index, guideline), and health/wellbeing. Full search strategy is presented in Appendix 9-1. I excluded studies that focused on neighbourhood or area-level factors, those that exclusively focused on vulnerable populations (e.g., refugees) and settings (e.g., slums/informal settlements, care/nursing homes) or temporary housing (e.g., student accommodation), as well as homes altered for caregiving purposes. Additionally, studies on homelessness (or severe housing deprivation (Hick et al., 2022)) were excluded as homelessness is beyond the scope of my project. Conference abstracts, editorials and studies not available in the English language were also excluded.

Studies underwent two phases of screening for eligibility based on the above criteria: (1) title and abstract and (2) full text. Once eligible publications were identified, I extracted information on characteristics of the study (author, year, and sample size, where available), the study's definition of housing quality and, where available, health outcomes (including measurement) using a customized data collection form.

To summarise and synthesise the extracted information, I developed housing quality domains based on the components included in the definitions of housing quality found across the studies. Where components overlapped (e.g., presence of cracks in floor or wall or ceiling/roof) or were closely related to one another (e.g., high indoor temperature, low indoor temperature and thermal comfort; or presence of different hazardous chemicals such as lead, asbestos and radon), they were collapsed into one domain.

2.1.1.2 Study characteristics

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram depicts the scoping review process (Figure 2.1). My review initially yielded 12,680 potentially relevant studies, of which 12,278 remained once duplicates were removed. The title and abstract screening found 12,040 studies that did not match in inclusion criteria and were consequently excluded. Of the 238 studies that underwent the full-text screening, 39 studies were eligible for inclusion in the review. Characteristics of the studies are discussed below, and a detailed table is provided in Appendix 9-2.

The number of households included in a given study ranged from 49 to 88,159 individuals (excluding multinational country-level studies). Three studies included countries globally. Twenty-four studies were from high-income countries: the USA (n=12), Canda (n=3), New Zealand (n=2), Sweden (n=2), Ireland (n=1), South Korea (n=1), Croatia (n=1), Finland (n=1), and one study on the UK and New Zealand. Low-and-middle income countries represented in the included studies are South Africa (n=2), Nigeria (n=2), Brazil (n=1), Columbia (n=1), India (n=1), Vietnam (n=1), and Uganda (n=1), as well as two studies that focused on multiple African countries (Iddi et al., 2022, Gao et al., 2021).

The number of components included in the definition of housing quality in a given study ranged from 5 to 67 components. In most studies, the components are derived from existing research or available data, although in some cases components were obtained from other sources such as the Ministry of Health (Pierse et al., 2020) or screening tools (Garg et al., 2022).

Where available, studies explored associations between housing quality and a range of health outcomes including general wellbeing, respiratory conditions, lead poisoning, child development, sleep health, mental health (anxiety, depression), and mortality. Some of the included studies, however, were reports specifically on housing quality or were studies that aimed to develop a housing quality measure for the specific population of interest, in light of the associations between housing quality and health (i.e., did not measure associations with health outcomes).

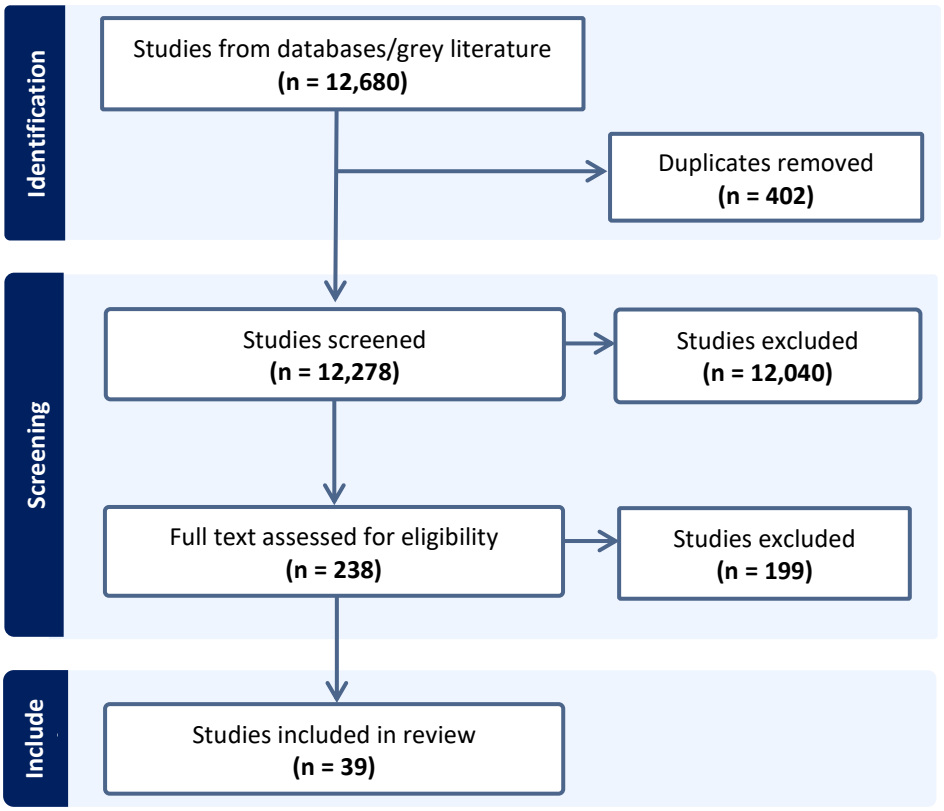


Figure 2.1. PRISMA flow diagram

2.1.1.3 Domains from housing quality definitions

Among the included studies, I identified the following 25 distinct domains of housing quality:

- accessibility (i.e., improvements for disabled or elderly populations)
- presence of assets (e.g., refrigerator, television, vehicle, etc.)
- children's resources (e.g., play area)
- cleanliness/presence of clutter
- communication/connectivity
- construction material
- state of floor, walls, and/or ceiling/roof
- storage place for food, kitchen utilities, etc.
- electricity and/or fuel
- hazardous chemicals (including radon, lead, asbestos and pesticides)
- greenery
- indoor air quality
- injury hazards (including fire safety)
- light (natural and artificial)
- crowding
- dampness and mould
- noise
- pests
- privacy
- security and safety
- structure
- thermal conditions
- ventilation and insulation
- water, sanitation and hygiene (WASH)
- waste management
- windows

Figure 2.2 summarises the frequencies of the different housing quality domains across the studies in this review. A more detailed table is available in Appendix 9-3.

No study included components from all domains. On average, studies accounted for 6 domains, ranging from 3 domains (n=7) to 14 domains (n=1) (Brkanić, 2017).

The most frequent domain was WASH (n=25). The domain encompassed a number of components including source/supply (Le et al., 2016), content (Frisk et al., 2009) drinkability (Cheung and Mui, 2022) of water, presence (Naess et al., 2005, Boch et al., 2021), design and type of toilet (De Vries et al., 2018, Orjiakor et al., 2023, Dias and de Oliveira, 2018), interior (Brkanić, 2017) or state of toilet facility (Herrin et al., 2013), and drainage system (Turunen et al., 2017, Johnson et al., 2005, Troxel et al., 2020), or some combination of these (Adair et al., 2014, Gao et al., 2021, Keall et al., 2010, Kobayashi et al., 2022, Luiz et al., 2009, Nolan and Winston, 2011, World Health Organization, 1967, World Health Organization, 2018, Iddi et al., 2022, Aliu and Adebayo, 2012). Some studies grouped these into a single component, such as "inadequate water and sanitation" (Chu et al., 2022, Seo and Park, 2021). The number and diversity of the components commonly used to define and/or measure WASH in different settings is one explanation for why this domain was the most frequent.

Domains with the second highest frequencies were: the state or condition of the floor, wall and ceiling/room (n=17), thermal conditions (n=17), crowding (n=16) and ventilation and insulation (n=16). The least frequent domains were privacy (n=3), children's resources (n=3) and greenery (n=2).

2.1.1.4 Measurement of housing quality domains

Housing quality domains were measured using subjective (e.g., survey questions about perception) or objective (e.g., measurements of pollutants or temperature) assessments. Some studies used a combination of subjective and objective measures – for instance, one study from New Zealand asked participants whether their house "smells musty" and "feels damp, " but also assessed the extent of visible mould on the walls of house (Keall et al., 2012).

Once components of a housing quality definition are selected, they are often combined to form a housing quality measure. Most studies dichotomised components (e.g., no dampness/mould = 0 and dampness/mould present = 1) and then summed to create a composite housing quality score. Among these studies, most composite scores assigned each component with an equal weight. In some instances, this was combined with the risk or likelihood that residents would be exposed to the hazard itself (Nriagu et al., 2011, Johnson et al., 2005). It is challenging to generate weights for different housing quality

components (and their effect on health outcomes) (Chu et al., 2022) as the existing epidemiological evidence is often insufficient or too heterogenous. In some instances, however, different components are given different weights (Kobayashi et al., 2022, Kain and Quigley, 1970). Still, some studies used *a posterior* approach, which uses statistical techniques such as factor analysis to develop the housing quality measure (Dias and de Oliveira, 2018, Adair et al., 2014, Cheung and Mui, 2022).

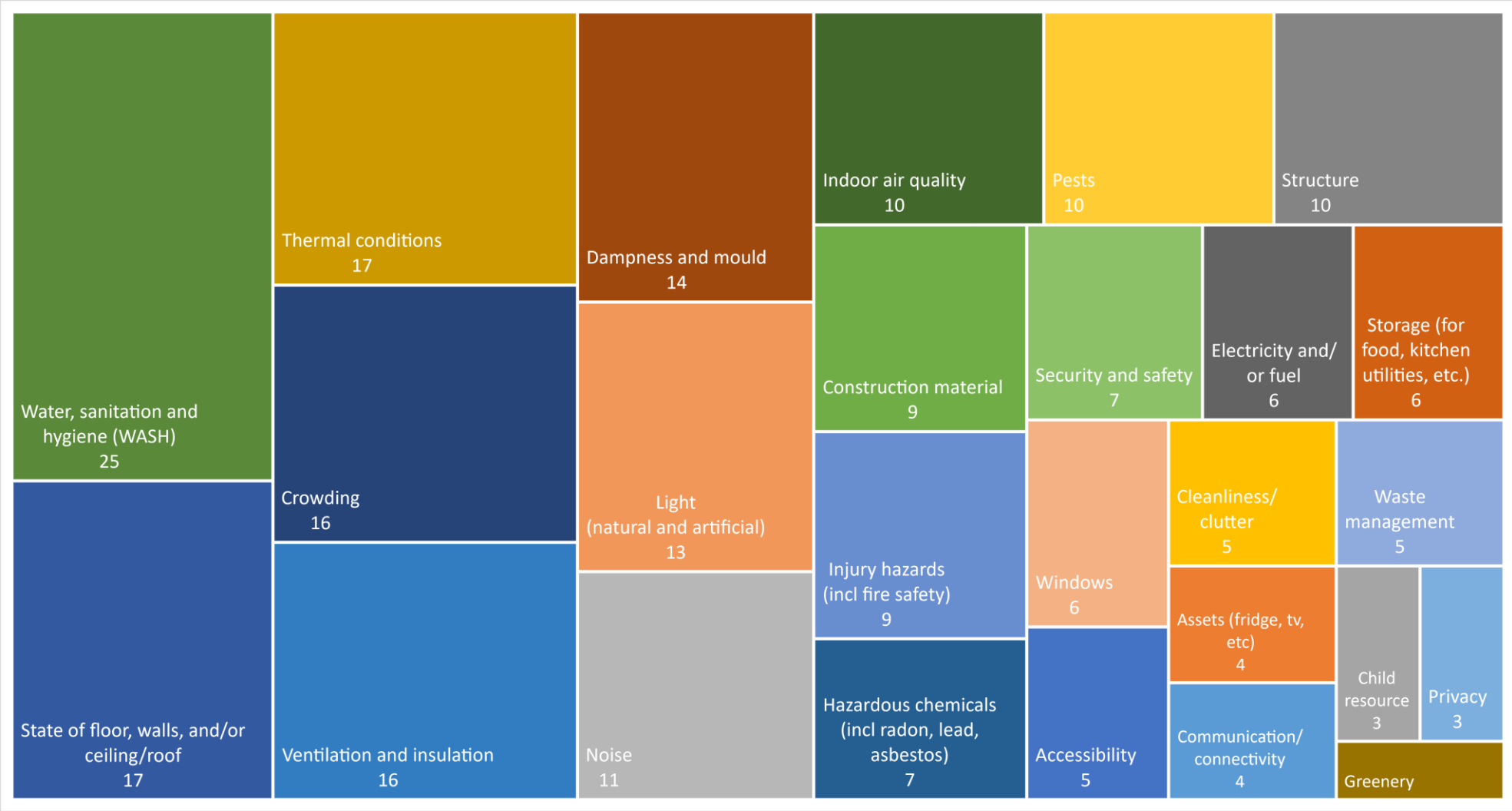


Figure 2.2. Housing quality domains in the studies included in this review and their frequencies

2.1.1.5 Discussion

This scoping review aimed to provide high-level insight on definitions of housing quality that exist in the literature. Based on the available definitions, the review established 25 domains of housing quality. While there was a geographic skew in the country of publication – with more than 60% of studies published in high income countries – the identified domains were relevant and cited across the different geographies. In other words, no domains were particularly relevant in a specific country or region – though more studies are needed to ascertain this.

My findings align to previous reviews. A Eurofound report found that the three most frequent categories included in definitions of inadequate housing in the literature were basic facilities (e.g., toilets), structural problems, and overcrowding (Eurofound, 2016, Hick et al., 2022). Additionally, the Organisation for Economic Co-operation and Development (OECD) identified "headline indicators" (i.e., factors that are of sufficient quality to monitor well-being across time and countries) were dwellings lacking basic facilities and number of rooms per person (Durand, 2015).

There is a debate in the literature whether a composite measure is a more accurate way for defining housing quality compared to separate components. Some argue that composite measures often have too many components, making them excessive and difficult to work with (Adair et al., 2014). Nolan and Winston (2011) highlight the importance of investigating dimensions of housing adequacy separately as different housing-related problems may be underlined by specific circumstances. In such cases, a composite measure may "mask rather than reveal" significant latent determinants of housing quality. However, the literature suggests that the relationship between some housing factors is not as strong or correlated as one may perceive (Hick et al., 2022). Thus, when attempting to define housing quality from a health lens, there is a need to balance the number of factors or domains considered with including factors that are known to be relevant. This should all be considered in light of the study's purpose and setting.

2.1.1.6 Limitations of the scoping review

This scoping review has limitations. First, the heterogeneity of the definitions makes it difficult to combine and summarise the studies into a single operative definition of housing quality. Due to this, domains of housing quality shared across the studies were identified and used to summarise the studies. Second, while all the studies included defined housing quality from the perspective of health, this was not done consistently across studies. Some did not measure a specific health outcome at all, or studies measured different health outcomes. Finally, there are limitations due to lack of evidence across certain regions of the world. This has the potential to bias the results of the review and

consequently what domains of housing quality are identified and most frequent. This emphasizes the need for more studies in diverse settings that observe housing quality with a health lens.

2.1.2 Existing housing quality assessment tools

Besides in literature and research, there have also been attempts to define and measure housing quality using housing quality assessment tools. While their use is not very widespread, housing quality assessment tools contain housing factors that are important to policy makers for monitoring compliance to rules and to property owners and managers for property management (Keall et al., 2010, Sinha et al., 2017). In addition, these assessment tools identify different hazards of a home that may impact the safety or health of its residents (Jacobs, 2006) – although this is rarely the intent (Sharpe et al., 2018). While assessment tools are informative about a single home, they can also be used as a means of obtaining data on the state of the housing stock in a specific location or region – though the sample may not necessarily be representative, and consequently prone to bias.

The development of a housing quality assessment is not straightforward as wide range of characteristics and factors could be considered. Parallel to the variety in housing quality definitions in literature (Section 2.1.1), housing quality assessment tools that exist are composed of a range of different components. In some instances, methods such as multiple-criteria decision analysis (Zopounidis, 1999) are used to identify and select or rank different components (Sinha et al., 2017).

A housing quality assessment tool should only consider the characteristics of the house itself. It is important to make this distinction explicit as housing quality can be impacted by other factors such as neighbourhood characteristics or resident behaviour. For instance, the presence of a functional heater does not equate to the use of the heater. According to Keall et al (2010), focusing on only the home and its characteristics has a number of advantages: (1) assessment is not impacted by change in residents, (2) if housing quality is assessed to be good for a vulnerable population, then one can assume that it is also healthy for other populations, and (3) a home can be assessed even if it is unoccupied at the time. Beyond its content, the cost and accuracy of housing quality assessment tools are also important considerations. Cost – monetary or time – may impact the practicality of a housing assessment tool in many settings.

Housing quality assessment tools have been developed globally (Sinha et al., 2017, Sharpe et al., 2018). I focus on a selection of five existing tools in the UK and the US: the Housing Quality Indicators (HQI) (Homes and Communities Agency, 2011) and Housing Health and Safety Rating System (HHSRS) (Office of the Deputy Prime Minister: London, 2006) in the UK and the Poor Quality Index (PQI) (Eggers,

2013), Housing Quality Standards (HQS) (U.S. Department of Housing and Urban Development, 2015), and National Healthy Housing Standard (NHHS) (National Center for Healthy Housing, 2014) in the US. Key characteristics of these housing quality assessment tools are summarised in Table 2.1.

Table 2.1. Key characteristics of existing housing quality assessment tools in the UK and US

	Assessment Tool	Source	Purpose	Composition
United Kingdom (UK)	Housing Quality Indicators (HQI)	Homes and Communities Agency (HCA)	To measure the quality of housing schemes funded by the HCA	10 indicators
	Housing Health and Safety Rating System (HHSRS)	Introduced under Housing Act 2004 (Office of the Deputy Prime Minister)	Help local authorities identify and protect against potential risks and hazards to health and safety	29 hazards in 7 categories
United States (US)	Poor Quality Index (PQI)	U.S. Department of Housing and Urban Development (HUD)	To measure the level of physical deficiencies in a home over time	35 components in 8 categories
	Housing Quality Standards (HQS)	HUD	To regulate HUD's Housing Choice Voucher program in the US	13 key aspects
	National Healthy Housing Standard (NHHS)	National Center for Healthy Housing and the American Public Health Association	To create, maintain and improve good quality housing conditions	7 requirements outlined in chapters with stretch provisions

A comparison of the components of the different assessment tools is presented in Table 2.2 to highlight similarities and differences across these tools. Among the areas of housing quality present in the individual assessment tools, the six most common (i.e., in at least four assessment tools) are:

- Structure/ physical condition of the home
- Safety and security
- Water and sanitation
- Pollutants and air quality
- Thermal comfort and temperature
- Electricity and lighting

Of these six housing quality areas, structure/physical condition of the home and electricity and light are measured in all five tools. Beyond these six, the exterior condition of the home and accessibility were less common metrics found in the assessment tools; and responsibility of the owner versus the occupant and sustainability of the home are only included in the NHHS and the HQI respectively.

2.1.2.1 Limitations of existing housing quality assessment tools

While these assessment tools provide insight into the housing quality factors that have been deemed relevant by different stakeholders, they are limited in various ways. Some tools are not comprehensive (e.g., overcrowding is not present in most), and some are much more detailed than others (e.g., the HQI's location indicator asks whether there is a school at 500m and/or between 500m and 1 km from the home). Implementation of many of these assessment tools is time consuming and requires either training or expert knowledge to conduct and provide the information needed to evaluate the home and neighbourhood (Nriagu et al., 2011, World Health Organization, 1967). In some instances, these assessments have been found to be unreliable as the home inspection outcomes by these trained personnel do not always align with government-led inspection results (Sandra Newman and Holupka, 2018), suggesting that these tools may be prone to bias. Additionally, housing quality assessment tools are rarely developed from a resident health and wellbeing perspective (Sharpe et al., 2018). The limitations of these assessment tools highlight the need for a method to define and develop a city-wide measurement of housing quality from a public health lens.

Table 2.2. Components of existing housing quality assessment tools in the US and UK

Relevant housing quality area	PQI categories	HQS key aspects	NHHS chapters	HQI indicators	HHSRS hazards categories
Related to tenure/roles of occupants			Duties of owners and occupants		
Related to the structure/ physical condition of the home	Outside structural problems	Site and neighbourhood		Location External environment Visual impact, layout and landscaping Open space Routes and movement Unit size	
Related to safety and security		Space and security Smoke detectors	Safety and personal security	Unit layout Noise, light, services and adaptability	Space, security, light, noise Falls Collisions, cuts, strains
Related to water and sanitation	Inside structural or other problems Bathroom problems Kitchen problems	Structure and materials Sanitary facilities Sanitary condition	Structures, facilities, plumbing, and space requirements	Unit layout	
	Water and sewer problems	Water supply Food preparation and refuse disposal	Moisture control, solid waste, and pest management		Hygiene, sanitation and water supply
Related to pollutants and air quality		Interior air quality Lead-based paint	Chemical and radiological agents		Pollutants (non-microbial)
Related to thermal comfort and temperature	Heating problems	Thermal environment	Thermal comfort, ventilation, and energy efficiency		Hyperthermal conditions
Related to electricity and lighting	Electricity problems Elevator problems	Illumination and electricity	Lighting and electrical systems	Noise, light, services and adaptability	Electric shocks, fires, burns
Related to accessibility		Access		Accessibility within unit	
Related to sustainability				Unit sustainability	

2.1.3 Existing housing quality and health frameworks

Besides definitions and assessment tools, frameworks have also been used to understand the multidimensional concept of housing quality. Conceptual frameworks or diagrams – particularly descriptive or structural ones – serve to "break up phenomenon into manageable pieces" and help to organise a body of knowledge (Paradies and Stevens, 2005). Despite the breadth of literature, a singular framework that comprehensively describe the relationship between housing quality – or even housing – and health does not exist. Here, I first present a selection of existing housing and health conceptual frameworks, as these often include at least one housing quality component, and then present a housing quality and health framework from the literature.

Figure 2.3 presents a framework from New Zealand, developed in 2022, that attempts to understand the pathways between housing and health (Howden-Chapman et al., 2022). As such, elements such as housing-related costs, tenure and neighbourhood noise are included. The social and economic pathways by which housing affects health, e.g., increases risk of respiratory, cardiovascular, and infectious diseases, are presented. This diagram has five layers, which, starting from the bottom, are social determinants, what people can afford, housing features, health hazards, and poor health outcomes. The lack of a clear delineation between housing features and health hazards is a limitation of this framework as it is difficult to differentiate which category a specific housing quality element would fall into. For instance, one may argue that injury hazards or high/low temperature are a feature of the home. Finally, key elements of housing quality such as pests/allergens and lighting are not included.

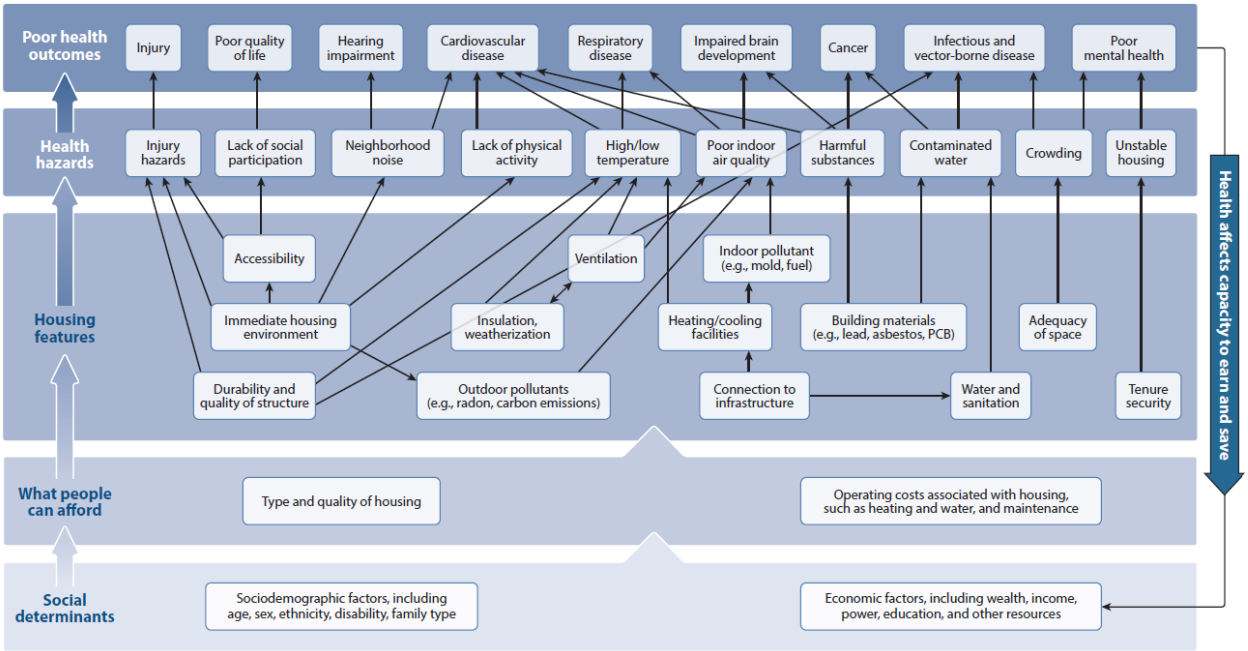


Figure 2.3. Housing pathways to health from (Howden-Chapman et al., 2022)

The housing and health schematic developed by Shaw (2004) presents housing as having both direct and indirect avenues to health, which are also divided into hard and soft factors (Figure 2.4). The focus of this framework is on industrialised settings (Shaw, 2004) and only a few key elements of housing (quality) are highlighted, i.e., it is not comprehensive. The top-right portion of this schematic (i.e., direct and hard factors) most closely aligns to the traditional definitions of housing quality. Additionally, health is impacted by economic status (as illustrated in the diagram), but also the sociodemographic factors of an individual which is not included here. Moreover, the relationship to health outcomes is not easily evident from the schematic.

The incorporation of 'indirect' factors is similar to a housing and health disparities conceptual model developed by Swope and Hernández (Swope and Hernandez, 2019) which presents housing conditions and quality as one of four housing pillars. The other three housing pillars are neighbourhood, affordability, and residential stability. These pillars are impacted by societal structures (e.g., class) and mechanisms (e.g., limited housing stock), and also impact health outcomes though mediators such as health behaviours and differential vulnerability.

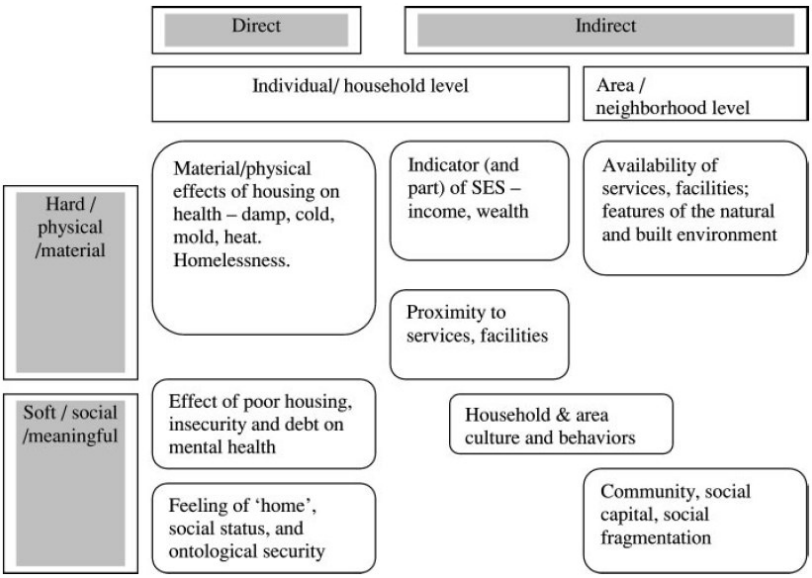


Figure 2.4. Schematic model of factors related to housing and health from (Shaw, 2004)

Sharpe et al (2018), who argue for a "whole systems approach" to obtain sustainable outcomes, developed a conceptual framework for housing and health (Figure 2.5) using the modified Drivers Pressures States Exposures Effects and Actions (DPSEEA) model. Housing quality elements are primarily reflected across the States (e.g., changes in indoor air quality, poor noise insulation) and Exposures (e.g., colder indoor temperatures, mould and bacteria levels) components. Both show how the environment is impacted by larger (i.e., global, societal or government) pressures or human interaction (Scottish Government 2008). This framework illustrates the different layers of housing as

related to health well but as it does not focus specifically housing quality, many components housing quality are not included such as lighting, pests, injury hazards and WASH.

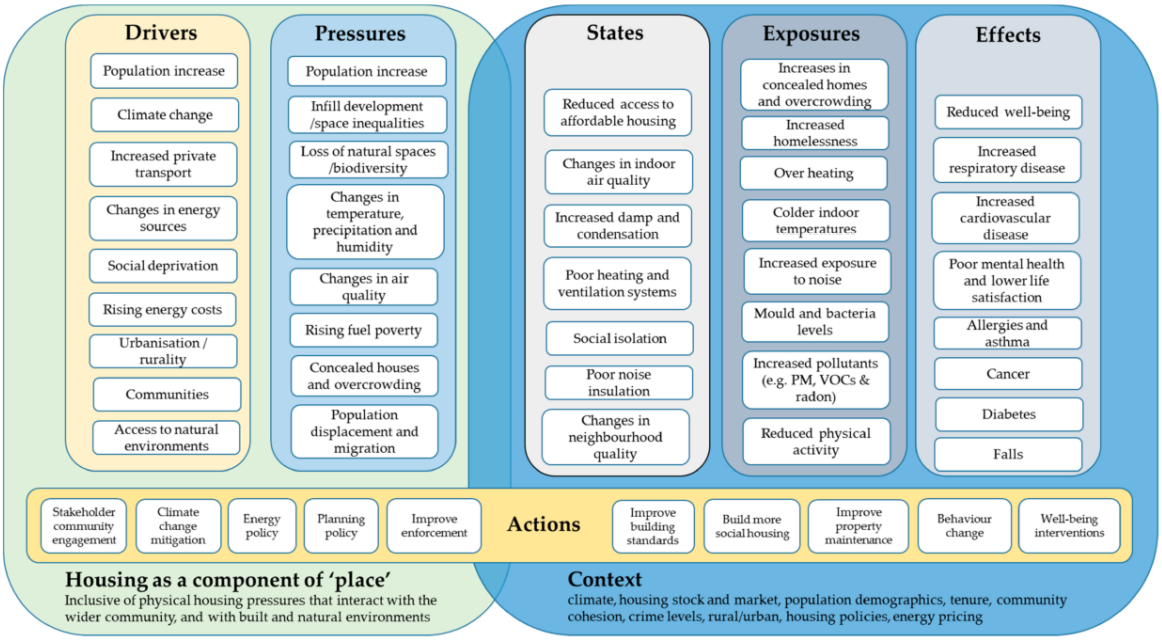


Figure 2.5. Health and housing conceptual framework from (Sharpe et al., 2018)

Some existing housing and health frameworks focus on specific health outcomes. For instance, the Roux (2003) focuses on the pathways that link the residential environment to cardiovascular conditions and risk. The schematic is presented in Figure 2.6. Besides the obvious limitations of constraining to a single health outcome, this framework is also developed with a broad lens which includes characteristics of the neighbourhood (e.g., availability and cost of nutritional food options).

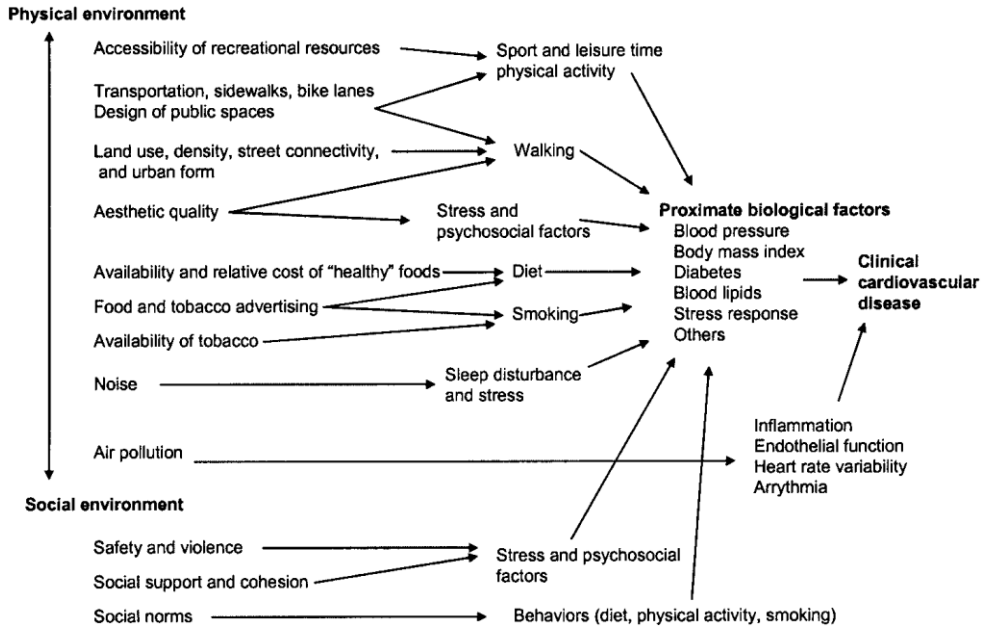


Figure 2.6. Pathways from residential environment to cardiovascular risk from (Roux, 2003)

Another example is the detailed conceptual framework of sustainable and healthy housing and the relationship with acute respiratory infections by Zúñiga-Bell et al. (2019). This framework illustrates relevant pathways in this relationship. For instance, Zúñiga-Bell et al. show that the combination of [poor] ventilation and overcrowding decrease air quality, which is a risk factor for respiratory conditions. This framework focuses on one health outcome, which consequently limits the areas of housing quality that can be included. Elements of housing quality that do not affect acute respiratory infections, such as noise pollution or privacy, are not included.

Figure 2.7 shows a housing quality-specific framework developed in 2019 (Stats NZ, 2019). The framework uses four interconnected components: habitability, functionality, environmental sustainability, and social and cultural sustainability and provides a more in-depth description of each of these components. The habitability and functionality components overlap with the more conventional definitions and understanding of housing quality as they have to do with the physical condition of a home – i.e., its construction, design, structure, and facilities. The environmental sustainability and social and cultural sustainability components provide a more contextual and temporal perspective to housing quality. This would include, for instance, the impact of phenomena such as climate change on housing, as well as the differences in the function of a house for different residents. While this framework provides a unique birds-eye view of housing quality, particularly with the inclusion of the temporal aspect, it does not engage with the nuanced elements of what encompasses housing quality. For instance, it is difficult to distinguish what "physical structure" or "facilities" entail, limiting the application of this framework.



Figure 2.7. Framework for housing quality from (Stats NZ, 2019)

2.1.3.1 Limitations

The large majority of existing frameworks provide a limited overview of the relationship between housing and health, i.e., there is not a specific focus on housing quality. The housing and health relationship is broad and involves a number of factors beyond housing quality such as affordability and neighbourhood characteristics – as depicted in the housing-health frameworks discussed above. A housing quality-specific conceptual framework is needed (only one was found in my review) to provide a comprehensive understanding of what is encompassed in housing quality from a health outcomes perspective as housing quality in of itself is multifaceted with different dimensions affecting varying kinds and number of health conditions. A housing quality specific framework would allow for a more nuanced approach to developing housing policies that can improve residents' health. Additionally, factors such as residents' sociodemographic characteristics should also be accounted for in a housing quality framework as these factors may mediate the impact of a housing quality factor on health, for instance older populations may be more vulnerable to injury in areas of the home with poor lighting. In light of these limitations of existing housing quality and health frameworks, I develop and present in Chapter 3 a housing quality and health framework with standard indicators that is operationalizable and comprehensive. This means that my framework not only uses and summarizes the robust existing body of housing quality literature, but also provides a means to measure housing quality as one would be able to better assess the availability and appropriateness of housing quality-related data. The comprehensiveness and geography-independent nature of my framework allow it to be flexible for a wide range of applications (e.g., in both cities and rural settings).

2.2 London context

This thesis uses London for a housing quality and health case study, as its large population, diverse social structure, old housing stock and higher cost of living compared to other urban areas in the UK increases the likelihood of its residents living in poor quality homes. Consequently, Londoners have an increased vulnerability to the effects of poor quality housing. London is composed of 33 boroughs (Figure 2.8) and has population of 8.8 million (Greater London Authority, 2022a). Between the last two Census years, 2011 and 2021, the London population grew by 7.7% (compared to a 6.6% increase in England) (Office of National Statistics 2022b). This trend seems to be due to an increase in population in Outer London in recent years (Greater London Authority, 2022a). The number of households in London has increased by 4.8% since 2011 – this suggests that the number of people per household has increased (Greater London Authority, 2022a).



Figure 2.8. Map of London boroughs (Greater London Authority, 2022a)

Even before the COVID-19 pandemic, London had the highest rate of poverty (even after accounting for housing costs), 27%, in the UK. 15% of Londoners were identified as being in fuel poverty and 20% have low or very low food security (WPI Economics and Trust for London 2022). According to the Office of National Statistics, London's Gini coefficient, a measure of inequality within an area ranging from 0 to 100% (i.e., none to total inequality), is 70% – the highest in the UK (Bela et al., 2020).

Moreover, low-income Londoners were more likely to experience a rise in their housing costs and overcrowding (Greater London Authority, 2022a).

London is also different in its ethnic makeup compared to the rest of England. As illustrated in Figure 2.9, London is the most ethnically diverse region of England and Wales. According to a report using data from the 2021 Census (Office of National Statistics 2022a), there was an 8% decrease in people who identify as White: English, Welsh, Scottish, Northern Irish or British – 36.8% in 2021 versus 44.9% in 2011. The population of this ethnic group ranges from 71% to 90% in other English regions (Office of National Statistics 2022a). When observing the breakdown of ethnic groups by geographic area, 49% of Blacks, 33% of Asians and 29.4% of those who identify as Mixed live in London (Office for National Statistics, 2022).

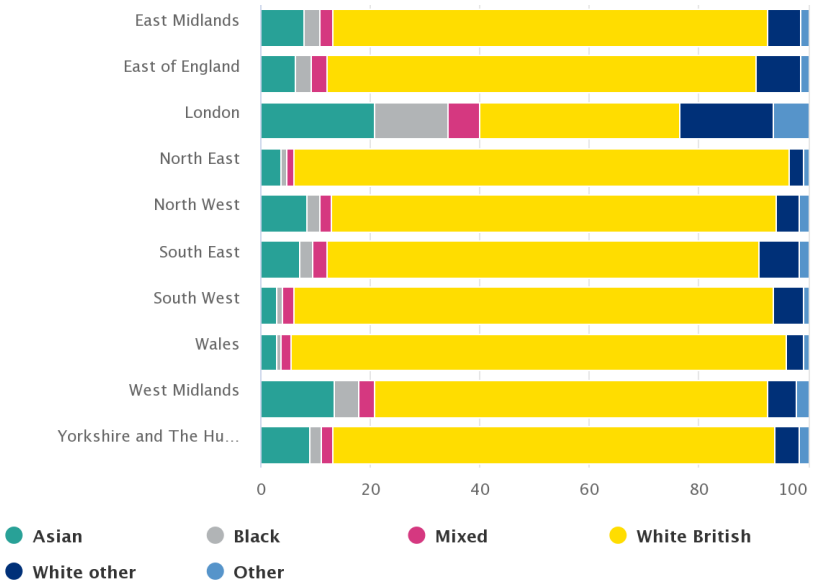


Figure 2.9. Areas of England and Wales by ethnicity (Office for National Statistics, 2022)

Ethnic minorities have been more impacted by the current London housing crisis, and there are stark differences in housing tenure and basic quality features by ethnicity (Munro et al., 2022, Gleeson, 2022). For instance, the populations with the lowest rates of home ownership are Black Africans (20%) and Arabs (17%) (Ministry of Housing, 2020b). Blacks and Asians were found to be more likely to experience an increase in their housing costs (Greater London Authority, 2022a). In terms of overcrowding, the Bangladeshi (24%), Pakistani (18%), Black African (16%), Arab (15%) and Mixed White and Black African (14%) groups had the highest rates. This is compared to only 2% of White British households facing overcrowding (Ministry of Housing, 2020c). A similar trend exists for damp problems in the home (Department for Levelling Up, 2020) and fuel poverty (Lee et al., 2022); but not

for rates of living in non-decent homes (Ministry of Housing, 2020a). Black and mixed/other ethnicity Londoners are more likely to report that they are dissatisfied with their home, compared to Asian and White Londoners (Gleeson, 2022).

Another important contextual factor is that the English population is ageing. The 65 years and over population accounts for 18.6% of the total population (up from 16.4% in 2011). While this population is only 11.9% of the London population, they seem to be in a worse socioeconomic position compared to their counterparts in other regions of England. For instance, Age UK London (2022) has found that 25% of older Londoners (50+) are living in poverty and 20% are in fuel poverty. This is compared to 18% and 15%, respectively, among this population in other parts of England. This is an important consideration as housing has a significant impact on this population's health and overall quality of life because the elderly spend more time at home than the majority of the rest of the population (Belcher et al., 2021, Centre for Ageing Better, 2020, Munro et al., 2022, Mulliner et al., 2020).

2.2.1 London housing stock

Just like its demographic composition, London's housing stock is unique to that in the rest of England. In terms of affordability, London has the highest housing-related prices (mortgage, private rent and social rent payments) in England (Munro et al., 2022, Department for Levelling Up, 2022b). Although Londoners have better income compared to the rest of the UK, a higher proportion of their income goes to housing costs (Bela et al., 2020). The average house price in London in 2022 was just over £540,000, compared to £311,000 across England – though inflation has a significant impact on London house prices (Greater London Authority, 2022a). Unlike other regions of the country, more than 50% of Londoners rent their home (Munro et al., 2022), with 29% of London households being private renters and 22% social renters (Department for Levelling Up, 2022b) (Figure 2.10).



Figure 2.10. Tenure in London vs rest of England (2021-22) (Department for Levelling Up, 2022b)

Overcrowding is hight in London (Munro et al., 2022, Ministry of Housing, 2020c). The estimated number of people per home in London is the highest compared to other regions in England and is increasing, due to population growth coupled with insufficient building of new homes (Greater London Authority, 2019). In addition to the number of residents, London homes seem to poorly accommodate residents with disabilities or special needs. A leading charity supporting the disabled reported that 72% of individuals with mobility problems cannot easily enter the doors of their house (Leonard Cheshire Disability, 2014).

Within London, there are significant differences in housing quality features across and within its boroughs (Helen Garrett et al., 2014, Lloyd and Gleeson, 2022). The age of the London housing stock varies across the city with, on average, the oldest homes (built before 1900) in west inner London and the newest homes (built in 2000 or later) in East London (Greater London Authority, 2015). As the age of a home is directly related to the state of key structural components such as the foundation, roof, and walls and need for renovations, this is relevant for housing quality (Lee et al., 2022). Despite London's high proportion of older homes, it has more decent homes compared to other regions of England – this is especially true for owned homes. This can likely be attributed to the stronger economy of Londoners (Department for Levelling Up, 2022c).

Construction of new homes has been a critical means of coping with the London housing crisis, although the rise in its population has significantly outpaced the building of new homes. While the number of newly constructed homes has been insufficient, their quality is generally better. For instance, recently built homes are more energy efficient than existing ones. Figure 2.11 illustrates the contrast in energy efficiency between London's existing vs new housing stock.

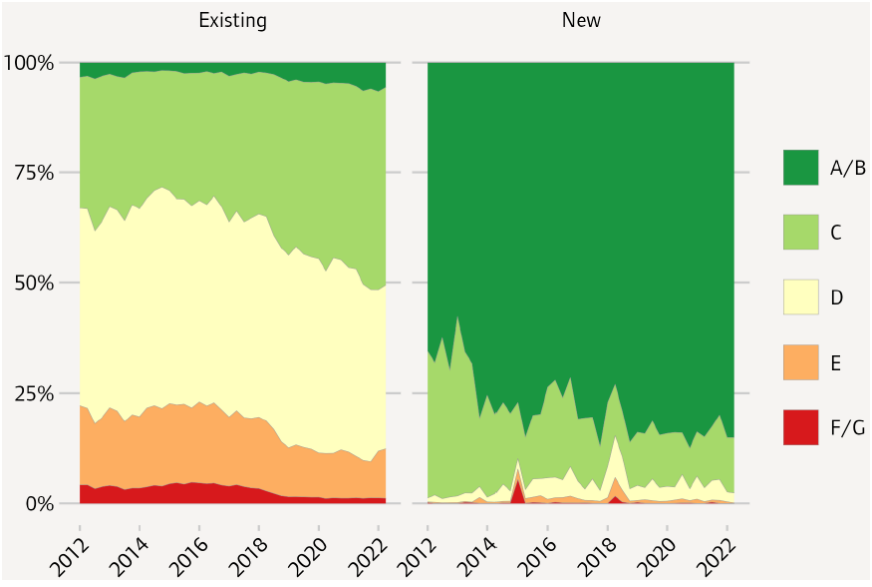


Figure 2.11. Energy efficiency band of existing vs new homes in London (from EPCs) (Greater London Authority, 2022a)

It has been estimated by the Building Research Establishment (BRE) that treating those affected by poor housing costs the National Health Service (NHS) £1.4 billion per year in England – which rises to £18.5 billion per year when including societal costs (i.e., considering impact on educational achievement, mental health, economy) (Garrett et al., 2021). Excess cold and falls have the highest contribution to this cost (Garrett et al., 2021). Although not as recent, the London-specific estimate for the cost of poor housing on the NHS is £56 million per year (£140 million when including societal costs) (Helen Garrett et al., 2014). This highlights the need for robust research and effective housing policies that can combat the impact of poor housing.

2.2.2 London housing-related policies

In London, phenomenon such as the Great Fire of London in 1666 and the cholera epidemic in the mid-1800s initiated concern and action on the housing quality front (Shaw, 2004, Sharpe et al., 2018), prompting a series of London Building Acts in the 19th century that stipulated on a range of housing characteristics including room height, wall thickness and fireplace design (Mathieson, 2010).

According to the English Housing Survey (EHS), 12% of homes in London currently failed to meet the Decent Home Standard (DHS) (Greater London Authority, 2022a) – down from 17% in in 2017 (Greater London Authority, 2019). The DHS, introduced in 2000 and revised in 2006 (Department for Communities and Local Government, 2004, Department for Communities and Local Government, 2006) defines a decent home as one that: (1) meets the current statutory minimum standard for housing – set by the Housing Health and Safety Rating System (HHSRS); (2) is in a reasonable state of repair; (3) has reasonably modern facilities and services; and (4) provides a reasonable degree of thermal comfort (Department for Communities and Local Government, 2006). While the number of non-decent homes is decreasing, the rate of improvements is lower among private rented homes. Nonetheless, high rates of overcrowding persist in the social rented sector (Munro et al., 2022).

The Mayor of London has included the need for high quality homes as one of five priorities in the Mayor of London's Housing Strategy (Greater London Authority, 2018), which most frequently uses the DHS to measure progress (Greater London Authority, 2022a). While the Strategy heavily focuses on the need for new and affordable homes, the Affordable Housing Programme (AHP) also requires that homes meet specific housing quality-related criteria – e.g., minimum for floor-to-ceiling height and energy efficiency (Department for Levelling Up, 2022a). The AHP also includes the sunlight clause which mandates that houses with 3 or more bedrooms must be dual aspect (i.e., has openable windows on at least two walls) and houses with less than 3 bedrooms should not face towards the north and should have at least a room that gets direct sunlight (Greater London Authority, 2021). The 2017 Grenfell Tower tragedy highlighted the significance of building and maintaining high-quality and

safe housing. Since then, the Building Safety Programme was established to ensure the safety of homes and implemented changes such as a ban on using combustible materials on new high-rise homes. Another scheme that the Mayor has implemented is the Warmer Homes Programme, which provides eligible low-income homeowners and private tenants a grant to make insulation and ventilation improvements (Greater London Authority, 2022b).

2.3 Chapter Summary

In the first half of Chapter 2, I provide a review of housing quality definitions in the literature, existing assessment tools and frameworks have provided a deep insight into the complex landscape of both defining and measuring housing quality. The multidimensionality of housing quality has evidently played a role in the lack of an existing definition of housing quality. These reviews have revealed the building blocks to define housing quality (i.e., by highlighting the recurring patterns and focus areas), but also the gaps that need to be addressed in order to comprehensively understand housing quality with a health perspective. The evidence and insights from this review lay a foundation for the remainder of this thesis, beginning with the development of my housing quality and health conceptual framework, which is the focus of Chapter 3.

The second half of Chapter 2 sets the stage for the case study geography, i.e., London, UK. I thoroughly discuss the unique demographic and housing stock characteristics of London, especially in comparison to the rest of the UK. I use this insight to select housing related data in London in Chapter 4, and also for selecting a housing quality domain to measure (Chapter 5) and estimating its association with health outcomes (Chapter 6).

3 Conceptual framework for housing quality and health

3.1 Methodology: framework and respective indicators

I synthesized and used the insights from my review of the existing literature, assessment tools and frameworks on housing quality and health discussed in Section 2.1 to develop a conceptual framework of housing quality that is operationalizable. In line with the paradigm seen in the existing housing quality related evidence, I defined housing quality using broad domains that highlight different dimensions of housing quality that are relevant to health outcomes. These domains reflect both those commonly found across my review of literature (see section 2.1), but also areas of housing quality with significant public health impact that have not received much consideration. I then delved further into each domain individually to identify indicators that would allow me to measure the domain, primarily based on what is relevant for health (discussed in Section 3.1.1). Both the selection of the housing quality domains and their respective indicators underwent multiple iterations with insight received from subject matter experts throughout this process.

My conceptual framework (Figure 3.1) has three elements: housing quality domains, meta-characteristics of housing and housing resident-related interacting factors. Housing quality domains are the thirteen (13) domains that collectively characterise housing quality comprehensively and have previously been shown to be associated with health. Meta-characteristics of housing are factors potentially impacting multiple housing quality domains. For example, housing location may affect the availability and quality of water (water and sanitation domain), the amount of ambient noise near the home (noise pollution domain), and phone/internet network availability (communication and connectivity domain). Housing resident-related interacting factors are elements such as age, gender and health status that are interrelated with meta-characteristics, domains, and determinants of health, as vulnerability and susceptibility to various health outcomes can be affected by such characteristics. For instance, the age of a household member may impact their perception of and vulnerability to indoor temperature (thermal comfort domain) and their ability to access various services near their home (location meta-characteristic).

My housing quality conceptual framework provides an approach to measure housing quality in any setting globally exhaustively and is, therefore, not geography specific. As such, one specific domain may be more relevant in some settings than others. For my MPhil thesis, I focus on one city, London, as a case study for operationalising my housing quality framework to measure and map a housing quality domain at the small-area level (Chapter 5) and assess its associations with health outcomes (Chapter 6). This is explained further in Section 3.3.1.

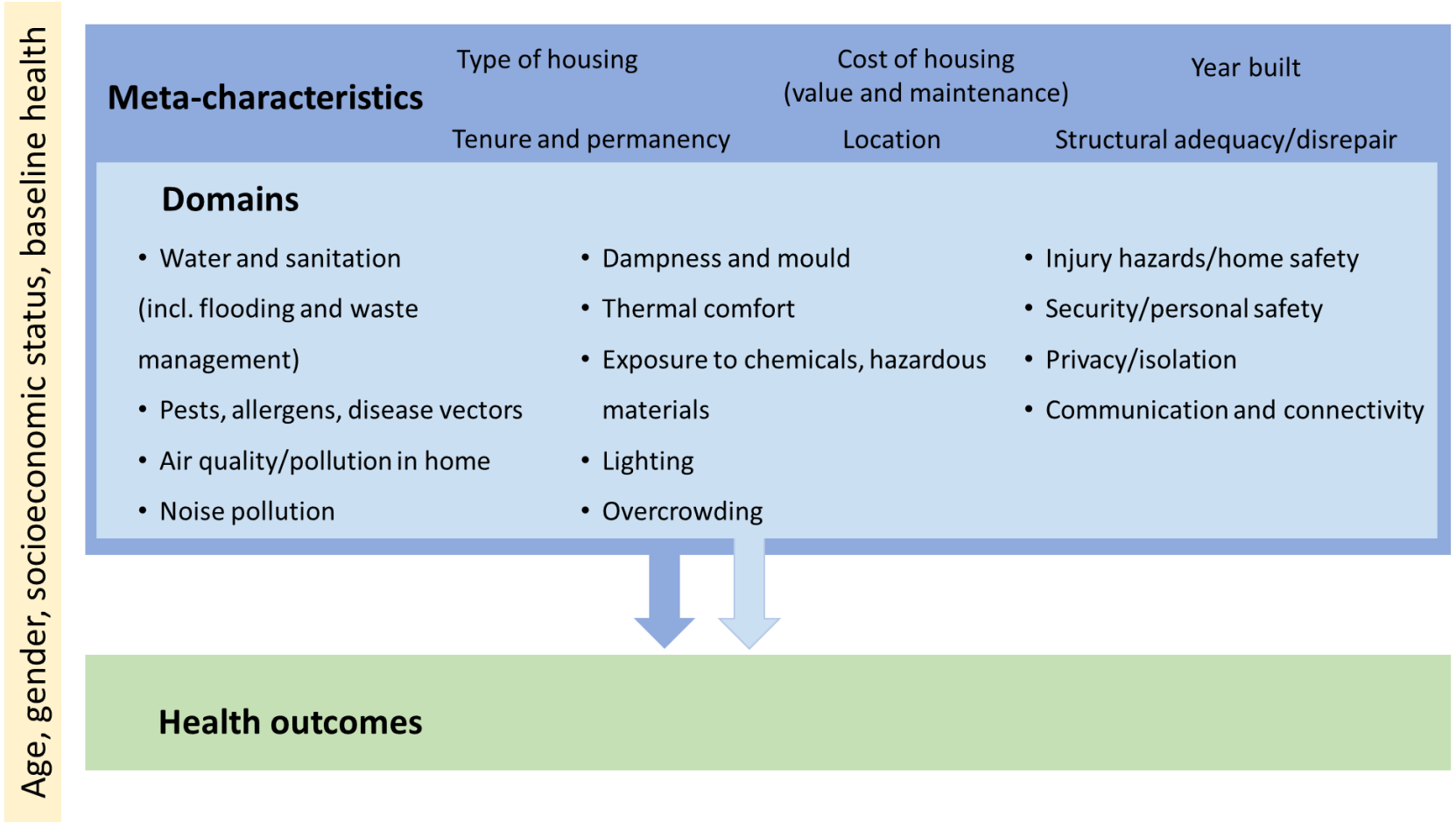


Figure 3.1. Conceptual framework of housing quality and health

3.1.1 Indicator selection for housing quality domains

To link housing quality with health outcomes, I first identified indicators to define and quantify each housing quality domain. Indicators provide the "crucial link" between the data and decisions about how to measure phenomena appropriately (Corvalán et al., 2000). To identify domain indicators, I used a method that broadly aligns with the WHO methodology, summarised by Mason et al. (2018) as having three components: scoping, selection, and design.

I categorized my indicators into two groups: standard indicators and domain indicators. Standard indicators, which were obtained from the literature, are indicators commonly used to facilitate the measurement of a specific domain. Domain indicators are elements that are relevant to one or multiple standard indicators and/or represent sources of exposure for the domain. The final subset of indicators used to measure a domain are selected based on the following criteria:

1. Relevance: the relationship between the indicator and the domain is clear
2. Distinctiveness: indicator cannot be measured by other indicators
3. Importance to health based on the epidemiological evidence
4. Measurable: data availability

3.2 Overview of housing quality domains

Here, I present an overview of the thirteen housing quality domains that my housing quality and health framework is composed of. First, a concise overview of the other twelve housing quality domains is provided, followed by Table 3.1, which details the associated health outcomes, standard indicators, and domain indicators by domain. Data availability by domain in London is presented in Appendix 9-4.

Next, I discuss housing quality domains that are particularly relevant for London. My analysis, largely as a result of data-related constraints, focused on one of these London-relevant housing quality domains: thermal comfort. Thus, in Section 3.2.3, I discuss this domain thermal comfort, in detail – i.e., including relevant health outcomes and standard indicators, which domain indicators I identified, and the subset selected to measure the domain in London.

3.2.1 Summary of all housing quality domains

A concise overview of the twelve housing quality domains (excluding thermal comfort which is discussed in Section 3.2.3) follows. The dampness and mould domain measures sources and problematic manifestations of excess moisture within the home. The water and sanitation domain measures water

access, water quality, sanitation, waste management and flooding. The pests, allergens, and disease vectors domain measures the presence and infestation of common household pests (e.g., bed bugs, mice and cockroaches), allergens (e.g., dust mites), and disease vectors (e.g., mosquitoes) in the home. The air quality/ pollution domain measures how clean the air within the home is. The exposure to chemicals, hazardous materials domain measures the presence of a range of substances in the home that can pose a number of health hazards such as asbestos, lead, arsenic, and benzene. The noise pollution domain measures noise in the home from sources both within and external to the home. The lighting domain measures light in the home from both natural light and artificial light sources. The overcrowding domain measures the state within a home where the number of residents surpasses the capacity of the space in the home. The injury hazards/ home safety domain measures the factors at the individual home level that contribute to the residents' risk of different home injuries. The security/ personal safety domain measures the factors at the individual home level that are relevant for residential security (though it is interrelated with neighbourhood factors). The privacy/isolation domain measures how a resident's home contribute to their privacy or isolation. The communication and connectivity domain measures how well residents are connected to others and services via phone and internet utilization.

Table 3.1. Overview of housing quality domains: associated health outcomes, standard indicators, and domain indicators *NB: Blue text indicates a meta-characteristic and red text indicates a different domain.*

Domain	Associated health outcomes	Standard indicators	Domain indicators
Thermal comfort	• Low indoor temperatures (World Health Organization, 2018, Ormandy and Ezratty, 2012, Braubach et al., 2011): ○ Increased blood pressure ○ Cardiovascular ○ Respiratory conditions • High indoor temperatures (World Health Organization, 2018, Ormandy and Ezratty, 2012, Braubach et al., 2011): ○ Heatstroke ○ Dehydration, ○ Hyperthermia • Mortality (Braubach et al., 2011)	• Environmental factors (ANSI/ASHRAE, 2017) ○ Air temperature ○ Radiant temperature ○ Air speed ○ Humidity • Personal factors: ○ Metabolic rate ○ Clothing insulation	• **Location** and orientation (Mavrogianni et al., 2014, Symonds et al., 2016, Ma et al., 2021) • **Built year** (Beizaee et al., 2021, Oreszczyn et al., 2006, Lamberti, 2020) • Presence of solid walls (Beizaee et al., 2021, Symonds et al., 2016), property type (Oreszczyn et al., 2006, Symonds et al., 2016) • Wall and roof insulation (Oreszczyn et al., 2006, Mavrogianni et al., 2012, Mavrogianni et al., 2014), • Construction fabric (Lamberti, 2020) • Window glazing (Lamberti, 2020, Mavrogianni et al., 2012, Mavrogianni et al., 2014), and window to wall ratio (Lamberti, 2020) • Overcrowding (Ormandy and Ezratty, 2012) ○ (including number of people in household, occupant gender and age (Lamberti, 2020), household head age (Oreszczyn et al., 2006)) • Resident behaviour (e.g., opening windows) (Mavrogianni et al., 2014). Additionally, energy/thermal efficiency rating (Beizaee et al., 2021, Oreszczyn et al., 2006)
Dampness and mould	• Respiratory conditions (Dales et al., 2008, Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development, 2006, World Health Organization Regional Office for Europe 2009, Davies et al., 2016, World Health Organization, 2018, Mendell et al., 2011, Ingham et al., 2019, Du et al., 2021) ○ Respiratory infections ○ Upper respiratory tract symptoms ○ Asthma (Quansah et al., 2012) ○ Allergies	• Presence of condensation on surfaces or in structures, mildew or mould growth, mouldy odour and a record of water penetration (Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development, 2006, World Health Organization, 2018, Ingham et al., 2019)	• **Built year** (Reponen et al., 2013) • **Disrepair** and construction material (World Health Organization Regional Office for Europe 2009) • Outdoor space (e.g., balcony, garden) • Number and size of windows • Room layout and size • Overcrowding (Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development, 2006, World Health Organization, 2018) • Indoor temperature and humidity (Du et al., 2021, Sharpe et al., 2018) • Safe and functioning heating/cooling system (Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development, 2006, World Health Organization Regional Office for Europe 2009, World Health

			Organization, 2018, World Health Organization Regional Office for Europe, 2009a) • Ventilation and insulation in the home (Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development, 2006, World Health Organization Regional Office for Europe 2009, World Health Organization, 2018, World Health Organization Regional Office for Europe, 2009a) • Poor cleanliness; clutter and home maintenance • Resident behaviour and activity (bathing, washing, cooking, drying clothes and people breathing)
Water and sanitation (incl. flooding & waste management)	• Waterborne diseases (World Health Organization Communicable Diseases Working Group on Emergencies, 2005, Howard and Jamie Bartram, 2003, Mara et al., 2010, Montgomery and Elimelech, 2007) ○ Typhoid ○ Cholera ○ Diarrhoea (Cairncross et al., 2010) ○ Dysentery ○ Hepatitis • Vector-borne diseases (World Health Organization Communicable Diseases Working Group on Emergencies, 2005, Pruss-Ustun et al., 2019, Sharmin et al., 2015, Howard et al., 2021) ○ Dengue ○ Malaria • Respiratory infections (Pruss-Ustun et al., 2019, Mara et al., 2010) • Maternal and child health (World Health Organization, 2019 (WHO/CED/PHE/WSH/19.149)) • Child mortality (Headey and Palloni, 2019) • Gastrointestinal disease (Alderman et al., 2012, Montgomery and Elimelech, 2007) • Neglected tropical diseases (World Health Organization, 2019 (WHO/CED/PHE/WSH/19.149), Mara et al., 2010, Montgomery and Elimelech, 2007) ○ Schistosomiasis	• Water access: quantity of water available to a household (Tamason et al., 2016, Guy Howard and Jamie Bartram, 2003), most accurately using a water meter (Tamason et al., 2016) • Water quality: metrics such as pH level, turbidity, or the presence of faecal indicator bacteria and chemical contaminants (World Health Organization, 2017) • Sanitation: number of people/ households per toilet/latrine (Patricia Billig et al., 1999, Obeng et al., 2015) • Waste management: coverage of services and frequency of waste collection (da Silva et al., 2019) • Flooding: Home flood hazard measured by probability and magnitude of flooding (National Research Council, 2015)	• Water access: ○ Type, number of and distance to water sources (Elliott et al., 2019) ○ Water intermittency and seasonality (Howard and Jamie Bartram, 2003) ○ Water storage • Water quality: ○ Presence and type of water treatment/ purification mechanisms: including distillation, filtration and, precipitation, among others (Sharma and Bhattacharya, 2016, UK House of Commons, 2003) ○ Plumbing/drainage infrastructure (Sharma and Bhattacharya, 2016) • Sanitation measure: ○ Accessibility (Stocks et al., 2014, Patricia Billig et al., 1999) ○ Distance (and time) to reach facility (Obeng et al., 2015) ○ Hygienic (Patricia Billig et al., 1999, Mara et al., 2010) • Waste management: ○ Method for waste disposal (e.g. picked up by private contractors; community bins; gutters, streets, holes and nearby bushes) (Ramatta Massa Yoada et al., 2014) ○ Proportion of waste sent to landfill versus recycled (Watson, 2013) • Flooding: (Pam Bowker et al., 2007) ○ Structural inadequacy (e.g., damaged mortar and soil type) ○ Type and interface of building materials (joint where different construction materials meet)

	○ Trachoma (Pruss-Ustun et al., 2019, Howard and Jamie Bartram, 2003) ○ Lymphatic filariasis		○ **Location**: water logging; floodplain or low-lying area (Qazi Azizul Mowla and Mohammed Saiful Islam, 2013) ○ Mitigating interventions such as flood barriers
Pests, allergens, and disease vectors	• Respiratory conditions including asthma and allergies (Sharpe et al., 2018, Council, 1993, Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development, 2006, Institute of Medicine, 2011) • Malaria (Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development, 2006) • Mental health (Shah et al., 2018)	• Pests: signs of pest infestation (Shah et al., 2018) ○ Cockroach infestation: alive or dead roaches, roach skins, roach frass ○ Rodent infestation: alive or dead rodents, rodent dropping, and evidence of gnawing, nesting, rub marks and sounds of pattering • Exposure to allergens: tests using air sampling and collection of settled dust (Council, 1993, Dales et al., 2008) • Exposure to disease vectors: calculating values such as the entomological inoculation rate (infectious bites per unit time) (Shaukat et al., 2010).	• **Disrepair** (e.g., cracks on the walls) (Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development, 2006, Council, 1993, Shah et al., 2018) • Dampness, moisture, and humidity (Council, 1993, Institute of Medicine, 2011, Bonnefoy et al., 2008) • Poor water infrastructure and sanitation (Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development, 2006, Institute of Medicine, 2011) • Cleanliness (Council, 1993, Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development, 2006) • Use of traps, poisons, or other pest elimination mechanisms (Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development, 2006, Shah et al., 2018) and use of an insecticide-treated nets.
Air quality/ pollution in the home	• Lung and other cancers (World Health Organization Regional Office for Europe, 2010, World Health Organization, 2009, World Health Organization, 2014, Braubach et al., 2011) • Premature death (World Health Organization, 2009) • Cardiovascular and respiratory conditions (World Health Organization Regional Office for Europe, 2010, World Health Organization, 2009, World Health Organization, 2014, Braubach et al., 2011, Kumar et al., 2022) • Low birthweight (World Health Organization Regional Office for Europe, 2010) • Dementia (Committee on the Medical Effects of Air Pollutants, 2022)	• Concentration of key pollutants including radon, carbon monoxide, formaldehyde, nitrogen dioxide, and trichloroethylene • Biomarkers test (e.g., cotinine) to test for second-hand smoke	• **Location** (ambient air quality) • **Structural adequacy; disrepair** (e.g., cracks in foundation) • Dampness and mould • Outdoor space (garden, porch, etc.) • Ventilation (e.g., in kitchen (Kumar et al., 2022)) & insulation • Water sources, such as springs, wells, and boreholes (high concentrations of radon in some countries) (World Health Organization Regional Office for Europe 2000, World Health Organization, 2009) • Fireplaces and combustion sources for cooking and heating (World Health Organization Regional Office for Europe, 2010, Dales et al., 2008) • Consumer products (furniture, cleaning products, paint, insecticides) (World Health Organization Regional Office for Europe, 2010) • Second-hand smoke: presence and frequency of smoking in the home (Campbell MA et al., 2017)

Exposure to chemicals, hazardous materials	• Child development (Zota et al., 2017, Public Health and Environment, 2010) • Leukaemia (World Health Organization Regional Office for Europe 2000, Turner et al., 2010) and other cancers (lung, stomach, mesothelioma, bladder) (Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development, 2006, World Health Organization Regional Office for Europe 2000) • Asbestosis (Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development, 2006) • Cardiovascular conditions (Braubach et al., 2011) • Respiratory conditions (Oregon State University, 2020) • Poisoning and burns (Oregon State University, 2020)	• Concentration of toxic chemicals including: asbestos (F/m^3), lead (µg/dL), arsenic (µg/L), benzene (mg/L)	• Building materials • Household products (e.g., detergents, pesticides, paints, cleaning products) with multiple hazardous chemicals such as ammonia, chlorine, and phenol (Zota et al., 2017, Dales et al., 2008, Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development, 2006, Public Health and Environment, 2010, Department of Public Health, 2019, World Health Organization Regional Office for Europe 2000, Oregon State University, 2020) • Home furnishings (e.g., carpets, curtains, and some furniture) (Zota et al., 2017) • *Asbestos*: building materials (Dales et al., 2008), soundproofing materials and heating appliances (e.g., drying machines and ovens) (Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development, 2006) • *Lead*: deteriorated lead-based paint, contaminated soil, and drinking water (from deterioration of plumbing pipes) (Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development, 2006, Public Health and Environment, 2010) • *Arsenic*: soil around houses, contaminating both wells and land (Department of Public Health, 2019), wood treated with preservatives, and pesticide (Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development, 2006) • *Benzene*: tobacco smoke, benzene-containing petroleum products, e.g., motor fuels (World Health Organization Regional Office for Europe 2000)
Noise pollution	Auditory and non-auditory(World Health Organization Regional Office for Europe, 2009b, WHO Regional Office for Europe, 2018, Braubach et al., 2011, Hammer et al., 2014, Stansfeld and Matheson, 2003, Bower et al., 2021): • Hearing impairments • Sleep outcomes (duration, quality, disturbance) • Cardiovascular disease • Hypertension • Stress and anxiety	Standard measures for noise which are all measured in A-weighted decibels, dB(A) (WHO Regional Office for Europe, 2018, Hammer et al., 2014): • L_{eq24h} for continuous average exposure over 24 hr • L_{den} for the period of day-evening-night (overall annoyance) • L_{night} for the night-time period (sleep disturbance)	• Ambient noise including from noisy neighbours • **Location** (traffic, neighborhood density; distance to and noise from roads, airport, railroads, construction, etc.) (WHO Regional Office for Europe, 2018, Braubach et al., 2011, Hammer et al., 2014, de Paiva Vianna et al., 2015) • Small scale manufacturing or business unit in the house • Household appliances (vacuum, extractor fan, etc.)(Jackson and Leventhall, 1975) and electronics (tv and radio)(WHO Regional Office for Europe, 2018, Hammer et al., 2014) • Overcrowding • Pets

	• Annoyance		• Number and type of windows; window glazing • Orientation, layout and height of a home (e.g., flat floor level) • Building material(Hammer et al., 2014),
Lighting	• Mental health (depression, anxiety) (Mary Jean Brown and Jacobs, 2011, Obayashi et al., 2018) • Sleep outcomes (duration, quality)(Veitch, 2013) • Injuries (burns, falls, slips, etc.) (Mary Jean Brown and Jacobs, 2011, Mashreky et al., 2010) • Vitamin D production (M. Nathaniel Mead, 2008) • Leprosy (Osibona et al., 2021) • Respiratory conditions (tuberculosis, acute respiratory infection) (Osibona et al., 2021)	• Amount of illuminance, which is expressed in lux (lumen/m^2), at different times throughout the day	• Height and orientation of the home • Number and size of windows (Peter Boyce et al., 2003) • Availability of outdoor space (e.g., balcony). • Density and placement of buildings near and around the home • Presence of electrical systems or fuel-based lighting (Weisbuch, 2018) • If the former, the number and type of lighting fixtures • Frequency of artificial light usage (behavioral) • Presence and use (i.e., closing/opening) of shades or curtains (behavioral)
Overcrowding	• Infectious disease, e.g., tuberculosis and COVID-19 (World Health Organization, 2018, Krieger and Higgins, 2002, Wilson and Barton, 2020) • Gastroenteritis and diarrhoeal diseases (World Health Organization, 2018) • Sleep quality (World Health Organization, 2018) • Intimate partner violence(World Health Organization, 2018) • Mental health (World Health Organization, 2018, Krieger and Higgins, 2002, Wilson and Barton, 2020, Singh et al., 2019, Sharpe et al., 2018)	• Number of people per (bed)room	• Number of people in the home, their relationships to one another (World Health Organization, 2018, Cable and Sacker, 2019) • Number of rooms, and the capacity of each room (i.e., floor area) (World Health Organization, 2018, Cable and Sacker, 2019)
Injury hazards/ home safety	• Injuries including falls, poisoning, being hit by a falling object and burns • Mortality	• Risk of different types of injuries including falls/slips, being hit by a falling object, structural collapse, drowning, burns/scalds/fires, and poisoning (Nina Zimmermann and Robert Bauer, 2007, Keall et al., 2011, World Health Organization, 2018)	• **Disrepair and building material**, including cladding (James P. Smith, Hilary I. Okagbue et al., 2018, Oseghale et al., 2015) • (Inadequate) lighting (Osibona et al., 2021) • Cleanliness and clutter in the home (Manning, 1983, Pynoos et al., 2010) • Safe storage of cleaning products, cosmetics, medicines, etc.

			• Renovation and installation of fall-proof mechanisms (e.g., parapets) decrease risk (Keall et al., 2011) • Fuel-based cooking/lighting (Mashreky et al., 2010, World Health Organization Regional Office for Europe 2000, Ahmed et al., 2009) • Fire prevention: presence of CO and smoke detector (Keall et al., 2011, Dales et al., 2008, Rohde et al., 2016) • Fire escape, extinguisher, or blanket • Availability of outdoor space (swimming pool, balcony) • Adaptations for accessibility
Security/ personal safety	• Mental health outcomes (Mai Stafford et al., 2007)	• Risk of housebreaking/ intrusion	• **Location** • **Housing type** • Communication and connectivity • Installation of security measures: locks, alarms, lights, cameras, etc. (Liz Levy et al., 2014) • Home fortification (walls, fences, gates) (Owusu et al., 2015, Cronje and Spocter, 2016) • Height of home • (e. g. flat story level)
Privacy/isolation	• Mental health (Hammig, 2019, Erin York Cornwell and Linda J. Waite, 2009, James Lubben et al., 2006) • Musculoskeletal disorders (Hammig, 2019) • Pre-mature mortality (Holt-Lunstad, 2020) • Cardiovascular disease (Holt-Lunstad and Steptoe, 2022) • Diabetes (Holt-Lunstad and Steptoe, 2022) • Dementia (Penninkilampi et al., 2018, Qiao et al., 2022, Wang et al., 2023)	• Social isolation: number of contacts that people have (Malcolm et al., 2019) and less (in number or frequency) participation in social activities (Erin York Cornwell and Linda J. Waite, 2009) • Loneliness: perceived quality of the person's relationships (Malcolm et al., 2019, Erin York Cornwell and Linda J. Waite, 2009)	• **Housing type** • Overcrowding (Liam Reynolds and Nicola Robinson, 2005) • Communication and connectivity • Noise and wall thickness • Accessibility (Bert Provan et al., 2016, Alonso, 2010) • Security measures (e.g., built walls or fences) • Outdoor space (balcony, garden) • Number and size of windows • Shared facilities
Communication and connectivity	• Positive: increased social capital, greater feelings of social support and lower levels of loneliness (Kearns and Whitley, 2019) • Negative: reduce social interactions; increase loneliness and depression (Kearns and Whitley, 2019, Jolly Masih and Rajasekaran Rajkumar, 2019) • Increased access to health services and information (Kevin Hernandez, 2019), including telehealth (Tomer et al., 2020)	• Network connection speed (Megabits per second) • Network strength (e.g., 3G, 4G, 5G)	• **Location** of the home (e.g. urban vs rural) (Kevin Hernandez, 2019) • Network coverage • Intermittency (Kevin Hernandez, 2019) • Ownership and use of a phone, computer or similar device

3.2.2 London-relevant housing quality domains

While the domains of my housing quality and health framework collectively provide a comprehensive definition of housing quality, the relevance of different attributes of housing quality are location dependent. This is even evident in how housing quality is defined and/or measured in different regions of the world. In the UK, domains such as indoor air quality/pollution, dampness and mould, overcrowding and thermal comfort are pressing and the focus of much UK-related research efforts.

Air quality/pollution has been deemed one of the most significant environmental health threats currently being faced by the UK. While much of the research has centred on ambient air pollution, indoor air quality has become increasingly studied. According to Vu et al. (2022), the mean indoor to outdoor ratios of particulate matter and NO_2 were 1.2 and 0.84 respectively – with peaks in their concentrations at different hours in the day. Ferguson et al. (2021) found that besides outdoor air pollution, factors inside the home such as ventilation and cooking/heating systems contribute to poor air quality in the home and explain the disproportionate burden in low-income households in London. While there is little evidence of significant variations in indoor heating or cooking amenities by socioeconomic status, the efficiency of these systems may vary. Occupant behaviour, such as smoking, was also found to have a significant role in concentration of air pollutants in the home. **Dampness and mould** is a well-known problem throughout the UK with approximately 904,000 homes in England dealing with dampness in 2021 (Balogun et al., 2023). A report by the London Assembly Environment Committee (2019) found that 6% of homes in London were affected by dampness, and this disproportionately affected rented homes. Besides proper and functioning ventilation, one of the contributors to dampness in the home in London is overcrowding. **Overcrowding** is present in about 3.5% of English homes, but most prevalent in London (Wendy Wilson, 2020). Moreover, overcrowding is also disproportionately higher among rented homes – especially social rent (Wendy Wilson, 2020, London Assembly Environment Committee, 2019). As such, many Londoners who rent their home face a multi-burden of poor housing quality, consequently putting them at higher risk for a number of associated health outcomes. **Thermal comfort** has been on the forefront of the UK agenda with the UK Department of Business, Energy and Industrial Strategy reporting that 13.2% of households in England (3.16 million) lived in fuel poverty in 2020, an improvement compared to 2010 (22.1%) that is attributed to improved energy efficiency and insulation of homes (Department for Business, 2022). This domain in the focus of this thesis and is discussed extensively within the London/UK context (see Section 2.2 for overview of the sociodemographic characteristics and housing stock of London).

3.2.3 Thermal comfort domain

The thermal comfort domain includes indicators that relate to residents' satisfaction with the thermal environment within the home (ANSI/ASHRAE, 2017). Thermal comfort relates to both cold and hot temperatures, and both are associated with health outcomes (World Health Organization, 2018, Ormandy and Ezratty, 2012, Braubach et al., 2011). Health outcomes associated with low indoor temperatures include increased blood pressure, cardiovascular and respiratory conditions. Those associated with high indoor temperatures include heatstroke, dehydration, and hyperthermia. Heat has even been deemed as the leading weather-related cause of death in the US (Samuelson et al., 2020), especially in light of recent changes in global and local temperatures due to the effects of climate change (Maller and Strengers, 2011). Certain population groups, such as the elderly, children, and infants and those with pre-existing health conditions, are more susceptible to such temperature-related health outcomes (Maller and Strengers, 2011, Anderson et al., 2013, Nakajima et al., 2019).

In order to measure the thermal comfort domain for any geographical context, I first identified its standard indicators based on the existing evidence base. According to the standard published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), thermal comfort is a function of both personal and environmental factors (ANSI/ASHRAE, 2017). The former are metabolic rate and clothing insulation. The latter are air temperature, radiant temperature (heat that radiates from a warm object), air speed and humidity. By measuring these ASHRAE factors, thermal comfort estimation models such as Fanger's Predicted Mean Vote (PMV) and the Predicted Percent Dissatisfied (PPD) (Ormandy and Ezratty, 2012) have been used. Alternatively, direct measurement (i.e., room temperature measurement over period of time) and subjective measurement (i.e., survey question about perception of home thermal environment) of thermal comfort are also used (Lamberti, 2020). These methods, however, are often costly and time-consuming to conduct at large scale over an extended period of time, especially in residential spaces (Rupp et al., 2015, Marszal-Pomianowska et al., 2021). Additionally, they are sometimes criticised for their lack consistency among respondents (Thomson et al., 2017) and in different building types and climates (Cheung et al., 2019, Lamberti, 2020).

Thus, I next selected domain indicators that are relevant to the above-mentioned standard indicators. Studies have found that home orientation and location (Mavrogianni et al., 2014, Symonds et al., 2016), as well as physical characteristics of the home including, presence of solid walls (Beizaee et al., 2021, Symonds et al., 2016), property type (Oreszczyn et al., 2006, Symonds et al., 2016), wall and roof insulation (Oreszczyn et al., 2006, Mavrogianni et al., 2012, Mavrogianni et al., 2014), construction fabric (Lamberti, 2020), glazing (Lamberti, 2020, Mavrogianni et al., 2012, Mavrogianni et al., 2014), and window to wall ratio (Lamberti, 2020) were important in predicting thermal comfort.

The age of the home is an indicator frequently identified as having an association with indoor thermal comfort (Beizaee et al., 2021, Oreszczyn et al., 2006, Lamberti, 2020). Occupancy characteristics, including number of people in household, age of head of household (Oreszczyn et al., 2006) and occupant gender and age (Lamberti, 2020) have also been identified as valuable indicators in predicting thermal comfort. One study found that occupant behaviour (e.g., opening windows) may have an important role in understanding and measuring thermal discomfort (Mavrogianni et al., 2014). Additionally, energy/thermal efficiency rating (Beizaee et al., 2021, Oreszczyn et al., 2006), indoor and outdoor temperature, indoor and outdoor relative humidity, and volume flow rate (Ma et al., 2021) have been found as indicators commonly included in models to predict thermal comfort.

A review of health vulnerability indices by Samelson et al. (2020) identified 15 variables that are related to housing and have an impact on heat exposure inside the home. However, only 6 variables were found across scientific papers across 30 countries, including the UK. These six were: construction year, central AC ownership, floor of residence, rooftop albedo, thermal mass, and housing quality (which was often not adequately characterised). Other variables deemed crucial by Samelson et al. but not found in their review included window properties, insulation levels, window-to-wall ratio and housing type. The lack of presence of these variables is primarily attributed to lack of data by the authors.

3.2.3.1 Domain diagram

To illustrate each domain and the relationship between its respective indicators, I created domain diagrams. These diagrams highlight both standard (◇) and domain (☐) indicators, as well as their relationship to one another. Additionally, where an identified indicator refers to or is significantly related to a meta-characteristic or other domain, this is indicated by the colour of the indicator box (blue and light blue, respectively). The thermal comfort domain diagram is presented in Figure 3.2. Domain diagrams for the remaining housing quality domains are provided in Appendix 9-5 through Appendix 9-16.

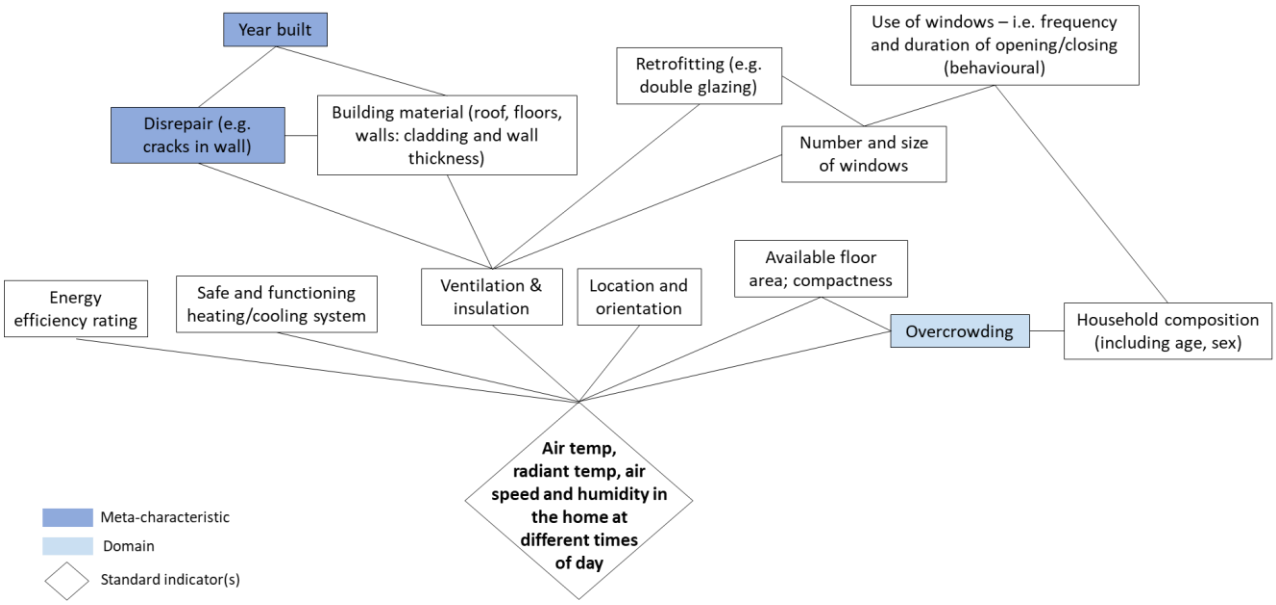


Figure 3.2. Domain diagram for thermal comfort domain

3.2.3.2 Selected subset of domain indicators for thermal comfort

Availability and accessibility of data play a significant role in one's ability to measure any phenomenon. Thus, I first explored available London data sources to understand which domain indicators could be measured using the existing data. Appendix 9-4. shows the variables available in the data sources to measure the identified indicators. Based on data availability and the other three criteria, I identified that heating, insulation, ventilation, and window glazing (with year built as a covariate) could be used to measure thermal comfort in London.

3.3 Chapter summary

Chapter 3 outlines the development of a housing quality and health framework that is comprised of 13 domains, each with a set of health-relevant domain indicators that can be used to measure the domain. My conceptual housing quality and health framework and the discussed indicators add to the current body of work in this area in two ways. First, my framework has ingested the currently available research and other works (e.g., housing quality assessment tools) and built a comprehensive set of domains that collectively cover all areas of housing quality. This is different from existing frameworks as there has not been an explicit intent to fully define housing quality comprehensively, which is reflected in the lack of certain domains in the existing frameworks. Second, my housing quality and health framework goes further then existing frameworks by identifying indicators for each domain that are both standard (in current practice) or can be used as proxies. The identification and

establishment of these indicators is a strength of this work as this allows the framework to be adaptable to a myriad of scenarios, i.e., different geographies or varying availability and types of data.

This framework sets the foundation for my analyses (Chapter 5 and 6) as it provides the structure by which I conduct I measure the thermal comfort domain (i.e., using indicators) in London.

3.3.1 From framework to empirical work

My housing quality and health conceptual framework provides a comprehensive lens to understand the different components of housing quality (i.e., domains) that relevant for health. The framework is not geography specific, meaning that different geographies and choose to focus on one, multiple or all the domains in order to characterize housing quality – albeit partially or completely. The selection of domains may further be constrained by availability and access to data, time allocated to the assessment of the domain(s) and other factors (e.g., study feasibility and availability of other resources).

Figure 3.3 shows the progression of the development of the conceptual framework (Chapters 2-3) to the empirical work conducted (Chapters 4-6) in this thesis. Among my 13 housing quality domains, those that are pressing for London are discussed in Section 3.2.2. Of these, one domain was selected as the focus of this thesis' case study due to data and time constraints. In the following chapters, present the development of a thermal efficiency metric for London and its association to health outcomes. I start by first providing an overview of the data used for my analyses in the next chapter, Chapter 4.

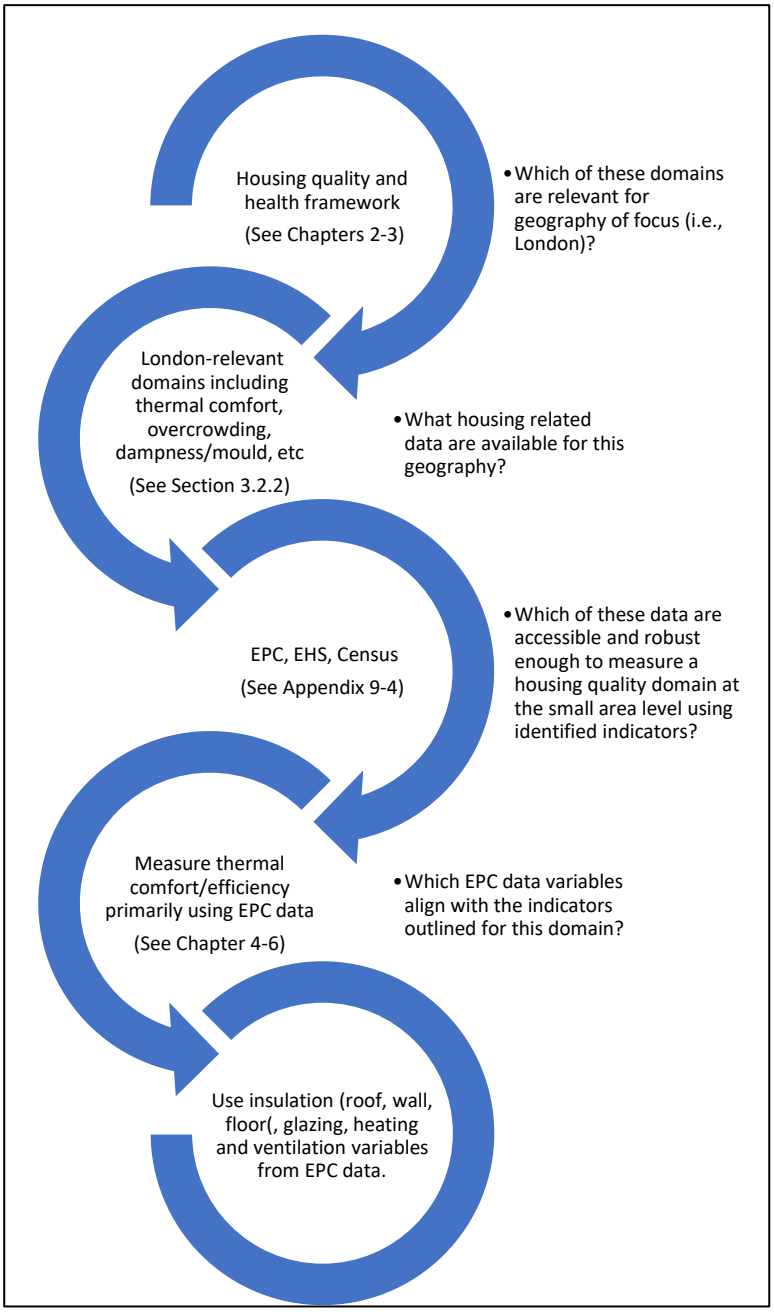


Figure 3.3. Flow from conceptual framework to empirical work

4 Exploration of data sources for a housing quality domain

In my first analysis (presented in Chapter 5), I measure home thermal efficiency at the small area level (Lower Super Output Area, LSOA) in London by integrating multiple housing-related datasets and also explore the association between the thermal efficiency metric and socioeconomic deprivation. In order to achieve this, I first identified and explored London data sources that are relevant to housing quality, thermal comfort and thermal efficiency within the home. This chapter provides an overview of my exploration of these different data sources. The main data source I use in my analysis is Energy Performance Certificates (EPCs) due to its suitability to measure domestic thermal-related variables and is consequently the focus of this chapter. In Section 4.1, I first give an overview of EPCs, then provide descriptives and then finally discuss the reliability of their data. In Section 4.2, I give an overview of other data sources I use, including the UK Census, "Dwellings by Property Build Period and Type" dataset, and the Index of Multiple Deprivation.

4.1 Energy Performance Certificates

To measure the domestic thermal environment within a home in London, I primarily use EPC data. EPCs are a key component of the European Union's Energy Performance of Buildings Directive, initially proposed in 2002 and most recently updated in 2018 (Official Journal of the European Union, 2018). The directive was proposed as buildings account for nearly 40% of final energy consumption across EU countries (European Commission, 2011). The purpose of EPCs is to provide information about a home's energy efficiency, use and cost, as well as an energy rating and recommendations on how to save money by reducing energy use.

In England, EPCs are conducted by accredited energy assessors, valid for 10 years, and have been required when a building is built, sold, or rented since 2008. EPC data are publicly accessible at the individual property level from the Department for Levelling Up, Housing & Communities. There are over 80 variables in the EPC data including property type; annual cost of heating; hot water and lighting; CO_2 emissions per year in tonnes/year; and type of heating system (full variable list in Appendix 9-17).

Based on the data gathered during the energy assessment of a building, the Standard Assessment Procedure (SAP) calculation is used to produce a domestic EPC rating. The reduced SAP (RdSAP) is used for existing dwellings and incorporates assumptions based on the housing requirements that were present when the dwelling was built. The EPC band (or rating) ranges from A (rating of 92+) to G (rating of 1-20), i.e., most energy efficient to least energy efficient. The SAP methodology has undergone some scrutiny. Murphy et al. (2011) highlighted the potential underestimation of heating

requirements for low-energy dwellings by using the SAP, which could have policy implications as building energy-efficient homes and increasing the energy efficiency of the existing housing stock are key focus areas for the UK government (Ed Potton and Hinson, 2020).

EPCs are used for a variety of reasons besides providing an energy rating for homes (Pasichnyi et al., 2019, Jenkins et al., 2017, Hardy and Glew, 2019). One of the most common areas where EPCs are relevant is policymaking – e.g., the UK's Minimum Energy Efficiency Standard (MEES), which set the minimum energy efficiency level for domestic private rented homes to EPC band E from April 2020 onwards (Department for Energy Security and Net Zero and Department for Business, 2020). EPCs have also been found to have an impact on housing prices, though the presence and magnitude of this impact vary by country (Coyne and Denny, 2021).

4.1.1 EPC data descriptives

I downloaded EPC data, at the individual property level from the Department for Levelling Up, Housing and Communities, from 01 October 2008 to 30 September 2021. The downloaded dataset includes more than 3.3 million London EPCs (i.e., EPCs combined across the 33 boroughs). For the purpose of my analyses, I only included years with data for all months of the year. Thus, EPCs conducted before 2009 and in 2021 were excluded (n=307,326). EPCs which did not meet the following plausibility criteria were also excluded:

1. The number of habitable rooms in the home was less than the number of heated rooms in the home (n=294)
2. The number of fixed lighting outlets was less than the number of low-energy fixed lighting outlets (n=677)
3. Total floor area was less than 10 m^2 (n=6,548)

EPCs missing data for key housing-related variables, including construction year band, tenure, built form, and housing insulation variables, were also dropped (n= 525,226). Finally, where multiple EPCs existed for one address in a given year, only the most recent EPC for that address for that year was included (n= 80,404, see Appendix 9-18 on detailed overview of EPC multiplicity). The final number of EPCs included for my analysis was 2,396,328.

On average, approximately 199,694 EPCs are available for London annually. The number of EPCs in London in a given year ranged from 134,382 in 2017 to 303,564 in 2009 (Table 4.1). The generally decreasing trend in the number of EPCs is not unexpected as EPCs are valid for 10 years and earlier years would require more homes to get an EPC as the requirement was undergoing implementation.

Table 4.1. Distribution of London EPCs by year

Year	Number of EPCs
2009	303,564
2010	228,993
2011	163,604
2012	181,703
2013	228,766
2014	224,409
2015	184,835
2016	154,379
2017	134,382
2018	169,125
2019	211,983
2020	210,585

EPC data have good spatial coverage, i.e., there is at least one EPC in each LSOA in a given year though the range is wide – for instance, in 2011 the range was between 2 and 229 EPCs per LSOA. As this level of detail is difficult to view from the whole city view, I observed the spatial coverage of EPCs separately for each borough. For example, the London borough Kingston upon Thames has 98 LSOAs (based on 2011 Census). The range of EPCs per LSOA in this borough is 9 to 227, between 2009 and 2020. As expected, areas with more households also show a greater number of issued EPCs (Figure 4.1 A). The distribution over time follows somewhat of a U shape (Figure 4.1 B), which is expected as the first peak reflect the implementation of EPCs and the second peak reflects when many homes would need to renew their EPCs as it would have reached its expiry date (i.e., 10 years). The renewal peak is not as high as the initial peak, however. This could be due to a number of reasons, such as many homes not renewing their EPC when it expires since an EPC is only required when a home is built, sold, or rented.

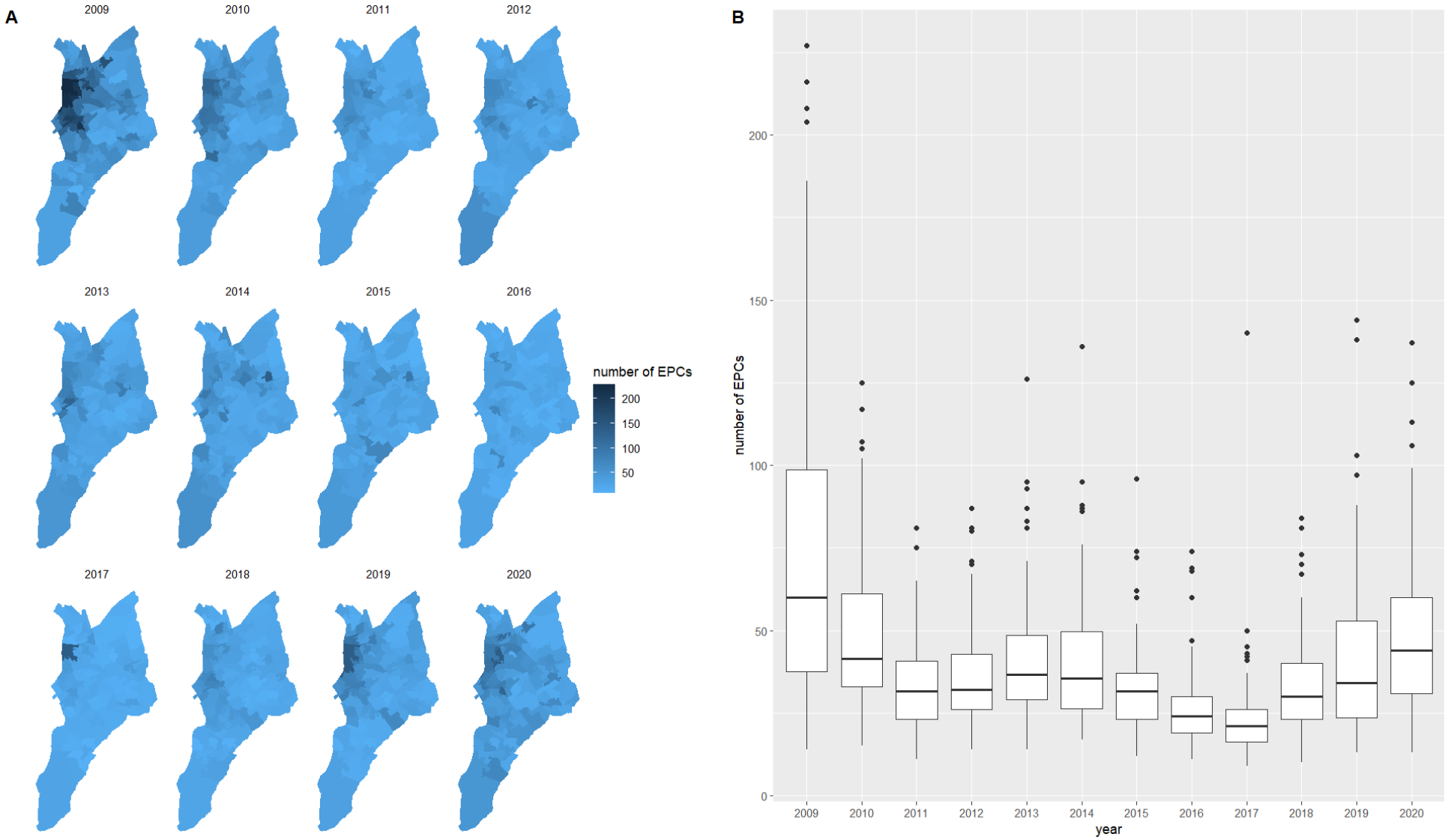


Figure 4.1. Distribution of the number of EPCs issued per LSOA in London borough of Kingston upon Thames between 2009 and 2020, via (A) map and (B) boxplot

4.1.2 Descriptives of a selection of housing-related EPC variables

Besides energy efficiency related variables, EPC data provide information on a number of housing variables including tenure, property type and year of construction. London is unique from other regions on the UK with respect to tenure and property type (see Section 2.2.1). Tenure can be classified as home ownership or rent, which can be either private or social. In the EPC data, the breakdown of tenure is 44.9%, 34.9% and 20.2% for own, private rent and social rent respectively. For property type, 61.2% of homes in London are flats and 38.8% are houses. When observing these two variables jointly (Figure 4.2), I observe that 56.1% houses are owned and 75% and 75.9% of flats are either private or social rent, respectively.

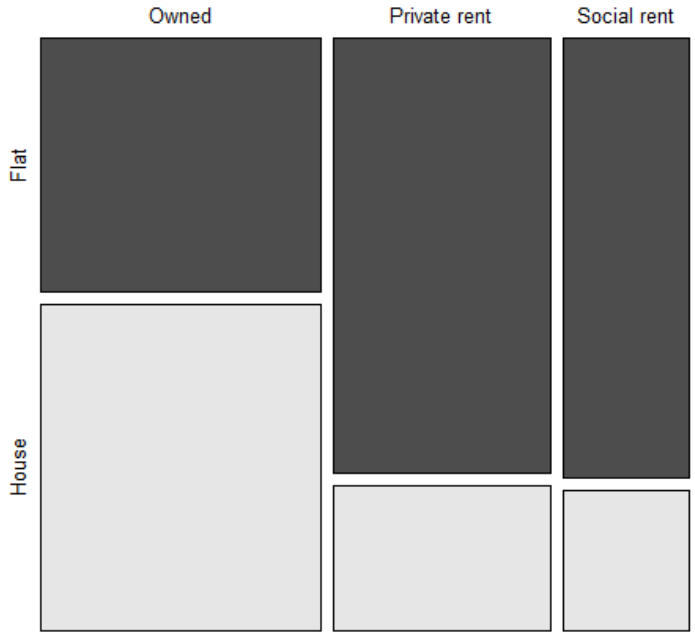


Figure 4.2. Tenure and property type among London EPCs (2009-2019)

The construction period of a home is significant as it has implications on how the dwelling was buit (e.g., design and materials used), and thus consequently impacts housing quality. The UK has one of the oldest housing stocks in Europe, which is also reflected in London's housing stock. Figure 4.3 shows that the majority of homes in London were built before 1950. Nonetheless, there was boom in home construction in the 1960s and 1970s with over 400,000 homes built in 1968 alone (Turner, 2015). A large portion of these homes were built by local authorities, with about 55,000 being residential tower blocks (Turner, 2015).

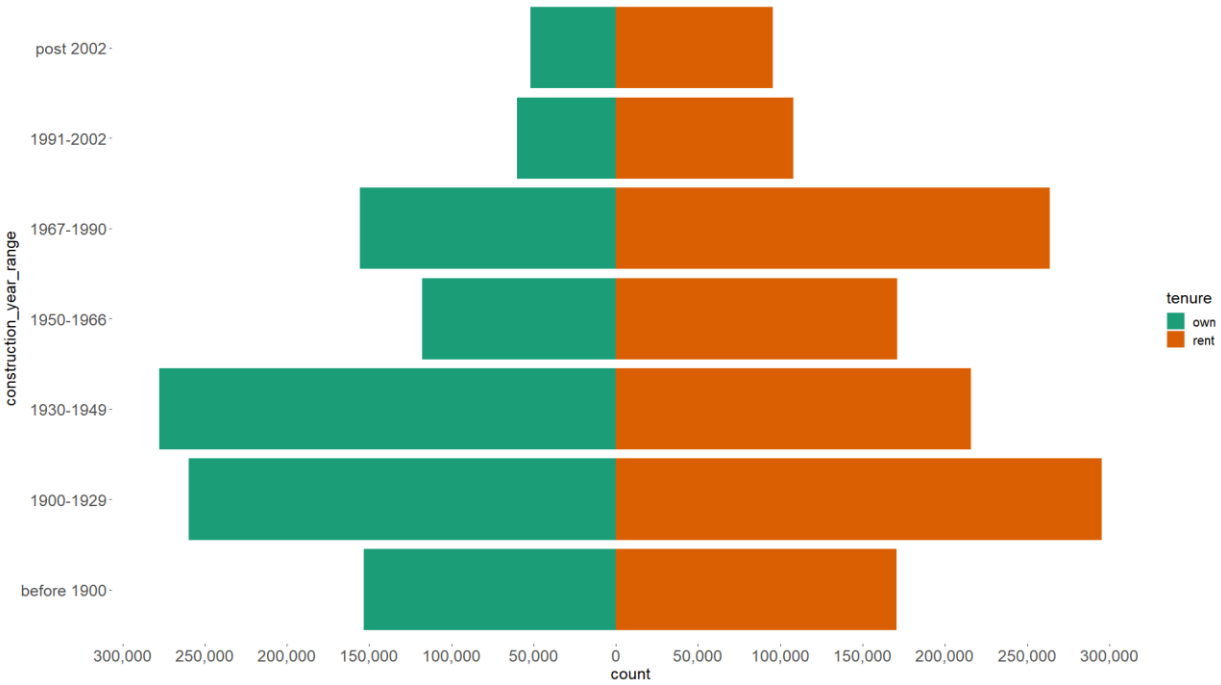


Figure 4.3. Construction year range by tenure of London EPCs

Ultimately, one of the main purposes for domestic EPCs is to obtain an estimate of the energy efficiency of homes. Figure 4.4 illustrates the cumaltive proportion of EPCs by energy efficiency rating between 2009 and 2020. As described above, the ratings for energy efficiency range from A (good energy efficiency) to G (poor energy efficiency). Over time, London EPCs show that there are fewer homes with the lowest energy efficiency ratings (E-G). Factors that contribute to this trend include retrofitting as well as the construction of new homes that are more energy efficient.

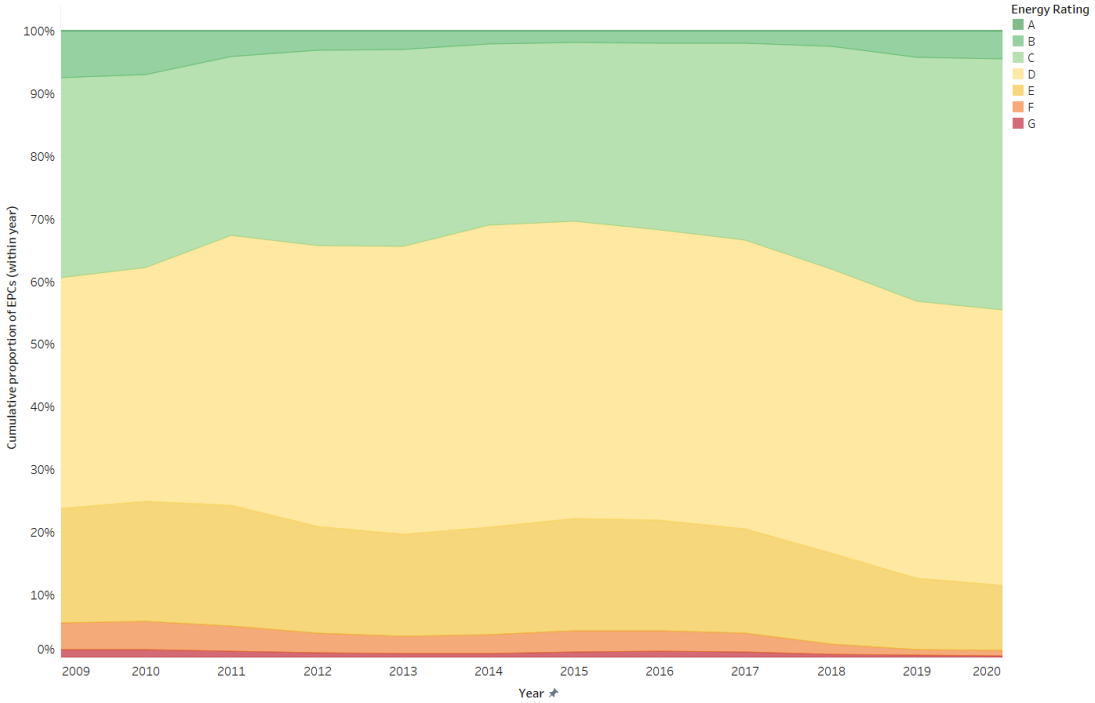


Figure 4.4. Cumulative proportion pf energy efficiency ratings by year for London EPCs

4.1.3 EPC data reliability

Despite the usability and strengths of EPC data, it has some limitations and concerns about the accuracy and reliability of the data have been raised. Factors that can potentially contribute to uncertainty in EPC data may be related to data collection, data lodgement, and modelling assumptions, among other things.

As mentioned, the value for energy consumption in the home is estimated for English EPCs, i.e., not measured. A recent study conducted in 1,374 British homes compared EPC to smart-meter measured annual energy use and found that homes with worse EPC ratings were more likely to show a significant difference from the meter measurement (Few et al., 2023). This highlights what has been called the "thermal performance gap", where homes that are more energy efficient often use more energy than expected, and homes that are less energy efficient often use less energy than expected. This phenomenon has been described and summarised elsewhere (Few et al., 2023, Cozza et al., 2020, Pasichnyi et al., 2019).

The calculations used for EPCs currently is based on the inspection and documentation of a qualified energy assessor. The assessments themselves are prone to errors that may arise due to the subjectivity of each assessor. One experiment attempted to observe this by conducting repeated assessments for 29 homes by different assessors and comparing the results based on their consistency and quality (i.e., via checking the recommendations provided and any evidence for following procedures properly) (Jenkins et al., 2017). Despite the small sample size, differences in the EPC assessment were found – some variables, such as total floor area and roof energy efficiency, showed the most inconsistency across assessments. Additionally, the information provided only gives insight on the presence of relevant characteristics in the home (e.g., heating system), but not the state of the items (Crawley et al., 2019).

Hardy and Glew (2019) published an analysis of 16 types of identified errors in EPCs, including EPCs with the same inspection date and building structure discrepancies (e.g., floor type, wall type) for the same property. They found that in the total EPC dataset, 27% of EPCs had at least one type of error. This figure was much higher among EPCs, which have been repeated for an address – 62%. This is not surprising, however, as one should note that once an EPC is lodged into the portal, it is impossible to edit. Thus, if an error exists in the initially entered data, a second separate EPC must be lodged. The study also found that error rates across different local authorities varied, though London had the highest error rate across England and Wales (Westminster borough had the highest error rate overall).

Crawley et al. (2019) attempted to quantify the uncertainty of the England and Wales EPCs between 2008 and 2016, which is before the 10-year expiration timeframe. Focusing on EPCs from existing dwellings (i.e., that use the RdSAP methodology), they found that dwellings that had 2 EPCs did not necessarily exhibit a positive change in their EPC band – in fact, 48% of dwellings remained in the same EPC band and 19% of EPCs even had a worse EPC band in the second EPC. Thus, multiple EPCs for a home within a short period of time may not be a result of retrofitting or other changes made by residents to "better" their home. Nonetheless, according to their model, a higher true EPC rating was less prone to error and misclassification than a lower EPC band.

Taylor et al. (2019) found the EPC dataset is reasonably representative of the English housing stock by comparing it to data from the English Housing Survey. Moreover, the analysis of EPC errors found that the errors identified only contributed to an average change of 4 points in the energy efficiency rating (Hardy and Glew, 2019). For EPC auditing, quality assurance requires that EPCs within 5 points of the audit value at least 95% of the time. This means that despite the observed errors, the EPCs would pass the audit.

Thus, despite the uncertainty and limitations of the scope of the EPC data, EPCs are a valuable source of data to measure domestic thermal efficiency in London. Data accessibility is a key consideration when preparing for data analysis. EPCs are one of the very few publicly available address-level datasets on housing in London. The temporal and spatial coverage of the EPC data also provides significant benefits for data analysis, especially compared to its counterparts like the English Housing Survey (EHS). The spatial and temporal robustness of the EPC data allows for geographic and time-related variability to be accounted for, as well as increases the reliability and generalizability of the data.

4.2 Other London housing-related data sources

In Chapter 5, I describe my methodology for developing my home thermal efficiency metric. While the primary data source for this metric is the EPC dataset, additional auxiliary housing-related data sources are needed with overlapping housing variables to conduct my small area estimation of home thermal efficiency. The two auxiliary data sources I use are the UK Census and the "Dwellings by Property Build Period and Type" dataset from the Valuation Office Agency (VOA).

The **Census** in England is conducted every 10 years, most recently in 2021, though data from the 2021 census had not been released at time of the analysis. The Census surveys every household in England but data are available only at aggregated geographical levels, such as the LSOA. Despite its poor temporal resolution, being conducted once every decade, the Census' complete spatial coverage of

London make it a strong auxiliary data source to provide robust insight into the geographic variation among London's LSOAs for variables of interest. While housing-related variables in the Census (Appendix 9-19) are limited, I use data on LSOA tenure (i.e., proportion and counts owned vs rented homes) and property type (i.e., proportion and counts of house versus flats) to supplement the EPC data in my analysis.

The "**Dwellings by Property Build Period and Type**" dataset made available by the VOA (2014) via the London Datastore includes data on property type and build period are provided separately at the local authority, MSOA and LSOA geography units. These data have only been provided once, in 2014-15 and are calculated based on domestic property data held by the VOA. Home age is defined using seven categories that broadly align with the pre-/inter-/and post-war housing periods: pre-1900, 1900-1929, 1930-1949, 1950-1966, 1967-1900, 1991-2002, and post-2002. The EPC dwelling construction year variable was also aggregated to align with these time periods.

To explore the association between my thermal efficiency score and socioeconomic deprivation, I additionally used data from the **English Index of Multiple Deprivation** (IMD)(McLennan et al., 2019). The IMD is the official measure of relative deprivation for small areas in England and is composed of seven domains with varying weights: income deprivation; employment deprivation; education, skills and training deprivation; health deprivation and disability; crime; barriers to housing and services; and living environment deprivation (Smith et al., 2015). The latter two domains are particularly associated with housing quality. The barriers to housing and services domain measures physical/geographical and financial (i.e., affordability) accessibility of housing and local services. The living environment deprivation domain measures the quality of the indoor (e.g., presence of central heating) and outdoor (e.g., air quality and road traffic accidents) living. As such, in my analyses, I only use data from the two domains that measure socioeconomic deprivation (Income and Employment). These two domains have the largest contribution to the IMD (43% combined).

5 Estimating home thermal efficiency at the small area level in London

This chapter presents the development of my small area home thermal efficiency metric for London, using the data described in Chapter 4. I first introduce the concepts of thermal comfort and thermal efficiency, then describe the methodology that I use to develop the domain metric, and finally present and discuss the methods and results of my small area estimation.

5.1 Overview of thermal comfort and thermal efficiency

5.1.1 Thermal comfort

Thermal comfort is a key element of healthy housing and is defined as the state of mind that is satisfied with the thermal environment and relates to both low and high temperatures (World Health Organization, 2018). According to ASHRAE, thermal comfort is a function of both environmental and personal factors (American Society of Heating, 2021). Environmental factors include indoor air temperature, radiant temperature (heat that radiates from a warm object), air speed, and humidity. Personal factors include clothing insulation and metabolic rate, which might vary by age, sex, health status and geographic location.

Key determinants of thermal comfort, based on the literature (Carlucci and Pagliano, 2012, Lamberti, 2020, Enescu, 2017), include home orientation, location (Mavrogianni et al., 2014, Symonds et al., 2016) and dwelling age (Beizaee et al., 2021, Oreszczyn et al., 2006, Lamberti, 2020), as well as physical characteristics of the home including, presence of solid walls (Beizaee et al., 2021, Symonds et al., 2016), property type (Oreszczyn et al., 2006, Symonds et al., 2016), wall and roof insulation (Oreszczyn et al., 2006, Mavrogianni et al., 2012, Mavrogianni et al., 2014), construction fabric (Lamberti, 2020), window glazing (Lamberti, 2020, Mavrogianni et al., 2012, Mavrogianni et al., 2014), and window to wall ratio (Lamberti, 2020).

The most common methods to estimate thermal comfort are i) direct measurement of room temperature, ii) surveying perception of thermal comfort, and iii) estimation models of thermal comfort such as Fanger's Predicted Mean Vote (PMV) and Predicted Percent Dissatisfied (PPD)(Ormandy and Ezratty, 2012).

While direct measurement of temperature is commonly used as a proxy of thermal comfort (Lamberti, 2020), it is costly and time-consuming to conduct at large-scale over an extended period of time, especially in individual houses (Rupp et al., 2015, Marszal-Pomianowska et al., 2021). It also is not the most accurate measure of thermal comfort as it does not fully account for residents' perception of

whether the temperature is comfortable to them. Housing surveys, such as the English Housing Survey, use residents' perception as a proxy for thermal comfort measurement (Lamberti, 2020) via survey questions such as "*During the cold winter weather, can you normally keep comfortably warm in your living room?*" (Department for Levelling Up, 2021). Such subjective measures are criticised for their lack of reliability and consistency (Thomson et al., 2017, Wang et al., 2018). For instance, age may be a confounding factor in thermal comfort perception as the young and elderly are much more sensitive to temperature (Ormandy and Ezratty, 2012). The PMV-PPD model (de Dear and Brager, 1998) is commonly used in setting thermal comfort standards internationally. PMV is an index that uses votes from a group to measure a mean value of their thermal sensation. PPD, which is based on the PMV, computes the proportion of people who would not be comfortable in a specific thermal environment. Though these seem to be a less subjective measures, there are concerns about their applicability and accuracy in different building types, climates and susceptible groups (Cheung et al., 2019, Lamberti, 2020, Ormandy and Ezratty, 2012, de Dear and Brager, 1998, Arakawa Martins et al., 2022, Xie et al., 2020, Zhang et al., 2022, Danks et al., 2021).

5.1.2 Thermal efficiency

Due to the personal and subjective factors that are inherent to thermal comfort, it is difficult to define and measure. A closely related measure, which is sometimes used interchangeably, is domestic thermal efficiency, which refers to a home's ability to maintain a comfortable indoor temperature as a result of its physical properties. In other words, it establishes whether a home has the characteristics needed to provide its occupants with a thermally comfortable indoor home environment. Energy efficiency of a home is also very often used as a synonym for thermal efficiency inaccurately. Energy efficiency relates to the use of less energy to heat, cool and run a building (i.e., reducing emissions). Thus, while this broader term does incorporate the notion of thermal efficiency, it is a separate phenomenon.

Though thermal efficiency is often incorporated into measurements of thermal comfort and energy efficiency, there are more instances where it is measured relative to the features of the housing stock or house (and their condition). A country-level study by Healy (2003) used levels of cavity wall insulation, roof insulation, floor insulation, and double glazing to measure thermal efficiency. Beyond insulation and window glazing, construction material, windows (size, placement, and other treatments such as adding blinds), doors, and heating are discussed and used a key indicators of thermal efficiency (Mothibi, 2005, Sustainability Victoria, 2019, Zero Carbon Hub, 2015). In addition, reduction of air leakage or draughts is vital to improving domestic thermal efficiency as sealing the home may

significantly reduce heat loss. This, however, must be balanced with the need for sufficient ventilation in the home, otherwise houses may face issues such as moisture buildup and overheating.

The UK Building Standard (Department for Levelling Up, 2023) used the U-value (W/m^2k), which is a measure of thermal transmittance where a lower value means better insulation (i.e., less heat loss), to set regulations to improve home energy efficiency. The standards provide different criteria for existing dwellings with existing elements (Figure 5.1), existing dwellings with new elements and new dwellings.

Element	U-value[1] W/(m²·K)	
	(a) Threshold	(b) Improved
Roof[2][3][4]	0.35	0.16
Wall – cavity insulation[2][5]	0.70	0.55
Wall – internal or external insulation[2][6]	0.70	0.30
Floor[7][8]	0.70	0.25

Figure 5.1. Limiting U-values for existing elements in existing dwellings from (Department for Levelling Up, 2023)

Similar to the measurement of thermal comfort, it is costly to produce such a measure over time for all homes within an area. Despite its importance, a thermal efficiency metric using publicly available data does not exist. In my first analysis, which I present in Section 5.2, I develop a thermal efficiency metric that captures the physical components that are required/prerequisite for good thermal efficiency in a London home. Developing a metric using the physical components of a home is important from a policy perspective as this can often be more straightforward to address via improved by targeted interventions. In the later sections of this chapter, I use this metric to estimate mean thermal comfort in London and explore the relationship between thermal comfort and socioeconomic deprivation.

5.1.3 Home thermal environment and health in the UK

5.1.3.1 High temperatures

In the UK, high indoor temperatures, and their health consequences, are becoming an increasing concern as the impact of climate change has yielded periods of high temperatures and this is expected to become more frequent and increase in intensity – especially in areas in the south of England such as London (Climate Change Committee, 2022). Kennedy-Asser et al. (2022) showed that regions of London were among the areas in the UK with higher heat risk when considering both climate hazards

and levels of socio-economic vulnerability (i.e., measured by combining IMD, proportion of population aged older than 65 years and population density), between 1990 and 2019 (Figure 5.2). London also has the recorded higher temperatures compared to its surrounding areas of up to 7°C (Climate Change Committee, 2022) due to the urban heat island effect. A report for the Energy Follow Up Survey (EFUS) states that the prevalence of overheating in living rooms and main bedrooms is higher in London compared to other regions of the UK – 28% versus 13% and 32% and 17% respectively (Department for Energy Security and Net Zero and Department for Business, 2021).

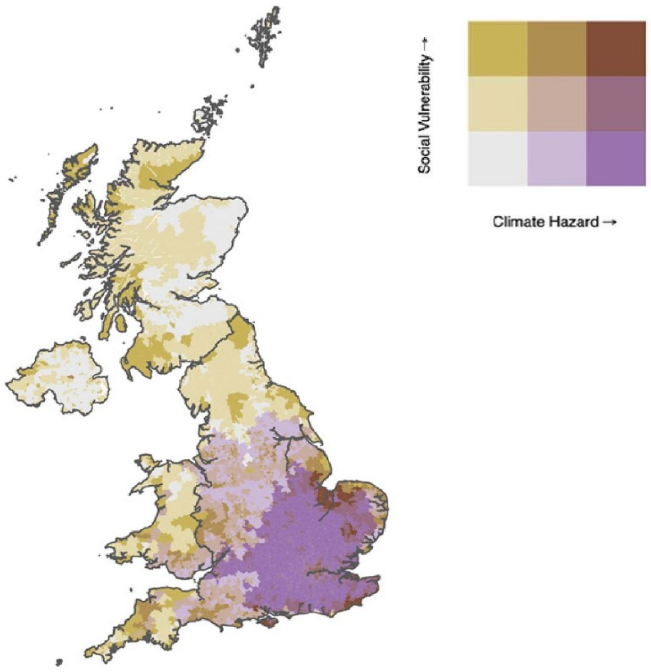


Figure 5.2. Relative risk, in terms of climate hazards and socio-economic vulnerability, across UK, from (Kennedy-Asser et al., 2022)

High temperatures can lead to a number of negative health outcomes both directly and indirectly. Vulnerability to these consequences is exacerbated by different sociodemographic factors, particularly in UK cities such as London. Evidence exists that higher indoor temperature is associated with heatstroke, dehydration, hyperthermia, and mortality (Ormandy and Ezratty, 2012, World Health Organization, 2018, World Health Organization Europe), as well as respiratory health (Sun et al., 2021), diabetes management, schizophrenia and dementia symptoms (Tham et al., 2020), maternal health (especially risk of preterm birth), mental health (especially increase in suicides), and risk of unintentional injuries (Climate Change Committee, 2022). A review by Arbuthnott and Hajat (2017) found that overall studies have found that increased summer temperatures are associated with a range of health outcomes including an increase in hospital admissions, myocardial infarctions, birth

outcomes, and – most consistently – heat-related mortality. The UK Climate Change Risk Assessment's conservative estimate for the economic burden of heat related deaths in the UK is between £260 million - £300 million per year. When the cost of heat-related morbidity is also accounted for, figures could be between £720 million - £950 million per year by the 2050s (Climate Change Committee, 2022).

5.1.3.2 Low temperatures

A recent Building Research Establishment (BRE) Trust report found that excess cold was the second most common serious hazard (the first being falls-associated hazards) in the housing stock in England, Wales and Northern Ireland (Piddington et al., 2020). Cold homes are associated with insufficient insulation and fuel poverty . The UK Department of Business, Energy and Industrial Strategy found that 13.2% of households in England (3.16 million) lived in fuel poverty in 2020, an improvement compared to 2010 (22.1%) that is attributed to improved energy efficiency and insulation of homes (Department for Business, 2022). However, the significant impact of the COVID-19 pandemic coupled with rapidly rising energy costs were estimated to increase the proportion of fuel-poor homes in England to 32% by October 2022, potentially reaching 66% by January 2023 (Department for Business, 2021).

Cold indoor temperatures are associated with increased risk of cardiovascular and respiratory diseases, hospital admissions, mortality in infants and mental health (Ormandy and Ezratty, 2012, World Health Organization, 2018, World Health Organization Europe, 2011). Countries, such as the UK, with more temperate and mild climates (i.e., not extreme heat in summer nor extreme cold in winter) often have homes with poor domestic thermal efficiency and consequently face greater winter mortality (World Health Organization, 2018, Geddes et al., 2011) – this is sometimes referred to as the "paradox of excess winter mortality". There are also economic implications, with health conditions due to cold private housing costing the NHS over £850 million annually (Public Health England, 2014).

Aylin et al. (2001) observed the relationship between temperature, housing, deprivation and excess winter mortality in Great Britain, among the 65+ population, between 1986 and 1996. The study found that there was an increased odds of mortality as outdoor temperatures decreased (1.5% higher odds for 1 °C decrease in the 24-h mean winter temperature below the 10-year national average). Not having central heating (from the UK Census) was significantly associated with a higher risk of mortality from all-causes (OR: 1.016, 95% CI: 1.009–1.022), coronary heart disease (OR: 1.017, 95% CI: 1.005–1.029), and stroke (OR: 1.029, 95% CI: 1.011–1.048). The association with mortality from respiratory

conditions was not significant (OR: 1.014, 95% CI: 0.998–1.031). Deprivation was not significantly associated with mortality from any cause.

Rudge and Gilchrist (2005) conducted a similar study looking at the impact of cold homes on excess winter morbidity in an older population. The study population, however, was limited to the London borough of Newham. A small area index of fuel poverty risk was developed using proportion of poor housing (defined as extent of homes with energy efficiency ratings below the 1991 national average), under-occupation (i.e., undercrowded home) and other factors. High fuel poverty risk showed a higher winter/summer morbidity ratio (OR: 1.7, 95% CI: 1.1–2.7 and OR: 1.6, 95% CI=0.9–2.8 in 1993 and 1996, respectively) compared to non-high fuel poverty risk.

The National Institute for Health and Care Excellence (NICE) identified four factors that should be taken into account when attempting to understand the cause for a cold home and its effect on residents' health: (1) efficiency of the heating system, (2) insulation of the home, (3) residents' ability to afford heating their home (i.e., income, cost of fuel which also relates to the temperature the home needs to be for the residents and how long the heating needs to be on), and (4) residents' vulnerability to cold due to age or existing medical conditions (National Institute for Clinical Excellence (NICE), 2015). Figure 5.3 presents NICE's simplified representation these four factors and their association between cold homes and health. I have circled in red the components that are related to the actual physical home, as this is the focus of this project.

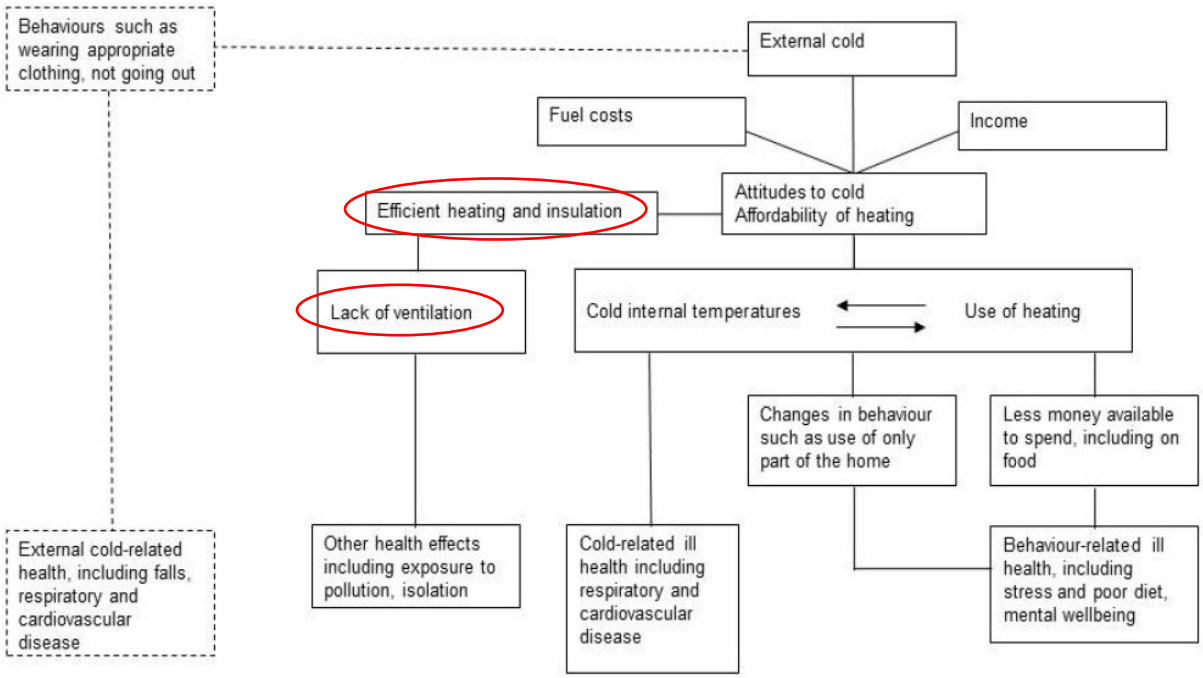


Figure 5.3. Pathways relating cold homes and poor health outcomes, from (National Institute for Clinical Excellence (NICE), 2015). *Red circles added for emphasis.*

5.1.3.3 Housing interventions and health outcomes

One way to combat the above-highlighted associations between the home thermal environment and health outcomes is housing interventions. Thomson has led a series of systematic reviews (Thomson et al., 2001, Thomson et al., 2009, Thomson et al., 2013) to summarise the evidence on housing interventions and their benefits to a range of health outcomes. These reviews are summarised below in Table 5.1. The most recent review, a 2013 Cochrane review, found that warmth-related interventions could potentially improve overall, respiratory, and mental health. These interventions also had indirect effects on health such as improving social relationships and decreasing absenteeism due to being sick.

Table 5.1. Summary of systematic reviews on housing interventions and health by Thomson et al

Publication year	Review period	Number of studies	Types of housing interventions	Health outcomes
(2001)	Up to 2000	18	• Rehousing • Refurbishment • Energy efficiency measures	• Self-reported physical • Mental health • Decreased visits to general practitioner • Reduced prescribing of hypnotic and respiratory drugs
(2009)	1887 - 2007	45	• Warmth and energy efficiency improvements (post-1985) • Rehousing or retrofitting ± neighbourhood renewal (post-1995) • Rehousing from slums (pre-1970) • Provision of basic housing (e.g., latrine) in low- or middle-income country (post-1990)	• General health • Respiratory health • Mental health • Illness or symptoms
(2013)	1887 - 2012	39		

5.2 Development of small-area home thermal efficiency metric

No city-wide thermal efficiency metric available at the small-area level exists. Without such a metric, it is difficult for small-area level epidemiological studies to study the health impacts of poor thermal efficiency for a city. As such, I developed a small-area home thermal efficiency metric using publicly

available data to address this gap. This metric can then be used to measure associations with health outcomes and identify hotspots of poor thermal efficiency in a city (in this case, London). My home thermal efficiency metric measures whether a home has the characteristics needed to provide its occupants with a thermally comfortable indoor home environment.

5.2.1 Methodology

To develop an LSOA home thermal efficiency metric, I first explored relevant variables in the EPC data and assessed their variability among London homes. Then, I used the selected EPC variables with auxiliary data to estimate mean home thermal efficiency score for each Lower Layer Super Output Area (LSOA) in London (N=4,835). I then explore associations between my thermal efficiency metric and socioeconomic deprivation. Figure 5.4 presents a schematic of the overall methodology of this analysis.

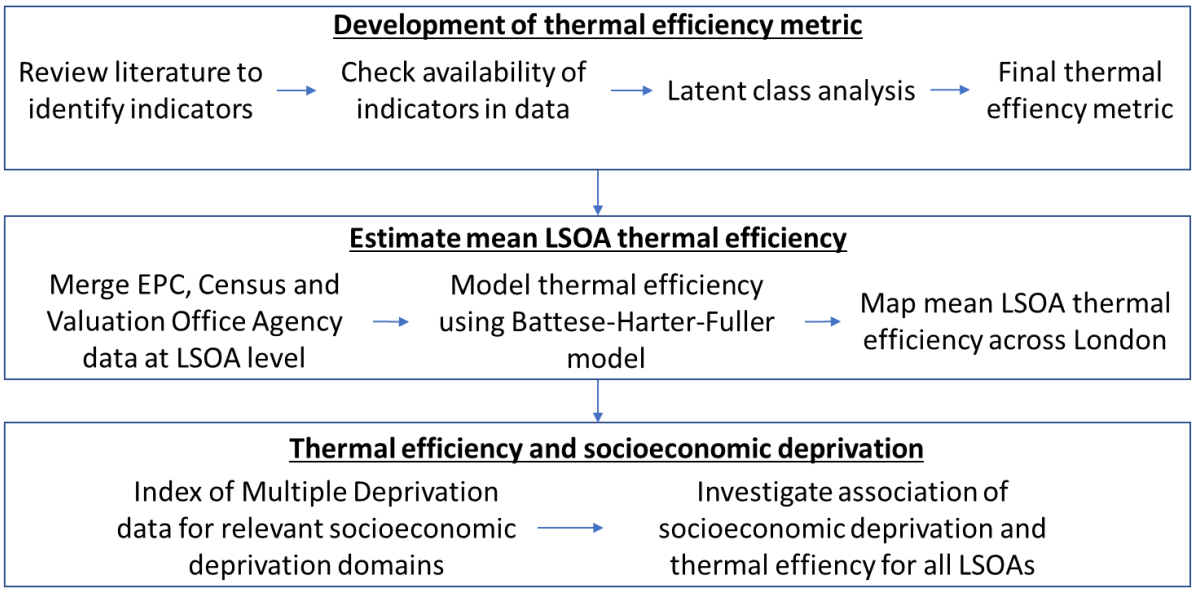


Figure 5.4. Schematic of study methodology

5.2.1.1 Data

I estimate mean thermal efficiency at the LSOA level by combining EPCs with auxiliary LSOA-level data from the Census and the VOA's "Dwellings by Property Build Period and Type" dataset. These data sources are discussed in detail in Chapter 4.

5.2.1.2 Development of thermal efficiency metric

Key determinants of thermal efficiency identified from literature are discussed in Section 5.1.2. Data availability informed the selection of variables for this analysis that developed a home thermal efficiency metric. The identified variables that were available in the EPC data were window glazing

(single vs multiple), heating (gas, electricity, other or none), ventilation (mechanical vs natural), floor insulation, wall insulation and roof insulation. The categories of measurement for the three insulation variables range from poor to very good.

Then, I conducted a latent class analysis (LCA) (Hagenaars and McCutcheon, 2002) to observe the variability of the above variables in the EPC data to ascertain which variables would be informative in estimating thermal efficiency in London. LCA is applied to categorical data and defines unobserved mutually exclusive and exhaustive classes within a population based on observed characteristics (Law and Harrington, 2016). LCA estimates the class membership probabilities and item-response probabilities. In my analysis, the first are the expected proportion of houses that are in each class and the latter is the distribution of the variables of interest within a given class. The final number of classes is found by a reiterative process in which models with an increasing number of classes are tested and compared. An LCA was conducted with 2, 3 and 4 classes and model selection was based on the Bayes Information Criterion (BIC). The LCA was used to identify patterns among variables to assess their relationships and determine how informative they might be for the small area estimation model (Section 5.2.1.4). Specifically, if a variable's conditional probability is high within one category and this is consistent across all latent classes, it may suggest that this variable does not help differentiate between the classes and, therefore, might be less informative for modelling purposes.

5.2.1.3 Descriptive statistics

Descriptive statistics (frequency and percentage) summarize the prevalence of housing and thermal efficiency characteristics. The housing characteristics included are tenure, construction year band, and property type; and for thermal efficiency characteristics, the indicators that compose the final thermal efficiency metric are included.

5.2.1.4 Small area estimation: Battese-Harter-Fuller model

EPCs supply data on a subset of homes in London over the study period (2009-2020). Estimating LSOA-level thermal efficiency solely based on these data would result in an ecological fallacy as these sampled homes would not necessarily be representative of the LSOA. Thus, I use a small area estimation (SAE) model that uses both individual-home and LSOA-level data to estimate mean thermal efficiency.

The SAE approach I used is the Battese-Harter-Fuller (unit-level) model (Battese et al., 1988), which provides the empirical best linear unbiased predictor (EBLUP) (Rao and Molina, 2015). The EBLUP leverages information from survey (i.e., EPC) and auxiliary data sources to estimate a more precise small area estimate when survey data have small sample sizes and thus cannot provide a reliable direct

estimate. The linear prediction model includes both fixed effects and random effects (to account for unexplained variability), and aims to get to the "best" combination of information from the data sources. This is assessed by the mean squared error (MSE) – where a smaller MSE is better. In summary, this linear mixed model estimates the relationship between an outcome and auxiliary variables using individual level data and then uses this relationship to build up to an area level estimate.

As such, the Battese-Harter-Fuller model is a composite model and estimates mean thermal efficiency score in an LSOA as the weighted sum of the sampled (s_a) and non-sampled homes (r_a):

$$\overline{\widehat{y_a^{EBLUP}}} = \frac{1}{N_a}\left(\sum_{i\in s_a} y_{ia} + \sum_{i\in r_a} \widehat{y_{ia}}\right)$$

where y_{ia} is the thermal efficiency score for house *i* in LSOA *a* and N_a is the total number of homes in the *a*-th LSOA (*a* =1, …, 4,835).

The sampled homes (s_a) are observed and consequently the individual level data are used to estimate their β and the random area effect:

$$\sum_{i\in s_a} y_{ia} = \boldsymbol{x}_{ia}^T\boldsymbol{\beta} + u_a + \epsilon_{ia}$$

where $\boldsymbol{x}_a^T$ is set of area-level auxiliary variables (i.e., tenure, property type and age of house *i* in LSOA *a*); u_a is a random area effect, which accounts for between-area variability not explained by covariates and is assumed to be normally distributed ($u_a \sim N(0,\sigma_u^2)$); and ϵ_{ia} is the error term.

The non-sampled homes (r_a) are predicted using the estimated β and random area affect from the sampled homes, and the area means of the auxiliary variables:

$$\sum_{i\in r_a} \widehat{y_{ia}} = \overline{X_a}\widehat{\boldsymbol{\beta}} + \widehat{u_a}$$

To assess the reliability of the estimates, the coefficient of variation (CV) is calculated. CV measures the dispersion of the data around the mean. In this study, CV is computed for each LSOA and represents the ratio of the standard deviation to the mean of the thermal efficiency metric.

5.2.1.5 Thermal efficiency and socioeconomic deprivation

I explored the difference between mean thermal efficiency of LSOAs and quintiles of two socioeconomic deprivation domains (income and employment) using the Kruskal-Wallis and Dunn's test of multiple comparisons. The first test ascertains whether at least one group (i.e., quintile) within a domain is statistically different from the others in terms of LSOA mean thermal efficiency score. Where a group is indeed statistically different, I used the Dunn's test, a multiple pairwise-comparison test, to determine which groups are different from the others. To correct for the multiple pairwise tests, the Holm-Bonferroni adjusted p-value is reported. A p-value of less than 0.05 is considered to be statistically significant for both tests.

5.2.2 Results

5.2.2.1 Descriptive analysis

Descriptive statistics of the prevalence of housing characteristics and thermal efficiency indicators for EPCs are presented in Table 5.2. As mentioned, the EPC data included over 2.3 million homes. Of this, the majority are rented with 34.9% of homes being rented privately and 20.2% of homes being socially rented. Most homes (61%) are flats and over 50% of homes were built before 1950.

When observing the thermal efficiency characteristics, the quality of floor insulation was almost equally distributed (47.5% poor and 52.5% good quality); wall insulation was more frequently poor (69.9%), and roof insulation was more frequently good (60.4%).

Table 5.2 Descriptive statistics of the housing characteristics and thermal efficiency indicators for London (2009-2020)

Variable	Freq	Percent
Housing characteristics		
Tenure		
Owned	1,075,967	44.9%
Private rent	835,431	34.9%
Social rent	484,930	20.2%
Property type		
Flat	1,466,952	61.2%
House	929,376	38.8%
Construction age range		
Before 1900	324,047	13.5%
1900-1929	554,929	23.2%
1930-1949	493,475	20.6%
1950-1966	288,857	12.1%
1967-1990	419,305	17.5%

1991-2002	168,148	7.0%
Post 2002	147,567	6.2%
Thermal efficiency characteristics		
Floor insulation		
Very good - Good	1,138,238	47.5%
Poor – Very poor	1,258,090	52.5%
Wall insulation		
Very good - Good	549,151	22.9%
Poor – Very poor	1,674,518	69.9%
Roof insulation		
Very good - Good	1,448,212	60.4%
Poor – Very poor	946,908	39.5%

5.2.2.2 Latent class analysis

An LCA was conducted on six variables that were identified for the thermal efficiency metric via literature and were available in the EPC data. The BIC of the LCA models using 2, 3, and 4 classes was similar (5,028,745 vs 4,971,221 vs 4,960,668, respectively), and thus I selected the model with the least number of classes. As shown in Table 5.3, glazing, ventilation and heating did not show much variability among homes in London, indicated by a single category within each of these variables having a conditional probability of greater than 95% irrespective of the class.

Table 5.3. Results from latent class analysis

Indicator	**Class 1** (probability)	**Class 2** (probability)
Glazing area		
Low	0.004	0.008
Average	0.970	0.951
High	0.026	0.041
Ventilation		
Mechanical	0.012	0.042
Natural	0.988	0.958
Heating area		
Less than 50%	0.014	0.010
Between 50% and 99%	0.017	0.006
Fully heated (100%)	0.969	0.984
Floor insulation		
Very poor	0.601	0.273
Poor	0.000	0.005
Good	0.002	0.001
Dwelling*	0.393	0.552
Insulated†	0.005	0.169

Wall insulation		
Very poor	0.953	0.086
Poor	0.001	0.007
Good	0.009	0.751
Insulated[†]	0.037	0.156
Roof insulation		
Very poor	0.217	0.002
Poor	0.247	0.168
Good	0.071	0.028
Very good	0.044	0.042
Dwelling[*]	0.361	0.518
Insulated[†]	0.060	0.243

[*]The dwelling category indicates where the assessor indicated another dwelling (e.g., *'another dwelling below'*, *'another premise below')* for the floor or roof insulation variable

[†]The insulated category indicates that the assessor was able to identify some type of insulation in the home, but could not necessarily make a judgement about its quality

Thus, the remaining 3 variables – floor, roof and wall insulation were combined to develop the final thermal efficiency metric for each sampled home within an LSOA (Figure 5.5). Each indicator was dichotomised with 1 for very poor or poor quality and 2 for good or very good quality. As such the thermal efficiency metric for a home ranged from 3 to 6, with a lower score indicating that the characteristics of the home are less likely to provide its occupants a thermally comfortable environment.

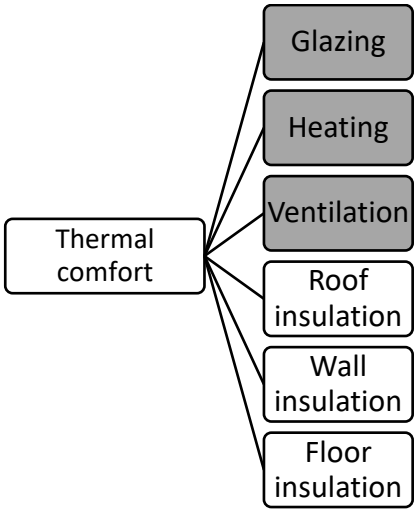


Figure 5.5. Thermal efficiency metric diagram showing the six variables selected via literature and in the EPC data and the variables excluded after latent class analysis (grey-shaded boxes)

5.2.2.3 LSOA mean thermal efficiency

The mean LSOA thermal efficiency score across London was 4.34 (SD: 0.48), ranging from 3.12 to 5.99. Figure 5.6 displays the spatial pattern of mean LSOA thermal efficiency, where a darker shade indicates a higher thermal efficiency score. Mean thermal efficiency score is higher (i.e., better) in LSOAs near central London and generally decreases with distance from the city centre.

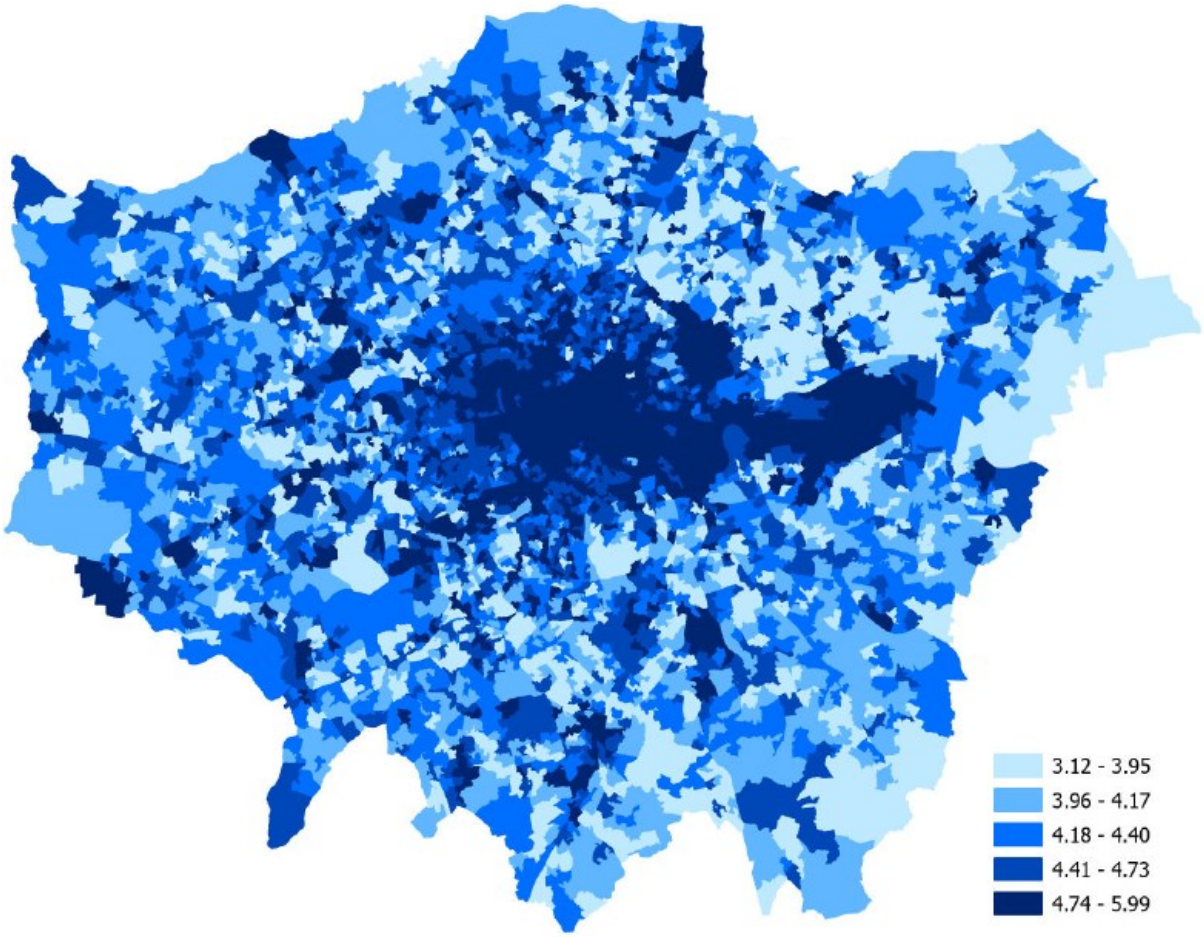


Figure 5.6. Map of mean LSOA thermal efficiency estimates for London (2009-2020)

Regression outputs are presented in Table 5.4. According to the unit level model, the LSOA home thermal efficiency score of LSOAs with a higher proportion of rented homes is 0.02 higher than LSOAs with a higher proportion of owned homes. Tenure did not have much of an effect on LSOA home thermal efficiency scores. LSOAs with a higher proportion of flats have higher thermal efficiency score ($\beta = 0.92$). LSOAs with a higher proportion of older homes are more likely to have a worse thermal efficiency score – this is especially true for LSOAs with the oldest homes (i.e., homes built after 1991, showed the strongest association with thermal efficiency).

Table 5.4. Model coefficients (β) and standard error (SE) for mean LSOA thermal efficiency score

	β	**SE**
Intercept	3.37	0.002
Rented home (tenure)*	0.02	0.001
Flat (property type) †	0.92	0.001
Home built between 1900-1929 ‡	0.00	0.001
Home built between 1930-1949	0.03	0.001
Home built between 1950-1966	0.10	0.002
Home built between 1967-1990	0.79	0.002
Home built between 1991-2002	1.44	0.002
Home built between after 2002	1.71	0.002

*Reference for tenure: owned home
†Reference for property type: house
‡Reference for construction year range: homes built before 1900

To assess the reliability of the models' estimates, the coefficient of variation (CV) was calculated (Figure 5.7). As expected, the CV decreased in areas with larger sample size. Overall, the CV is within the range of good reliability. While the average CV across all areas is 0.40, there is larger variability in areas with smaller sample sizes.

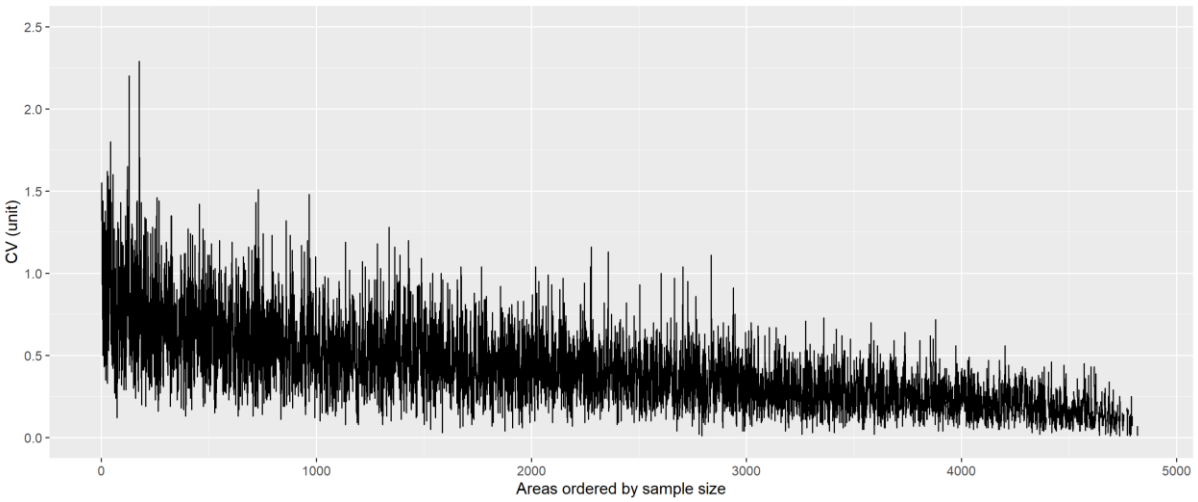


Figure 5.7. Coefficient of variation of EBLUP estimates for mean LSOA thermal efficiency score (2009-2020)

5.2.2.4 Mean LSOA thermal efficiency score and socioeconomic deprivation

I explored the association between the LSOA thermal efficiency score and two domains of socioeconomic deprivation: income and employment. According to the Kruskal-Wallis test, for both domains, at least one quintile is different in terms of LSOA mean thermal efficiency score compared to the other quintiles (income: $\chi^2_{Kruskal-Wallis} = 440.95$, $p < 0.001$ and employment: $\chi^2_{Kruskal-Wallis} = 365.96$,

$p < 0.001$). According to the Dunn test (Figure 5.8), LSOAs in the more deprived quintiles significantly differ ($p < 0.001$) from those in the least deprived quintiles in both deprivation domains.

More deprived LSOAs have a higher mean thermal efficiency score compared to the least deprived areas. However, the majority of LSOAs with the highest mean thermal efficiency score (i.e., >5.5) are in the least deprived quintile and most LSOAs with the lowest mean thermal efficiency score (i.e., < 3.5) are in the most deprived quintile – for both IMD domains (Figure 5.9).

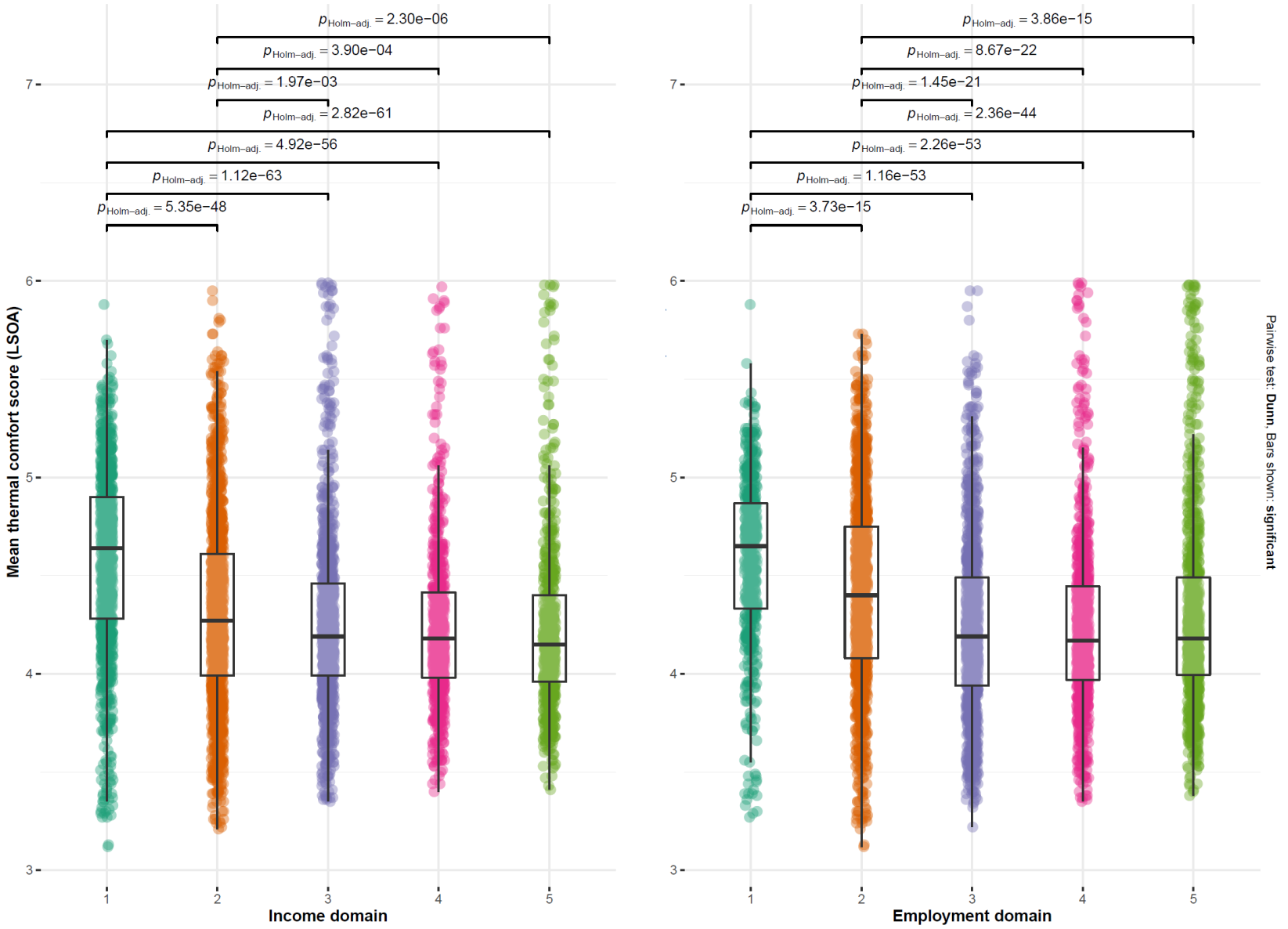


Figure 5.8. Mean difference in thermal efficiency score across (A) income and (B) employment quintiles (where quintile 1 is most deprived)

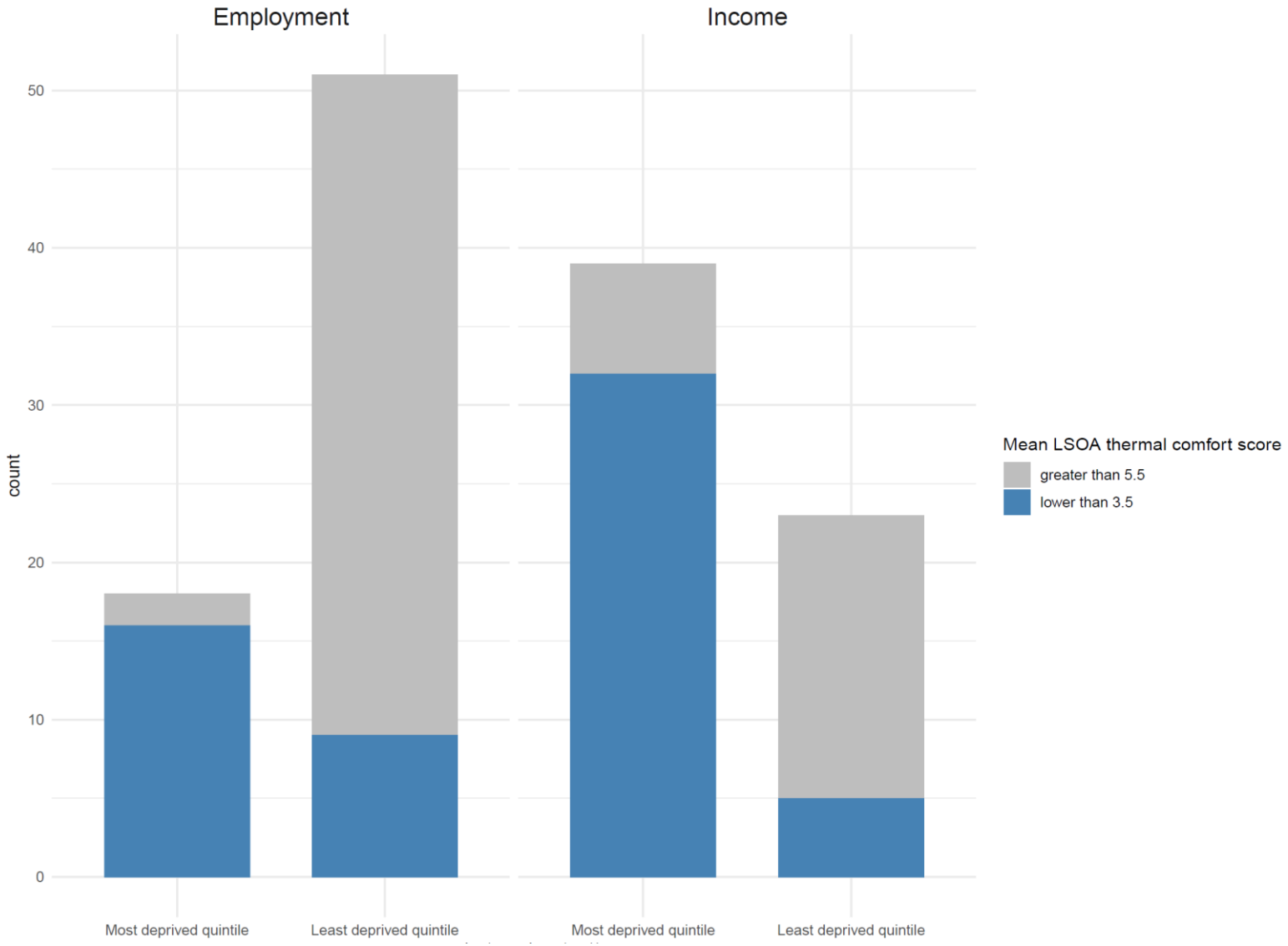


Figure 5.9. Number of LSOAs with the highest (>5.5) and lowest (<3.5) mean thermal efficiency score in the most and least deprived (A) employment and (B) income quintiles

5.2.3 Discussion

This chapter presents (1) an overview of thermal comfort and thermal efficiency, (2) the methodology for estimating mean LSOA thermal efficiency for London using the Battese-Harter-Fuller model and results, and (3) my exploration of the relationship between mean LSOA thermal efficiency and two socioeconomic deprivation domains, income and employment.

5.2.3.1 Summary of results

My thermal efficiency metric, conceptually, measures the extent to which a home has the physical characteristics needed to provide its residents with a thermally comfortable home environment. The final thermal efficiency metric was constructed using the following characteristics: roof, wall and floor insulation and ranged from 3 (low) to 6 (high).

The mean thermal efficiency score of LSOAs in London from 2009 to 2020 was 4.34 (SD: 0.48), ranging from 3.12 to 5.99, with higher scores in LSOAs found towards the centre of London. House construction year was found to be a key determinant for thermal efficiency. Older homes have worse thermal efficiency compared to more-recently built homes. This aligns with other studies that found that homes built before 1850 present the greatest risk to excess cold (Ormandy and Ezratty, 2015). The UK Office for National Statistics (ONS) recently reported that built year is the most important factor associated with energy efficiency in England – due to evolving construction methods, improved regulations, and deterioration over time (2022). It should, however, also be noted that these figures are likely impacted by the fact that older homes dominate the London housing stock (only 6.2% of the housing stock has been built in the last 21 years).

Property type was also found to be an important determinant for home thermal efficiency. Compared to houses, flats have relatively better thermal efficiency. ONS reported that flats and maisonettes were found to have higher energy efficiency scores compared to other property types in London (Office of National Statistics, 2022). This is likely due to attributes of flats such as having a smaller surface area and fewer exposed walls compared to homes. Additionally, it is common for flats have another flat below and/or beneath (i.e., the 'dwelling' category for the EPC roof/floor insulation variables), providing good insulation and consequently good thermal efficiency. Housing age and property type also effect energy efficiency, which is strongly correlated with thermal efficiency and comfort (Moon and Jung, 2016, Halhoul Merabet et al., 2020, Ormandy and Ezratty, 2015).

When exploring the relationship between mean LSOA thermal efficiency score and two socioeconomic deprivation domains, results were counterintuitive. Mean LSOA thermal efficiency was found to be higher and statistically significantly different in the most deprived quintiles compared to least

deprived quintiles in both income and employment deprivation domains. These differences may be attributed to multiple factors and their interplay.

First, there is a higher proportion of rental homes in more deprived areas, resulting in higher mean thermal efficiency in these LSOAs. Second, more deprived areas are more likely to have had government intervention for housing quality improvements that relate to thermal efficiency and energy efficiency, such as the Mayor of London's Warmer Home programme which provides free heating, insulation and ventilation improvements for low-income families in London (Mayor of London, 2022).

Third, older homes are more likely to be towards central London, which is also one of the less deprived areas of the city. This means that less deprived LSOAs may still have low thermal efficiency score because of the physical characteristics of their housing stock. Additionally, changes that have been made to a home may not be reflected in the EPC data as EPCs are not required if the home is not being rented or sold, or changes made to the home may not be reported in the EPC data.

However, when observing LSOAs with the best mean thermal efficiency score (i.e., > 5.5) and worst mean thermal efficiency score (i.e., < 3.5), results were more intuitive. LSOAs with the best mean thermal efficiency score are largely in the least deprived income and employment quintile and LSOAs with the worst mean thermal efficiency score are mostly in the most deprived quintile. This could reflect the relationship between socioeconomic status and likelihood of investing in home improvement or retrofitting (European Parliament, 2017, Raissi and Reames, 2020).

5.2.3.2 Strengths and limitations

This analysis develops a thermal efficiency metric that using only insulation-related variables. While insulation is likely one of the most significant factors for thermal efficiency, incorporating additional variables would have provided a more comprehensive definition of thermal efficiency. This limitation was due to data availability and the homogeneity across London for the other initially selected factors. Additionally, the insulation data were quite nuanced and thus were categorized into broad categories ranging from very poor to very good but also including 'dwelling' and 'insulated.' More clear and precisely recorded data would have allowed for a more robust definition of insulation (e.g., based on the type or thickness of insulation).

Although this analysis does not include personal and subjective factors, it is important from a policy perspective to develop a metric on the physical determinants of thermal efficiency. Other cities can use a similar approach – identifying all available variables in their housing data and then checking how informative they will be in the model via LCA – to develop a city-specific thermal efficiency metric.

The use of EPC data is a strength of this analysis as this is a prominent source of energy-related data in the UK and data are available for nearly all LSOAs in most years. However, these data do not allow for analysis of a temporal dimension due to how they are generated, i.e., not a random sample and potential self-selection bias. Another limitation of the EPC data is that they are valid for 10 years, which means that thermal efficiency related home improvements may not necessarily be accounted for. Data for EPCs is collected by qualified assessors who are required to perform with integrity, however data may potentially have issues or errors (e.g., when lodging data) arising from individual assessors (Ahern and Norton, 2019). Nonetheless, the use of routinely collected data makes the presented methodology to measure thermal efficiency at the small-area level transferable to other cities that may have similar data available.

5.2.3.3 Implications

While recently built homes are more likely to be energy efficient and have better thermal efficiency, London has one of the oldest housing stocks and thus a focus on improving their thermal efficiency is critical, especially in the current energy crisis. Low-income households, which have disproportionately higher energy costs and generally live in less energy efficient houses (Raissi and Reames, 2020), should continue to receive government interventions related to thermal efficiency. Though future research should identify what types of retrofitting (e.g., wall vs roof insulation) are cost effective and most effective. While any retrofitting is beneficial, roof insulation is generally less expensive and simpler to perform compared to wall or floor insulation. This may explain why 60.4% of EPCs reported having very good or good roof insulation in the home (versus 22.9% and 47.5% with very good or good wall and floor insulation, respectively). As such, targeting which area of the home must be retrofit in standards or which area should be retrofit first may be warranted. A study using EPC data in Ireland noted that while the impact of the 'easier' retrofitting is evident, there is a significant amount of additional energy saving that can come from "deeper measures" including external wall insulation and internal dry-lining installation (Ahern and Norton, 2019). The authors also state that the increase in (state-funded) retrofitting of homes seems to be reducing the commonly observed strong association between age of the home and energy efficiency.

Still, the results of this analysis also point to the need to target older homes, whose residents may be from various socioeconomic backgrounds, for the assessment and improvement of their homes' thermal efficiency. At the most comprehensive level, London city and borough leaders should implement interventions to bring homes to a minimum standard of thermal efficiency across London. This would be the most beneficial approach across different London's diverse subpopulations and bring equitable improvements throughout the city.

6 Associations of home thermal efficiency with health admissions

6.1 Introduction

This chapter presents a small area health analysis assessing the link between home thermal efficiency, using the metric developed in Chapter 5, and health, i.e., hospital admissions for a selected number of outcomes. Small area analysis is an epidemiological study design to assess the impact of environmental exposures on health at a small geographical scale (e.g., county or neighbourhood) (Piel et al., 2020) rather than individual-level, making it useful for informing policy and supporting decisions at more granular levels, for instance through the identification of hot-spots of higher risk in a city. Small area studies have examined a range of environmental exposures. For example, the UK Small Area Health Statistics Unit (SAHSU), based at Imperial College, has conducted studies such as road traffic noise and cardiovascular related morbidity and mortality (Halonen et al., 2015) and bioaerosol emissions and respiratory hospital admissions (Roca-Barcelo et al., 2020).

These studies often link diverse types of data, including health, environment, and population data, with spatial and/or temporal components to measure the association between an environmental exposure and specific health outcomes. These data frequently have varying spatial and temporal resolutions; and as such small area studies often combine data that have high spatial resolution but low temporal resolution, such as decennial censuses, with data that have low spatial resolution but high temporal resolution such as annual government surveys. Moreover, the statistical methods used to analyse these spatial data allow for the "borrowing of strength" from neighbouring areas, based on Tobler's First Law of Geography, which states that *everything is related to everything else, but near things are more related than distant things* (Tobler, 1970), as the premise.

This chapter describes and provides the results from the small area health analysis I conducted to measure the association between home thermal efficiency and a selection of health outcomes.

6.2 Data

6.2.1 Exposure: home thermal efficiency metric

The development of the LSOA-level home thermal efficiency metric is detailed in Chapter 5. In brief, the cross-sectional metric was constructed based on literature-derived housing determinants of thermal efficiency by combining individual house-level data from EPCs from 2009 to 2020 with auxiliary LSOA-level data from the UK Census (2011) and Valuation Office Agency (2014) using the Battese-Harter-Fuller model (Rao and Molina, 2015).

The home thermal efficiency metric ranged from 3.0 to 6.0, with a lower score indicating worse thermal efficiency. For ease of interpretability (i.e., due to its narrow range), the scores of the home thermal efficiency metric were categorized into quintiles for this small area health analysis: lowest [3.12-3.69], low (3.69-4.27], fair (4.27-4.84], good (4.84-5.42], and best (5.42-5.99].

6.2.2 Outcome: hospital admissions

I obtained hospital admissions data from the Hospital Episode Statistics (HES) held by the SAHSU and provided by NHS Digital. Hospital admissions between 1st January 2009 and 31st December 2019 were included to align with the time period of the exposure (2009-2020) and avoid the start of the Covid-19 pandemic in 2020, which impacted healthcare admissions.

The data included information on the reason for admission, LSOA of patients' residence at time of admission to hospital, sex, and 5-year age category (i.e., exact age was not included). Currently the NHS uses the 10th revision of the International Statistical Classification of Diseases and Related Health Problems (ICD10). Usually, the first diagnosis code recorded is referred to as the primary code or the primary reason for the patient's admission to the hospital. I included data for the first episode for a given condition in a given year. Health outcomes of interest included those previously identified in the literature as having a direct link to poor home thermal efficiency: all hospital admissions (excluding births and injuries; ICD10: A00-R99); all cardiovascular diseases (ICD10: I00-I99) and as a subset all ischemic heart disease (ICD10: I20-I25), all stroke (ICD10: I61, I63, I64); as well as all respiratory diseases (ICD10: J00-J99) and as a subset all asthma (ICD10: J45-46), all chronic obstructive respiratory diseases (COPD, ICD10: J40- 44), and all lower respiratory tract infections (LRTI, ICD10: J20-22) admissions. Specific cardiovascular and respiratory outcomes were also analysed for outcome-relevant ages groups, namely asthma in children/young adults and in adults over 20 years separately due to the difference in mechanism and disease management; LRTI in children/young adults and adults over 65 years separately; and COPD, stroke and ischemic heart disease in adults over 65 years.

Hospital admissions with the same primary diagnosis within 1 year were considered as readmission and excluded. This was done to avoid double-counting for recurring readmissions (e.g., parents repeatedly taking their asthmatic child to the hospital in a short period of time). Readmission over a short period of time might reflect poor access to primary care or disease severity instead of incidence, which is the disease measure of interest. Readmissions for the same condition in different years was included to allow for the fact that patients might have moved house and would be included in the disease count of a different LSOA.

Hospital admissions records with missing or invalid age or sex data were excluded. Hospital admission counts for each LSOA were aggregated over the study period to avoid instability in model outputs due to small numbers.

6.2.2.1 Ethical approval

The project has been approved by the SAHSU-UK Health Security Agency Liaison Committee Meeting. The study was covered by national research ethics approval from the London-South East Research Ethics Committee - reference 22/LO/0256. Data access to confidential patient information without consent was covered by the Health Research Authority - Confidentiality Advisory Group under Regulation 5 of the Health Service (Control of Patient Information) Regulations 2002 ('section 251 support') - HRA CAG reference: 20/CAG/0028.

6.2.3 Covariates

Covariates adjusted for in this analysis were defined *a priori*, and included ethnicity, income deprivation, air pollution, and smoking. Data for all covariates were available for the whole study area at the LSOA level and depending on data availability, data from the year closest to the mid-point of the study period (i.e., 2014) was used.

Ethnicity and income were selected as covariates for this study as it is known that health outcomes vary by race/ethnicity and socioeconomic status due to a number of factors such as access to and quality of healthcare, genetic disposition and differences in health-related behaviours. Ethnicity is also linked to fuel poverty and consequently may potentially influence the relationship between thermal efficiency and health (Bouzarovski et al., 2022).

Ethnicity data was obtained from the 2011 UK Census and was defined as the percentage of residents within an LSOA that identified as non-White race/ethnicity, which includes Asian or Asian British; Black, African, Caribbean or Black British; Mixed or multiple ethnic groups; and the Other ethnic group.

Information on income is also not available at LSOA level. I therefore used information on income deprivation, obtained from the income domain of the 2015 IMD. The income domain provides the proportion of the population in the area who are deprived with respect to low income, defined as those who are unemployed and those who are employed but have low earnings.

Indoor air pollution has a key impact on indoor air quality which is intertwined with ventilation, insulation and other thermal-comfort related characteristics of the home. Among others, nitrogen dioxide (NO_2) is a common source of indoor air pollution that is frequently measured and has known

effects on health (Ferguson et al., 2021). In this analysis, annual average NO_2 concentrations for 2015 at the LSOA level (calculated by taking the average across all 25m grid cells with centroid within the LSOA) were obtained from an existing Land Use Regression model which mapped NO_2 at 25m resolution (Wang et al., 2022).

Finally, smoking was included as a model covariate as it is a known risk factor for a range of both cardiovascular and respiratory illnesses. Information on smoking rates is not available at the LSOA level. Instead, I used 2014 tobacco expenditure data (i.e., £ spend per person (population ≥16 years) per week on tobacco products) from CACI Ltd as a smoking proxy.

6.3 Statistical analysis

6.3.1 Descriptive statistics

Descriptive statistics (frequency and percentage) summarise the health outcomes included in this analysis by sex, age category and income quintile. As the exposure and covariate data are available at the LSOA-level, descriptive statistics are summarised for the home thermal efficiency metric, ethnicity, air pollution, and smoking at the LSOA-level. For these variables, the mean, median, 25th and 75th percentile values were calculated. I calculated the Kendall rank correlation coefficient (τ) to test for potential multicollinearity between the home thermal efficiency metric and covariates.

6.3.2 Small area health analysis

6.3.2.1 Expected counts

I estimated age and sex standardised rates of cause-specific hospital admissions for each LSOA using mid-year London population estimates by sex and 5-year age groups from the Office for National Statistics (ONS). When merging the ONS population data with the health data, there are instances where the number of admissions is greater than the population count for each LSOA-age-sex group. The steps taken to resolve this issue are discussed in Appendix 9-20.

To obtain the standardised rates, I used the standardised incidence rate (SIR) formula which is the ratio of the observed number of cases (i.e., admissions) to the expected number of admissions. The observed number of cases is the total number of admissions in a given LSOA. The expected number of cases in LSOA *i*, E_i, is calculated as:

$$E_i = \sum_{j=1}^{34} N_{ij}\lambda_j$$

Where N is the population in the j-th age-sex group (n=34 groups) in LSOA *i*, and λ is the rate of admissions in London in the j-th age-sex group. This rate is calculated by dividing the number of admissions in the j-th age sex group by the population the j-th age-sex group. This was obtained using the expected function in the R *SpatialEpi* package.

6.3.2.2 Bayesian model

I then developed a Bayesian spatial model to explore the association between the outcome (number of hospital admissions for a given health outcome) and the exposure (home thermal efficiency) at the small-area level (LSOA).

For the i-th small area, the count of hospital admissions (y_i) is modelled as:

$Y_i \sim$ Poisson ($E_i\ \theta_i$), i = 1, … , 4,835 LSOAs,

where:

E_i is the expected number of cases of a given health outcome in each LSOA (i.e., offset) and

θ_i is the rate of hospitalisations during the study period in LSOA i.

The logarithm of θ_i is expressed as:

$$\log(\theta_i) = \beta_0 + \beta_{n,i}X_{n,i} + \boldsymbol{b}$$

where:

β_0 is the global intercept,

$\beta_n X_n$ (n=1…n) are the coefficients for the exposure variable and covariates included in the model to adjust for LSOA characteristics, and

b is the random effect, which is decomposed as

$$\boldsymbol{b} = \frac{1}{\sqrt{\tau}}(\sqrt{1-\varphi}v + \sqrt{\varphi}u)$$

where:

τ is the marginal precision,

φ the proportion of the marginal variance explained by the spatial effect,

v is the unstructured spatial effect, and

u is the structured spatial random effect.

In this analysis, I use the reparameterised BYM model (Riebler et al., 2016), where the spatially structured and unstructured are standardised so that their variance equals to one, making it possible to interpret these components separately. φ is interpreted as the proportion of the marginal variance seen is due to the structured spatial effect versus the unstructured spatial effect (i.e., if φ is greater than 0.5, the structured spatial component explains the majority of the marginal variance seen).

This model builds on the classical Besag– York–Mollie (BYM) model (Besag et al., Annie), where the unstructured spatial effect accounts for overdispersion and the unstructured spatial component accounts for spatial variability. A conditional autoregressive (CAR) prior distribution is placed on the spatially structured random effect, so that the prevalence in one LSOA is influenced by the average prevalence of neighbouring LSOAs, also taking into account the number of neighbouring LSOAs.

Using the age and sex standardised rates of cause-specific hospital admissions and random effect, I fitted three models for each health outcome. Model 1 is unadjusted and is expressed as:

$$\log(\theta_i) = \beta_0 + \beta_{thermal\ efficiency_{quintile\ n},i} X_{thermal\ efficiency_{quintile\ n},i} + \boldsymbol{b}$$

Model 2 adjusts for the following LSOA-level confounders: ethnicity, air pollution and smoking, and is expressed as:

$$\log(\theta_i) = \beta_0 + \beta_{thermal\ efficiency_{quintile\ n},i} X_{thermal\ efficiency_{quintile\ n},i} + \beta_{ethnicity,i} X_{ethnicity,i} + \beta_{air\ pollution,i} X_{air\ pollution,i} + \beta_{smoking,i} X_{smoking,i} + \boldsymbol{b}$$

Model 3 adjusts for ethnicity, air pollution and income. Model 3 is expressed as:

$$\log(\theta_i) = \beta_0 + \beta_{thermal\ efficiency_{quintile\ n},i} X_{thermal\ efficiency_{quintile\ n},i} + \beta_{ethnicity,i} X_{ethnicity,i} + \beta_{air\ pollution,i} X_{air\ pollution,i} + \beta_{income,i} X_{income,i} + \boldsymbol{b}$$

Models were fitted using Integrated Nested Laplace Approximation (INLA) (Rue et al., 2009), a computationally efficient method that uses a blend of numerical integration to estimate Bayesian inference for latent Gaussian models, using the R software (Version 4.2.2).

I also explored whether income was an effect modifier in the association between home thermal efficiency and hospital admissions for all health outcomes, all CVD outcomes and all respiratory outcomes, adjusting for ethnicity, air pollution and smoking. Data were stratified by the IMD income domain quintiles.

For all results, I report relative risk along with 95% credible intervals for each home thermal efficiency quintile.

6.4 Results

6.4.1 Descriptive statistics

Descriptive statistics for hospital admissions by health outcomes are presented in Table 6.1. The total number of hospital admissions (excluding injuries and births) during the study period, 2009-2019, was 6,577,462. The proportion of admissions for males compared to females is nearly equal (49.4% and 50.6%, respectively). The majority of hospital admissions were in adults (20-64 years) and the elderly (65+), which account for 44.3% and 39.6% of all admissions respectively (compared to admissions in children/young adults (0-19 years), 16.1%). 60.5% of all admissions are among the two most deprived quintiles of the income deprivation domain.

Over the study period, there were 665,003 CVD-related hospital admissions, the majority were male (55.5%) and among the elderly (63.5%). The majority of CVD-related hospital admissions came from LSOAs in the two most income deprived quintiles (56.6%). The number of IHD and stroke-related hospital admissions was 168,596 and 93,946, respectively. While the majority of hospital admissions were among men for both IHD and stroke, the proportion was much higher for IHD (65.7%) versus stroke (51.7%). Conversely, the proportion of IHD admissions among the elderly was lower for IHD (57.3%) versus stroke admissions (71.8%). More than 55% of IHD and stroke admissions occurred among the two most deprived quintiles.

Over the study period, there were 945,088 respiratory-related hospital admissions, evenly distributed between men and women (50.9% and 49.1%, respectively). While the elderly population had the highest proportion of respiratory-related hospital admissions (45.5%), the distribution between children/young adults and adults was comparable (25.7% and 28.9%, respectively). With regards to the IMD income domain, 62% of respiratory-related hospital admissions occurred in the two most deprived quintiles.

There were 160,547 LRTI admissions, 140,366 COPD admissions and 108,407 asthma admissions over the study period. The near-equal distribution of admissions between men and women was also true for all three of the specific respiratory outcomes (males account for 51.8% of LRTI, 51.6% of COPD and 44.1% of asthma admissions). However, the age distribution for admissions for these specific respiratory conditions varied. For LRTI, children/young adults had the largest proportion of

admissions, 48.2%, followed by the elderly and then adults. For COPD, the elderly accounted for 74.6% of admissions and adults for 25.2%. Not surprisingly, children/young adults only accounted for 0.2% of COPD admissions. Children/young adults, however, accounted for 41% of asthma admissions. Adults and the elderly accounted for 44.3% and 14.7% of the remaining hospital admissions for asthma, respectively. Across all three of these specific respiratory conditions, 60% of admissions occurred among the two most deprived quintiles.

Descriptive statistics for the home thermal efficiency metric and covariates are presented in Table 6.2. As discussed in Chapter 5, the mean LSOA home thermal efficiency score across London is 4.34 (SD: 0.48), ranging from 3.12 to 5.99. On average, the percentage of people who identify as non-White across LSOAs is 39.29% (range: 1.84 - 96.46). Figure 6.1 shows the spatial distribution of the percentage of non-White ethnicity across Greater London by LSOA, with high percentages of non-White ethnicity in towards the West, Northwest and Northeast of London. Annual average concentrations of NO_2 were highest in LSOAs in central London and generally decrease with distance from the city centre (Figure 6.2). The mean annual level of NO_2 across all LSOAs was 32.91 $\mu g/m^3$ (range: 17.69 - 64.42 $\mu g/m^3$). The average tobacco expenditure across London LSOAs was 6.22GBP per week per person (range: 1.95 - 10.46 per week per person). Generally, there seems to be higher tobacco expenditure towards central London (Figure 6.3).

Table 6.1. Descriptive statistics of hospital admissions by health outcome from 2009 to 2019

	All admissions (excluding injuries and births)		Admissions from cardiovascular conditions						Admissions from respiratory conditions							
			All		Stroke		IHD		All		Asthma		COPD		LRTI	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%
Total	6,577,462		665,003		93,946		168,596		945,088		108,407		140,366		160,547	
Sex																
Male	3,248,250	49.40	369,200	55.50	48,590	51.70	110,688	65.70	481,114	50.90	47,773	44.10	72,455	51.60	83,109	51.80
Female	3,329,212	50.60	295,803	44.50	45,356	48.30	57,908	34.30	463,974	49.10	60,634	55.90	67,911	48.40	77,438	48.20
Age category																
Child/YA (0-19)	1,057,857	16.10	9,572	1.40	377	0.40	63	0.00	242,722	25.70	44,495	41.00	291	0.20	77,457	48.20
Adult (20-64)	2,915,328	44.30	233,378	35.10	26,098	27.80	72,003	42.70	272,768	28.90	48,001	44.30	35,319	25.20	30,773	19.20
Elderly (65+)	2,604,277	39.60	422,053	63.50	67,471	71.80	96,530	57.30	429,598	45.50	15,911	14.70	104,756	74.60	52,317	32.60
Income																
1 (least deprived)	553,241	8.40	66,140	9.90	9,664	10.30	15,053	8.90	74,695	7.90	5,562	5.10	7,874	5.60	13,855	8.60
2	739,527	11.20	84,493	12.70	12,241	13.00	20,404	12.10	102,537	10.80	8,501	7.80	12,772	9.10	18,436	11.50
3	1,300,596	19.80	137,808	20.70	19,128	20.40	36,014	21.40	181,671	19.20	19,702	18.20	23,849	17.00	31,248	19.50
4	2,048,147	31.10	198,341	29.80	27,492	29.30	51,397	30.50	296,196	31.30	37,506	34.60	45,162	32.20	49,752	31.00
5 (most deprived)	1,935,951	29.40	178,221	26.80	25,421	27.10	45,728	27.10	289,989	30.70	37,136	34.30	50,709	36.10	47,256	29.40

YA = young adult; IHD = ischemic heart disease; COPD = chronic obstructive pulmonary disorder; LRTI = lower respiratory tract infections

Table 6.2. Descriptive statistics for home thermal efficiency metric, Non-White ethnicity, average concentration of nitrogen dioxide, and tobacco expenditure at LSOA level for London

	Mean	**50% (Median)**	**Range**
Home thermal efficiency metric	4.34	4.27	3.12 - 5.99
Non-White ethnicity (%)	39.29	36.91	1.84 - 96.46
Nitrogen dioxide (μg/m^3)	32.91	32.51	17.69 - 64.42
Tobacco expenditure (£ per week per person)	6.22	6.13	1.95 - 10.46

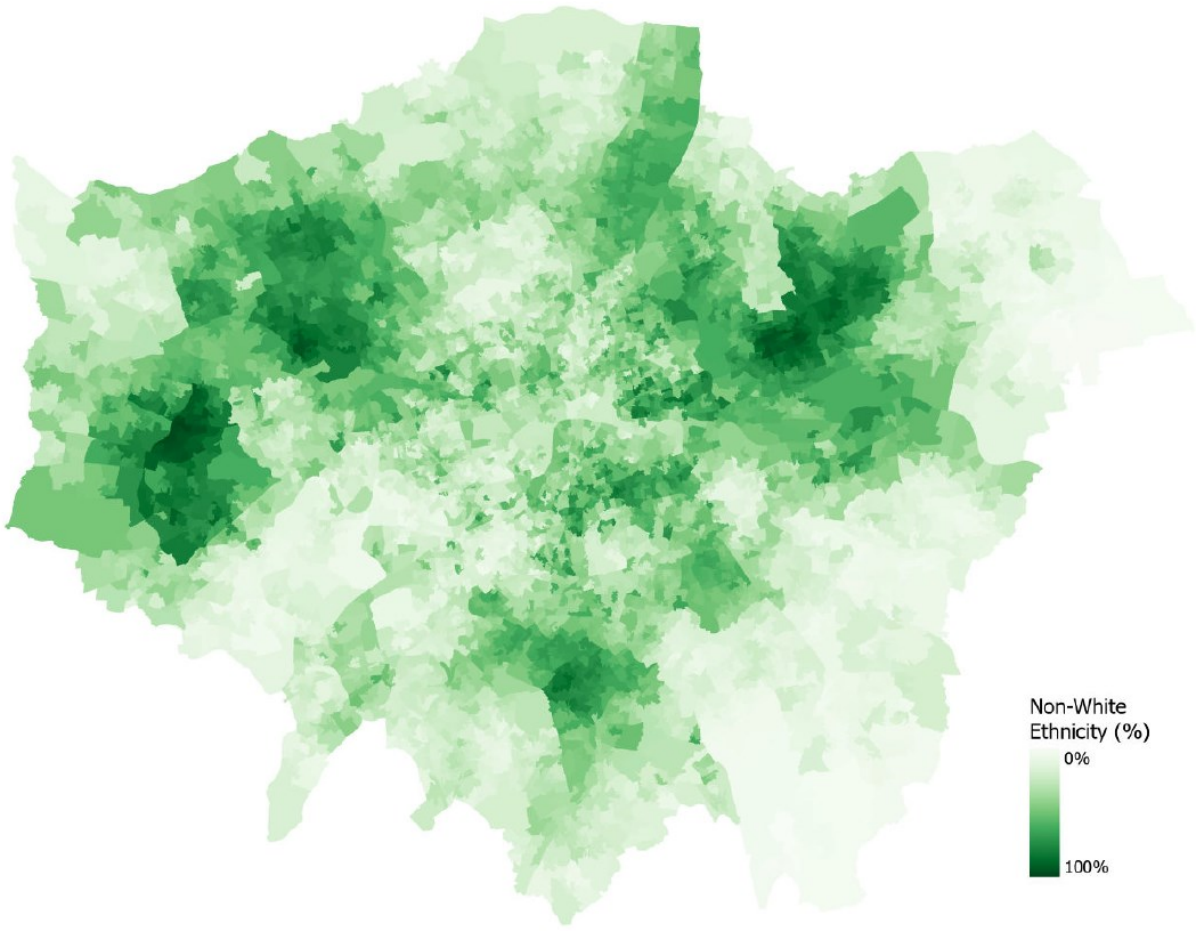


Figure 6.1. Ethnicity (% non-White) by LSOA for Greater London based on 2011 Census



Figure 6.2. Annual average nitrogen dioxide (NO_2) concentrations (µg/m^3) by LSOA for Greater London from Land Use Regression model which mapped NO_2 at 25m resolution (Wang et al., 2022)

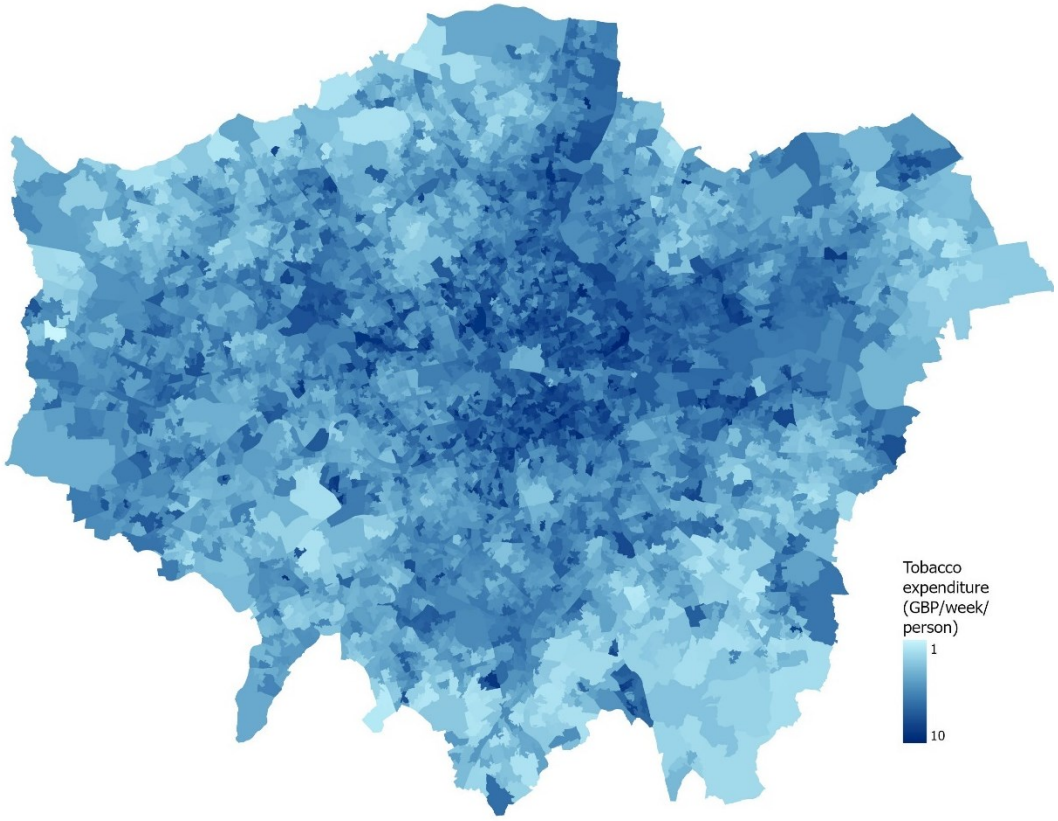


Figure 6.3. Tobacco expenditure (smoking proxy) by LSOA for Greater London based on 2014 CACI data

6.4.2 Multicollinearity

I tested for multicollinearity as this would affect the interpretability of the model outputs and inform selection of covariates to be included in the mode. The results of the correlation analysis are presented in Figure 6.4. While the cut-off for a strong correlation is somewhat arbitrary, I consider a Kendall correlation coefficient (τ) of >0.6 as strong, 0.6-0.3 as moderate, and <0.3 as low. There is a moderate positive correlation between the home thermal efficiency score and smoking (τ = 0.32). The correlation between the home thermal efficiency score and other covariates is low (NO_2: τ = 0.22; income deprivation: τ =0.18; non-White ethnicity: τ = 0.11). Smoking shows a strong correlation with income deprivation (τ: 0.64), and as such I did not include both potential confounders in the same model. However, to determine how these two confounders separately affect the association between home thermal efficiency and health outcomes, while adjusting for the other confounders, two separate models were fitted.

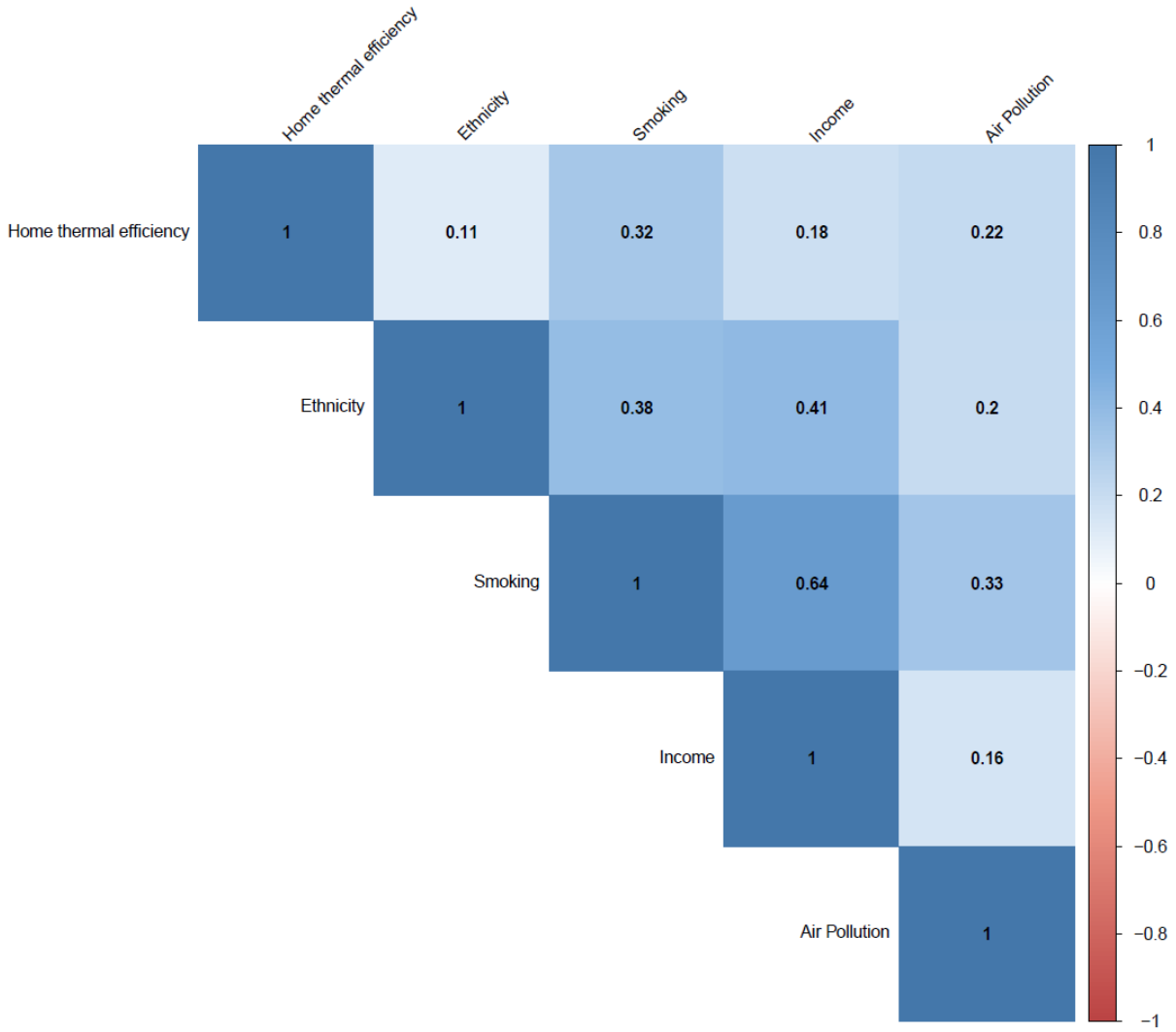


Figure 6.4. Correlation matrix showing Kendall correlation coefficient between exposure variable (home thermal efficiency metric) and confounders.

6.4.3 All hospital admissions (excluding injuries and births), all CVD admissions and all respiratory admissions

The risk ratio (RR) measures the risk of being admitted to the hospital for an individual living in an LSOA with an average of the worst thermal efficiency score compared to LSOAs with best average thermal efficiency scores.

Table 6.3 presents the results from the analysis on the association of home thermal efficiency with all hospital admissions (excluding injuries and births), all CVD admissions and all respiratory admissions for all three models. Figure 6.5 summarizes the results from Model 2 (i.e., model adjusted for ethnicity, air pollution and smoking). Figures for all models by health outcome are available in Appendix 9-21 (all admissions), Appendix 9-22 (all CVD admissions) and Appendix 9-23 (all respiratory admissions).

In the unadjusted model (Model 1), the overall direction of the association is that the risk for hospital admission decreases with lower thermal efficiency scores – the opposite of what is seen in Model 2 and 3. This highlights the relevance of the confounding variables adjusted for in the other models.

In Model 2, which is adjusted for ethnicity, air pollution and smoking, there seems to be an increased RR for admission with lower thermal efficiency scores. Results showed that for individuals living in LSOAs in the low and lowest home thermal efficiency quintiles, there is a 31% (RR = 1.31, 95% CI: 1.26 – 1.35) and 29% (RR = 1.29, 95% CI: 1.24 – 1.34) increase in the risk of admissions for any health outcome, respectively. Similarly, there is also a 30% increase in the risk of all CVD admissions (RR = 1.30, 95% CI: 1.22 – 1.39 and RR = 1.30, 95% CI: 1.21 – 1.4 for the low and lowest quintiles, respectively). The confidence intervals for CVD admissions, however, are wider, most likely due to fewer number of CVD admissions. The RR for respiratory admissions was lower compared to CVD. For LSOAs with the lowest home thermal efficiency score quintiles, there was just over a 20% increase in the risk of respiratory admissions (RR = 1.22, 95% CI: 1.16 – 1.29 and RR = 1.21, 95% CI: 1.13 – 1.28 for the low and lowest thermal efficiency score quintiles, respectively).

It is important to note that even LSOAs in the good thermal efficiency score quintile had a significant increase in risk of hospital admissions compared to the best quintile. For instance, LSOAs with a good thermal efficiency score (i.e., second quintile) had a 22% increase in risk of any hospital admission (RR = 1.22, 95% CI: 1.18 – 1.26), and 18% increased risk for CVD related admissions and (RR = 1.18, 95% CI: 1.11 – 1.26) and a 16% increased risk for respiratory related admissions (RR = 1.18, 95% CI: 1.09 – 1.22).

In Model 3, which adjusted for income instead of smoking, showed statistically significant results for all hospital admissions and all CVD admissions. For all admissions, results show an equal amount of

increased risk (11%) regardless of home thermal efficiency quintile. For CVD admissions, the increased risk was 14% for both of the lowest home thermal efficiency quintiles though results were borderline significance. The results for respiratory admissions were not statistically significant for any home thermal efficiency quintile.

A separate analysis was also conducted to explore whether income was an effect modifier in the association between home thermal efficiency and these three health outcomes, adjusting for ethnicity, air pollution and smoking. The data were stratified by the IMD income domain quintiles, and results did not show evidence of effect modification by income quintile. Results were not significant for income quintile 5 for all three outcomes, and also for quintile 2 for all CVD admissions and for quintiles 3 and 4 for all respiratory admissions. Results are presented in Appendix 9-36.

Table 6.3. Relative risk (RR) and 95% confidence intervals (95% CI) for hospital admissions for all health outcomes (excluding births and injuries), all CVD outcomes and all respiratory outcomes associated with quintiles of home thermal efficiency.

All admissions						
	Model 1*		**Model 2†**		**Model 3‡**	
	RR	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**
Best	1	1.00	1	1.00	1	1.00
Good	1.29	(1.23, 1.35)	1.22	(1.18, 1.26)	1.11	(1.08, 1.15)
Fair	1.19	(1.13, 1.24)	1.28	(1.24, 1.32)	1.11	(1.08, 1.14)
Low	1.10	(1.05, 1.15)	1.31	(1.26, 1.35)	1.11	(1.08, 1.15)
Lowest	1.12	(1.06, 1.18)	1.29	(1.24, 1.34)	1.11	(1.07, 1.15)
All cardiovascular admissions						
	Model 1*		**Model 2†**		**Model 3‡**	
	RR	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**
Best	1	1.00	1	1.00	1	1.00
Good	1.23	(1.15, 1.32)	1.18	(1.11, 1.26)	1.11	(1.04, 1.19)
Fair	1.15	(1.07, 1.23)	1.26	(1.18, 1.34)	1.13	(1.05, 1.2)
Low	1.09	(1.02, 1.17)	1.30	(1.22, 1.39)	1.14	(1.07, 1.22)
Lowest	1.15	(1.07, 1.24)	1.30	(1.21, 1.40)	1.14	(1.07, 1.23)
All respiratory admissions						
	Model 1*		**Model 2†**		**Model 3‡**	
	RR	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**
Best	1	1.00	1	1.00	1	1.00
Good	1.21	(1.13, 1.29)	1.16	(1.09, 1.22)	1.05	(0.99, 1.1)
Fair	1.09	(1.03, 1.16)	1.21	(1.14, 1.27)	1.03	(0.97, 1.08)
Low	0.98	(0.92, 1.05)	1.22	(1.16, 1.29)	1.02	(0.97, 1.07)
Lowest	0.99	(0.93, 1.07)	1.21	(1.13, 1.28)	1.00	(0.95, 1.06)

*Model 1 is unadjusted.

†Model 2 is adjusted for ethnicity, air pollution and smoking.

‡Model 3 is adjusted for ethnicity, air pollution and income.

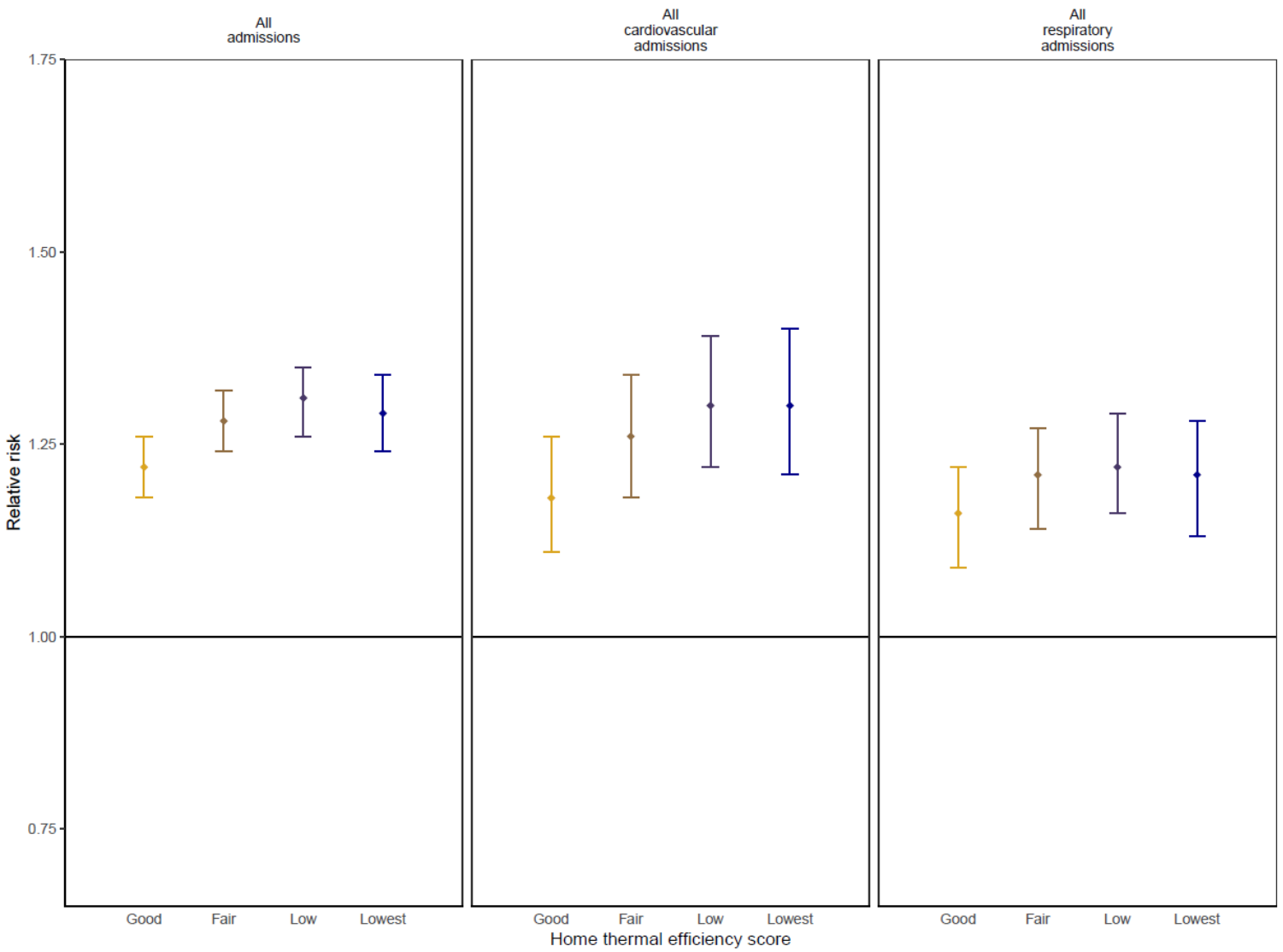


Figure 6.5. Relative risk (RR) and 95% confidence intervals (95% CI) for hospital admissions from all health outcomes, all CVD outcomes and all respiratory outcomes associated with quintiles of home thermal efficiency, adjusted for ethnicity, air pollution and smoking (reference category is 'best' thermal efficiency score).

6.4.4 Cardiovascular-related hospital admissions

Table 6.4 presents the results from the analysis on the association of home thermal efficiency with stroke and IHD. For both of these outcomes, I focused on all admissions for the specific outcomes as well as admissions among the elderly (65+) population as this age group has the highest prevalence for both IHD and stroke. Figure 6.6 summarizes the results from Model 2 (i.e., model adjusted for ethnicity, air pollution and smoking). Figures for all models by health outcome are available in Appendix 9-24 (all stroke admissions), Appendix 9-25 (stroke admissions among the elderly), Appendix 9-26 (all IHD admissions) and Appendix 9-27 (IHD admissions among the elderly).

In the unadjusted model (Model 1), results show a lower risk of admissions (i.e., a RR less than 1) across all thermal efficiency quintiles except the good quintile (RR = 1.03, 95% CI: 0.88 – 1.211) for all stroke admissions. These results, however, were not statistically significant and a similar pattern is observed for stroke admissions among the elderly. For all IHD admissions, there is an increase in risk as thermal efficiency decreases though only statistically significant results for the good (RR = 1.15, 95% CI: 1.01 – 1.31) and lowest (RR = 1.22, 95% CI: 1.07 – 1.39) thermal efficiency quintiles. Results are not statistically significant for IHD admissions among the elderly.

In Model 2, which is adjusted for ethnicity, air pollution and smoking, results were not statistically significant for neither all stroke admissions nor stroke admissions among the elderly. For all stroke, results showed an increased risk of admission of 10% (RR = 1.10, 95% CI: 0.94 – 1.28) and 11% (RR = 1.11, 95% CI: 0.95 – 1.31), respectively, for individuals living in LSOAs categorised in the low and lowest home thermal efficiency quintiles. For stroke admissions among the elderly subpopulation, a reduction in risk for hospital admissions was observed for all quintiles of the home thermal efficacy metric. The RR's ranged from 0.83 (95% CI: 0.70 – 1.00) in the good quintile to 0.92 (95% CI: 0.76 – 1.11) in the lowest quintile. Though, as stated, these results are not significant.

Compared to individuals living in LSOAs with the best home thermal efficiency, individuals living in LSOAs in the low and lowest home thermal efficiency quintiles had a 30% (RR = 1.30, 95% CI: 1.14 – 1.47) and 29% (RR = 1.29, 95% CI: 1.13 – 1.47) increased risk of IHD admissions, respectively. The increase in risk for IHD admissions for the fair quintile was 21% (RR=1.27, 95% CI: 1.07 – 1.37), and decreased to 9% for the good quintile – though this result was not statistically significant (RR = 1.09, 95% CI: 0.96 – 1.23). Among the elderly population, the observed association between thermal efficiency and IHD admissions was not statistically for any thermal efficiency quintile.

Model 3 also showed a similar pattern for all IHD admissions, though the RRs were of smaller magnitude. Model 3 showed a 15% and 14% increase in risk for the low (RR = 1.15, 95% CI: 1.01 – 1.3)

and lowest (RR = 1.14, 95% CI: 1.00 – 1.30) thermal efficiency quintiles respectively. For IHD admissions among the elderly, results were not statistically significant, and the RR ranged from 0.85 (95% CI: 0.72 – 1.00) in the good quintile to 0.93 (95% CI: 0.79 – 1.10) in the lowest quintile. For stroke, the RR did not vary across thermal efficiency quintiles for both all admissions and admissions among the elderly. For all stroke admissions, the RR ranged from 0.96 (95% CI: 0.82 – 1.13) in the lowest quintile to 0.94 (95% CI: 0.81 – 1.10) in both the fair and low quintiles. The results for all stroke admissions were not statistically significant for any quintile. For stroke admissions among the elderly, the RR ranged from 0.82 (95% CI: 0.68 – 0.99) in the lowest quintile to 0.79 (95% CI: 0.67 –0.94) in both the fair and low quintiles.

Table 6.4. Relative risk (RR) and 95% confidence intervals (95% CI) for hospital admissions for stroke and ischemic heart disease associated with quintiles of home thermal efficiency. Model 1 is unadjusted; Model 2 is adjusted for ethnicity, air pollution and smoking; Model 3 is adjusted for ethnicity, air pollution and income.

Stroke admissions						
	Model 1*		**Model 2†**		**Model 3‡**	
	RR	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**
Best	1	1.00	1	1.00	1	1.00
Good	1.03	(0.88, 1.21)	1.00	(0.86, 1.17)	0.95	(0.81, 1.11)
Fair	0.93	(0.80, 1.08)	1.06	(0.91, 1.23)	0.94	(0.81, 1.10)
Low	0.86	(0.74, 0.99)	1.10	(0.94, 1.28)	0.94	(0.81, 1.10)
Lowest	0.96	(0.82, 1.13)	1.11	(0.95, 1.31)	0.96	(0.82, 1.13)
Stroke 65+ admissions						
	Model 1*		**Model 2†**		**Model 3‡**	
	RR	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**
Best	1	1.00	1	1.00	1	1.00
Good	0.85	(0.71, 1.01)	0.83	(0.70, 1.00)	0.80	(0.67, 0.95)
Fair	0.76	(0.64, 0.90)	0.87	(0.73, 1.03)	0.79	(0.67, 0.94)
Low	0.70	(0.59, 0.84)	0.89	(0.75, 1.06)	0.79	(0.67, 0.94)
Lowest	0.79	(0.65, 0.95)	0.92	(0.76, 1.11)	0.82	(0.68, 0.99)
IHD admissions						
	Model 1*		**Model 2†**		**Model 3‡**	
	RR	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**
Best	1	1.00	1	1.00	1	1.00
Good	1.15	(1.01, 1.31)	1.09	(0.96, 1.23)	1.03	(0.91, 1.17)
Fair	1.11	(0.98, 1.26)	1.21	(1.07, 1.37)	1.09	(0.96, 1.23)
Low	1.10	(0.97, 1.24)	1.30	(1.14, 1.47)	1.15	(1.01, 1.30)
Lowest	1.22	(1.07, 1.39)	1.29	(1.13, 1.47)	1.14	(1.00, 1.30)
IHD 65+ admissions						
	Model 1*		**Model 2†**		**Model 3‡**	
	RR	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**
Best	1	1.00	1	1.00	1	1.00
Good	0.91	(0.77, 1.07)	0.87	(0.74, 1.03)	0.85	(0.72, 1.00)
Fair	0.87	(0.74, 1.02)	0.95	(0.81, 1.11)	0.88	(0.75, 1.03)
Low	0.86	(0.73, 1.00)	1.01	(0.86, 1.19)	0.92	(0.79, 1.08)
Lowest	0.97	(0.82, 1.15)	1.02	(0.86, 1.21)	0.93	(0.79, 1.10)

*Model 1 is unadjusted.

†Model 2 is adjusted for ethnicity, air pollution and smoking.

‡Model 3 is adjusted for ethnicity, air pollution and income.

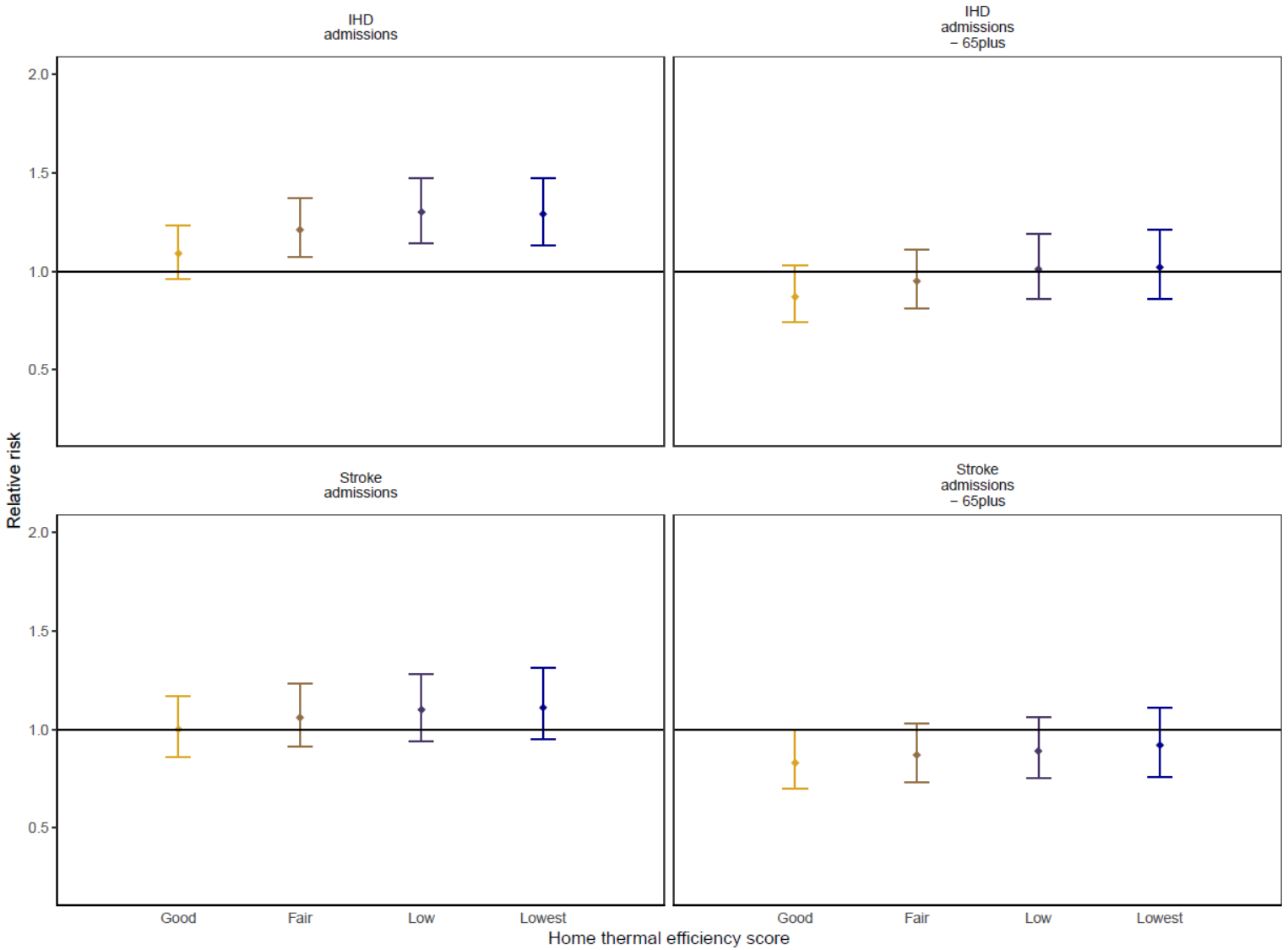


Figure 6.6. Relative risk (RR) and 95% confidence intervals (95% CI) for hospital admissions from ischemic heart disease (IHD) and stroke associated with quintiles of home thermal efficiency, adjusted for ethnicity, air pollution and smoking (reference category is 'best' thermal efficiency score).

6.4.5 Respiratory-related hospital admissions

Table 6.5 presents the results from the analysis on the association of home thermal efficiency metric with hospital admissions for asthma, lower respiratory tract infections (LRTI) and chronic obstructive pulmonary disease (COPD). Besides all admissions for these respective diseases, I also conducted separate analysis for outcome-relevant ages groups: asthma in children/young adults and in adults over 20 years separately due to the difference in mechanism and disease management; LRTI in children/young adults and in the elderly; and COPD in the elderly. Figure 6.7 summarizes results from Model 2 (i.e., model adjusted for ethnicity, air pollution and smoking). Figures for all models by health outcome are available in Appendix 9-28 (all asthma admissions), Appendix 9-29 (asthma admissions among children/YA), Appendix 9-30 (adult asthma admissions), Appendix 9-31 (all LRTI admissions), Appendix 9-32 (LRTI admissions among children/YA), Appendix 9-33 (LRTI admissions among the elderly), Appendix 9-34 (all COPD admissions), and Appendix 9-35 (COPD admissions among the elderly).

The unadjusted model (Model 1) shows a lower RR for asthma admissions as home thermal efficiency worsens, except in the lowest quintile which has the same RR as the good quintile – though these results are either borderline or not statistically significant. There are no statistically significant results for asthma admissions among adults or among children and young adults; as well as for LRTI for all admissions as well as for admissions among children and young adults. Among the elderly, the unadjusted model shows that there is a decreased risk for LRTI admissions across all home thermal efficiency quintiles, and there is little difference in the magnitude of the risk across quintiles as well. Similarly, the unadjusted models (i.e., all admissions and admissions among the elderly) for COPD shows a decrease in risk across quintiles except in the good quintile for all COPD admissions – though this is not statistically significant. Different from the LRTI results, however, the decrease in risk is lower in the lowest two home thermal efficiency quintiles. For instance, the RR for the low and lowest quintiles for COPD admissions among the elderly is 0.61 (95% CI: 0.53 – 0.71) and 0.63 (95% CI: 0.54 – 0.74) respectively, compared to 0.95 (95% CI: 0.82 – 1.1) in the good quintile.

In Model 2, which is adjusted for ethnicity, air pollution and smoking, individuals living in LSOAs in the low and lowest home thermal efficiency quintiles, there is a 37% increase in risk of asthma admissions (RR = 1.37, 95% CI: 1.21 – 1.55 and RR = 1.37, 95% CI: 1.20 – 1.57, respectively). Individuals living in LSOAs in the fair home thermal efficiency quintile also showed a statistically significant increase in risk of asthma hospital admissions, with a RR of 1.27 (95% CI: 1.13 – 1.44). When focusing on adults, there was a significant 20% increase in risk of asthma admissions for the low and lowest categories of home thermal efficiency (RR = 1.2, 95% CI: 1.03 – 1.39 and RR = 1.2, 95% CI: 1.02 – 1.41, respectively). For

the child and young adult population, low home thermal efficiency quintile showed the highest risk (RR: 1.21, 95% CI: 1.02 – 1.44). This was also the only quintile with a statistically significant result. The lowest thermal efficiency quintile showed a non- statistically significant 11% (RR: 1.11, 95% CI: 0.92 – 1.34) increased risk of asthma admissions for child and young adults.

For all LRTI admissions, results were significant for the fair, low and lowest home thermal efficiency quintiles however the lower-bound of the confidence interval for these associations were either 1.00 or close to 1.00. The increased risk for LRTI admissions among individuals in LSOAs in both low and lowest home thermal efficiency quintiles was 16% (RR = 1.16, 95% CI: 1.04 – 1.29 and RR = 1.16, 95% CI: 1.03 – 1.3, respectively). For LRTI admissions among children and young adults, the range of RR 0.09 – from 1.04 (95% CI: 0.9 – 1.2) in the lowest quintile to 0.98 (95% CI: 0.86 – 1.12) in the good quintile. However, these results were not statistically significant for any home thermal efficiency quintile. For LRTI hospital admissions among the elderly, results suggested a decrease in risk for hospital admissions across all home thermal efficiency quintiles (e.g., RR = 0.78, 95% CI: 0.64 – 0.96 in the lowest thermal efficiency quintile). Results are statistically significant for this subpopulation, but the higher-bound of the confidence interval are close to 1.00.

For both all COPD admissions and COPD admissions among the elderly, results are not statistically significant. In the lowest home thermal efficiency quintile, there is a 7% increase in risk for COPD admissions across the total population (RR = 1.07, 95% CI: 0.93 – 1.22) and a 1% increase in risk among the elderly population (RR = 1.01, 95% CI: 0.86 – 1.18).

Model 3, which adjusted for income instead of smoking, showed a statistically significant increase in only the low and lowest home thermal efficiency quintiles for all asthma admissions (RR = 1.17, 95% CI: 1.04 – 1.33 and RR = 1.17, 95% CI: 1.02 – 1.34, respectively) and only in in only the low home thermal efficiency quintile for asthma admissions among children and young adults (RR = 1.19, 95% CI: 1.01 – 1.42). Results for other quintiles in these sub-populations as well as for all quintiles for adult asthma admissions were not statistically significant. Additionally, results suggested a significant reduction in risk for LRTI admissions among the elderly, all COPD admissions, and COPD admissions among the elderly across all home thermal efficiency quintiles. Within these outcomes, there was little difference in the risks by home thermal efficiency quintile. For instance, for LRTI admissions among the elderly, the range of the reduction in risk of admissions was from 0.73 (good and fair quintiles) to 0.7 (lowest quintile).

Table 6.5. Relative risk (RR) and 95% confidence intervals (95% CI) for hospital admissions for asthma, LRTI and COPD associated with quintiles of home thermal efficiency.

Asthma admissions						
	Model 1*		**Model 2†**		**Model 3‡**	
	RR	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**
Best	1	1.00	1	1.00	1	1.00
Good	1.25	(1.09, 1.43)	1.17	(1.03, 1.33)	1.09	(0.95, 1.24)
Fair	1.14	(1.00, 1.29)	1.27	(1.13, 1.44)	1.12	(0.99, 1.27)
Low	1.09	(0.96, 1.24)	1.37	(1.21, 1.55)	1.17	(1.04, 1.33)
Lowest	1.25	(1.09, 1.44)	1.37	(1.20, 1.57)	1.17	(1.02, 1.34)
Asthma adult admissions						
	Model 1*		**Model 2†**		**Model 3‡**	
	RR	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**
Best	1	1.00	1	1.00	1	1.00
Good	1.15	(0.98, 1.34)	1.07	(0.91, 1.24)	1.00	(0.86, 1.16)
Fair	1.04	(0.90, 1.21)	1.17	(1.01, 1.35)	1.04	(0.89, 1.20)
Low	0.97	(0.83, 1.12)	1.20	(1.03, 1.39)	1.04	(0.90, 1.20)
Lowest	1.12	(0.95, 1.32)	1.20	(1.02, 1.41)	1.03	(0.88, 1.22)
Asthma children/YA admissions						
	Model 1*		**Model 2†**		**Model 3‡**	
	RR	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**
Best	1	1.00	1	1.00	1	1.00
Good	1.15	(0.96, 1.37)	1.13	(0.95, 1.35)	1.11	(0.93, 1.33)
Fair	1.14	(0.96, 1.35)	1.17	(0.98, 1.38)	1.14	(0.96, 1.35)
Low	1.16	(0.98, 1.37)	1.21	(1.02, 1.44)	1.19	(1.01, 1.42)
Lowest	1.11	(0.92, 1.34)	1.11	(0.92, 1.34)	1.09	(0.91, 1.32)
LRTI admissions						
	Model 1*		**Model 2†**		**Model 3‡**	
	RR	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**
Best	1	1.00	1	1.00	1	1.00
Good	1.09	(0.98, 1.22)	1.07	(0.96, 1.20)	1.01	(0.9, 1.13)
Fair	1.06	(0.95, 1.18)	1.12	(1.00, 1.25)	1.02	(0.91, 1.13)
Low	1.04	(0.94, 1.16)	1.16	(1.04, 1.29)	1.04	(0.94, 1.16)
Lowest	1.08	(0.96, 1.21)	1.16	(1.03, 1.30)	1.04	(0.92, 1.17)
LRTI children/YA admissions						
	Model 1*		**Model 2†**		**Model 3‡**	
	RR	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**
Best	1	1.00	1	1.00	1	1.00
Good	0.98	(0.86, 1.13)	0.98	(0.86, 1.12)	0.93	(0.81, 1.07)
Fair	0.97	(0.86, 1.11)	0.99	(0.87, 1.13)	0.93	(0.82, 1.06)
Low	0.99	(0.87, 1.13)	1.03	(0.91, 1.18)	0.97	(0.85, 1.11)
Lowest	0.99	(0.86, 1.14)	1.04	(0.90, 1.20)	0.97	(0.84, 1.12)
LRTI 65+ admissions						
	Model 1*		**Model 2†**		**Model 3‡**	
	RR	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**
Best	1	1.00	1	1.00	1	1.00

Good	0.77	(0.63, 0.93)	0.75	(0.62, 0.90)	0.73	(0.60, 0.88)
Fair	0.71	(0.59, 0.85)	0.79	(0.66, 0.95)	0.73	(0.61, 0.87)
Low	0.65	(0.55, 0.78)	0.8	(0.66, 0.96)	0.71	(0.59, 0.86)
Lowest	0.70	(0.58, 0.86)	0.78	(0.64, 0.96)	0.70	(0.57, 0.86)
COPD admissions						
	Model 1*		**Model 2†**		**Model 3‡**	
	RR	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**
Best	1	1.00	1	1.00	1	1.00
Good	1.05	(0.91, 1.20)	0.96	(0.85, 1.09)	0.83	(0.73, 0.94)
Fair	0.85	(0.74, 0.97)	1.07	(0.95, 1.20)	0.77	(0.69, 0.87)
Low	0.66	(0.58, 0.75)	1.09	(0.96, 1.23)	0.73	(0.65, 0.82)
Lowest	0.65	(0.56, 0.75)	1.07	(0.93, 1.22)	0.70	(0.61, 0.80)
COPD 65+ admissions						
	Model 1*		**Model 2†**		**Model 3‡**	
	RR	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**
Best	1	1.00	1	1.00	1	1.00
Good	0.95	(0.82, 1.10)	0.89	(0.77, 1.02)	0.78	(0.68, 0.90)
Fair	0.76	(0.66, 0.88)	0.96	(0.84, 1.10)	0.72	(0.63, 0.83)
Low	0.61	(0.53, 0.71)	1.00	(0.87, 1.15)	0.70	(0.61, 0.80)
Lowest	0.63	(0.54, 0.74)	1.01	(0.86, 1.18)	0.69	(0.59, 0.81)

*Model 1 is unadjusted.

†Model 2 is adjusted for ethnicity, air pollution and smoking.

‡Model 3 is adjusted for ethnicity, air pollution and income.

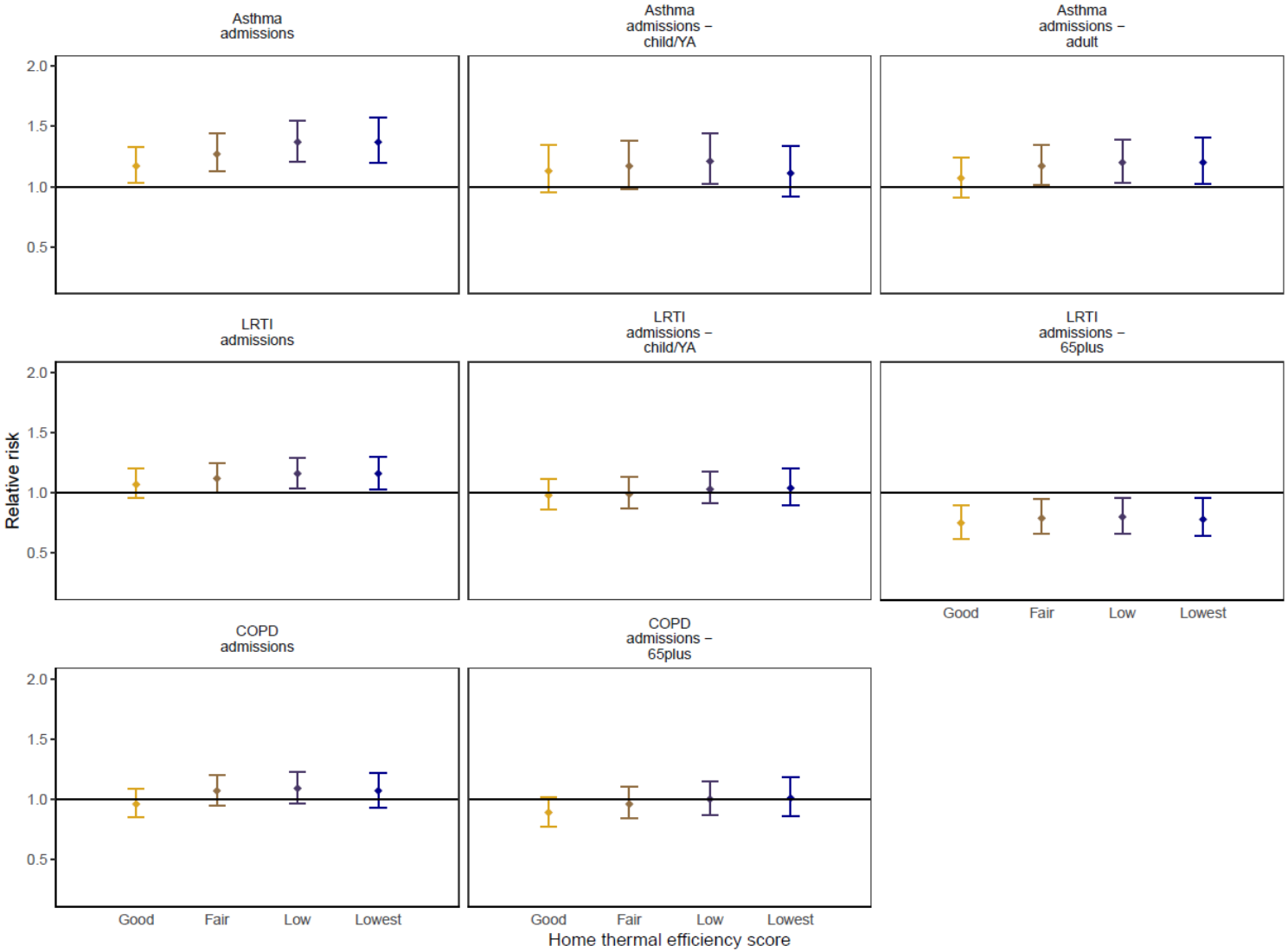


Figure 6.7. Relative risk (RR) and 95% confidence intervals (95% CI) for hospital admissions from asthma, lower respiratory tract infections (LRTI) and chronic pulmonary obstructive disorder (COPD) associated with quintiles of home thermal efficiency, adjusted for ethnicity, air pollution and smoking (reference category is 'best' thermal efficiency score).

6.5 Discussion

I conducted a cross-sectional small area health analysis to explore the association between home thermal efficiency at the LSOA-level in London and a range of health outcomes in the London over the study period, 2009-2019. The thermal efficiency metric used was developed using EPC data and measures whether a home has the physical properties (i.e., different types of insulation) needed to provide its residents with a thermally comfortable home environment. The selected health outcomes were those identified as having an association with poor home thermal efficiency and included: all hospital admissions (excluding births and injuries); all cardiovascular diseases and a subset of CVD diseases: ischemic heart disease and stroke; as well as all respiratory diseases and a subset of respiratory diseases: all asthma, chronic obstructive respiratory diseases (COPD), and lower respiratory tract infections (LRTI) admissions.

6.5.1 Summary of main findings

Overall, there was an increased risk for all hospital admissions (excluding births and injuries), all CVD admissions and all respiratory admissions with decreasing LSOA home thermal efficiency scores after adjusting for ethnicity, air pollution and smoking. Compared to individuals living in LSOAs in the best home thermal efficiency quintile, there was a 31% (RR = 1.31, 95% CI: 1.26 – 1.35) and 29% (RR = 1.29, 95% CI: 1.24 – 1.34) increase in the risk of admissions for all health outcomes, excluding births and injuries, among individuals living in LSOAs in the low and lowest home thermal efficiency quintiles, respectively. Results were similar for all CVD admissions (RR = 1.30, 95% CI: 1.22 – 1.39 and RR = 1.30, 95% CI: 1.21 – 1.4 for the low and lowest quintiles, respectively). For all respiratory conditions, there was a 22% (RR = 1.22, 95% CI: 1.16 – 1.29) and 21% (RR = 1.21, 95% CI: 1.13 – 1.28) increase in risk of hospital admissions for the low and lowest thermal efficiency score quintiles, respectively. These findings were all statistically significant. When adjusting for income instead of smoking, the direction of the association between all hospital admissions (excluding births and injuries), all CVD admissions and all respiratory admissions with home thermal efficiency remained, however the magnitude of the risk decreased while still statistically significant.

For specific CVD outcomes, a similar pattern across home thermal efficiency quintiles was observed for IHD admissions – both in the total IHD admissions and IHD admissions among the elderly, although results for the latter were not statistically significant. For all stroke admissions, the pattern across home thermal efficiency quintiles was consistent though not statistically significant, with an 11% (RR = 1.11, 95% CI: 0.95 – 1.31) and 10% (RR = 1.10, 95% CI: 0.94 – 1.28) increase in the risk of admissions among individuals living in LSOAs in the low and lowest home thermal efficiency quintiles, respectively. For stroke admissions among the elderly, results show a protective effect, i.e., a lower

risk in the exposed versus the unexposed, however these results are not statistically significant. For specific respiratory outcomes, the overall pattern is generally consistent for all the selected outcomes. Similar to what is observed in stroke admission among the elderly, the RR for LRTI admissions among the elderly is less than 1 for all home thermal efficiency quintiles. Though, these results are statistically significant although the higher bound of the 95% confidence interval is close to 1.00.

My findings are generally consistent with literature as a poor home thermal efficiency leads to a poor thermal environment (i.e., too hot or too cold) in the home, which has been previously associated with a range of health outcomes, especially CVD and respiratory related health outcomes (World Health Organization, 2018, Jessel et al., 2019). While there does not seem to be any studies that explore home thermal efficiency in of itself, studies on the association between energy efficiency and/or thermal comfort and health outcomes exist, though with conflicting results. My results align with a study by Kearns et al (2023), which found that an energy efficiency intervention which installed wall insulation in homes increased residents' thermal comfort and reduced CVD and respiratory hospital admissions in Scotland – though in this study, respiratory conditions saw a higher decrease in hospital admissions compared to CVD conditions. Another study found that better energy efficiency was associated with lower risk of winter-/cold-related mortality – with mortality increasing by 2.2% (0.6%, 3.9%) in the coldest fifth of homes versus -0.1% (-1.7%, 1.5%) in the warmest fifth of homes (Wilkinson et al., 2005).

Conversely, an ecological study conducted by Sharpe et al. observed the association between area-level home energy efficiency ratings and interventions (e.g., boiler upgrades, improved insulation, and glazing) and hospital admissions at the LSOA level in England concluded that a unit increase in mean EPC rating was associated with increase of 0.5% in asthma and CVD admissions, and 1% higher COPD admission rates (Sharpe et al., 2019). These results suggest that worse energy efficiency scores may have a protective effect – similar to some of the results of my unadjusted model. Similarly, Symonds et al (2021) found that the proportion of the population with 'good or very good' self-reported health was positively associated with median SAP rating (OR = 1.02, 95% CI: 0.96 – 1.08) and air infiltration rate (OR = 1.10, 95% CI: 1.03 – 1.18) in London LSOAs. When focusing on LSOAs in the most deprived income quintile, the results for the median SAP rating are statistically significant (OR = 1.06, 95% CI: 1.00 – 1.12). These results could be due to a number of factors that reflect the complex nature of the relationship between the home thermal environment and health such as (1) unintended consequences of energy efficiency improvements such as air tightness leading to reduced ventilation and poorer health outcomes (Shrubsole et al., 2014), (2) reverse causality, i.e., the most vulnerable

are more likely to receive government-led home interventions to improve energy efficiency, (3) the role of resident behaviour, or (4) limitations of the study design.

The difference in the magnitude of the association between home thermal efficiency and health outcomes when adjusting for smoking versus income may be due to a number of factors. First, this difference may be highlighting the complex but different mechanisms by which smoking and income affect the association between home thermal efficiency and health. Smoking may have a more direct impact on CVD and respiratory outcomes, but likely has a weaker association with home thermal efficiency. Income is both indirectly related to health outcomes, via e.g., access to or delay of healthcare and poor communication (Okunrintemi et al., 2019), and also home thermal efficiency. Moreover, in the development of thermal efficiency metric, factors known to be associated with housing quality and income such as property type (flat vs house) and tenure (rent vs own) (Symonds et al., 2021) were already accounted for. As such, this may have also reduced the affect seen in this analysis when adjusting for income.

The lack of clear results for the elderly population is also found in existing studies. For instance, Hughes et al. observed the association between indoor home temperature and healthcare visits, including visits to GPs, Accident and Emergency, Inpatients, Outpatients and social care professionals among the elderly over winter months in Bath, UK (Hughes et al., 2019). The study found little evidence for an association between home temperature and visits to medical personnel for different health outcomes. Still, there are UK studies that have suggested the that the reduction of hospital admissions associated with housing improvements, including wall insulation, is greater for the elderly population (Rodgers et al., 2018). These findings, however, are not directly comparable as the interventions take a whole-house approach and do not solely focus on the thermal environment of the home.

6.5.2 Strengths and limitations

The use of the EPC and HES data is a strength of this analysis as these sources of big data are comprehensive and robust. The slight discrepancies in the timing of the different data sources used in this analysis, however, is a limitation. The health data are only used to 2019 to avoid the start of the COVID-19 pandemic. The EPC data used for the home thermal efficiency metric are to 2020 (see Chapter 5) as that was the last full year of data at the time the data were extracted, but as EPCs are valid for 10 years or updated when a home is built, rented or sold, it is reasonable to assume that the majority of EPCs did not change outside of the study period. Data for confounders were used based on data availability or, where multiple years of data were available, the year closest to the mid-point of the study period.

Another limitation of this analysis is that confounders were adjusted for at the small area level, and not the individual level. This was due to the lack on individual-level data for confounders. Thus, it is important to acknowledge that results must be interpreted at the area level as they may not apply to individuals. Limitations of the thermal efficiency metric are discussed in Chapter 5, but it is important to note that the metric only consists of insulation-related variables. Thus, additional research which allows for the inclusion of additional variables relevant to the thermal environment in the home is needed to confirm the consistency of these results.

This study used data from London which is an urban area in a high-income country. Thus, results may not be generalisable to other regions of the UK, rural areas or other cities in different economic standing. Additional research is needed to establish whether results can be transferred to such settings.

6.6 Chapter summary

This chapter presented a small area health analysis of the association between home thermal efficiency and hospital admissions for a selected number of health outcomes. The results are generally consistent with existing literature, which positive and statistically significant associations between the lowest quintiles (i.e., worse) of home thermal efficiency and hospital admissions for all causes (excluding births and injuries), all CVD conditions and all respiratory conditions, after adjusting for ethnicity, air pollution and smoking. Results were less consistent when observing the association between home thermal efficiency and specific CVD (i.e., stroke and IHD) and respiratory (i.e., asthma, LRTI and COPD) conditions, even when subsetting to specific populations such as the stroke admission among the elderly. This reflects the complex nature of the association between the thermal environment in the home and health, and the need to understand the role of potential reverse causality and unintended consequences of home energy improvements.

7 Conclusion

7.1 Overview

The aim of this thesis was to define housing quality through a public health lens, measure a domain of housing quality at the small-area level in London and estimate its associations with health. To achieve this aim, I developed five objectives which provide a roadmap from the conceptual housing quality and health framework (Chapters 2-3) to the empirical analyses that focus on one domain of housing quality, i.e., thermal efficiency (Chapters 4-6).

My first objective was to review housing quality definitions in literature, assessment tools and frameworks to provide a detailed underpinning of the existing research and evidence base. My review highlighted the complexity and heterogeneity in defining and measuring housing quality. I found that although I was able to identify certain recurring areas of focus across the evidence, a need for a comprehensive overview of housing quality from a public health perspective was lacking. This review, along with an overview of the demographic composition and housing stock of London, UK is detailed in Chapter 2.

My second objective was to develop a housing quality and health conceptual framework (Chapter 3) based on the insight I gained from my review. My housing quality and health framework is composed of 13 domains, each with multiple indicators I have proposed that could be used to measure the domain. My housing quality and health conceptual framework is not geography-specific, but instead provides an approach to exhaustively measure housing quality in any setting globally.

In Chapter 4, I achieved my third objective, which was to identify and explore housing quality data sources to quantify housing quality domains in London. I identified relevant data sources and conducted exploratory analyses to ensure the quality and robustness of the data, especially the EPC data, which is the primary data source for this thesis' analyses.

My fourth objective was to develop a cross-sectional metric to measure and map a housing quality domain at the small-area level in London using data from Objective 3. I developed a home thermal efficiency metric (Chapter 5), which measures the degree to which a home has the physical attributes necessary to provide its residents with a thermally comfortable home environment. A review of thermal comfort and thermal efficiency indicators provided insight into the existing evidence and was coupled with the EPC data to identify the variables that could be used to measure home thermal efficiency in London. I then explored the variability of the selected variables via LCA to ascertain the variables that would be informative in estimating thermal efficiency in London. I merged the EPC data

with Census and VOA data and applied the Battese-Harter-Fuller model to estimate the mean thermal efficiency score for each London LSOA. The mean thermal efficiency score of LSOAs in London from 2009 to 2020 was 4.34 (SD: 0.48), ranging from 3.12 to 5.99, with higher scores in LSOAs found towards the centre of London.

My final objective was to conduct a Bayesian small-area analysis, using R-INLA, to estimate associations between domestic thermal efficiency and relevant health outcomes and assess how these differ across the socioeconomic spectrum. I estimated age and sex standardised rates of cause-specific hospital admissions for each LSOA using London mid-year population estimates by sex and 5-year age groups from ONS and then developed a Bayesian spatial model to explore the association between hospital admissions for selected health outcomes and home thermal efficiency in London LSOAs. I found that as home thermal efficiency worsens, there is an increased risk of admissions for all causes (excluding injuries and births), all CVD admissions and all respiratory admissions after adjusting for ethnicity, air pollution and smoking. These associations, however, were not as well-defined in the analysis of risk of hospital admissions for specific CVD and respiratory health outcomes.

Overall, in this thesis I provide insight into how to integrate multiple existing housing-related data to identify indicators available for a housing quality domain, develop a metric for that domain, and use the metric to gain insight into the relationship between a housing quality domain and health outcomes in an urban setting.

7.2 Public health implications

The findings of this thesis are significant as there are public health implications from the housing quality and health framework and the home thermal efficiency metric and health outcomes analysis, for London and beyond.

7.2.1 Conceptual framework and data

It is important to measure housing quality, a key socio-determinant of health (Krieger and Higgins, 2002), at the small-area level as it provides the spatial granularity needed to assess differences in exposure and their effect on health. This knowledge can then be used to provide insight into the development of targeted, sustainable and evidence-based housing quality standards and policies. The outcomes of my thesis have the ability to play an important role in this process.

My conceptual framework sets the stage for cities first to comprehensively understand which areas of housing quality are relevant from a public health perspective. Stakeholders such as those involved in

home construction, housing research and policy, as well as council representatives, homeowners and tenants, are able to use this framework to identify different areas of housing quality which are relevant to their settings and get solid understanding of what types of indicators can be used to measure the domain (Wimalasena et al., 2022). As such, the framework provides a means to gauge the usability and usefulness of any existing housing quality data in how it can inform the measurement of different domains via indicators and narrow the gap in understanding housing quality from a public health lens (Chohan et al., 2015) in cities globally. For instance, WASH is an important housing quality domain to measure in Bangladesh (OECD and Organization, 2020). One available resource is the Population and Housing Census, which includes information on the main source of drinking water and the type of toilet facilities. However, it does not include information on variables such as distance to water sources, water quality, number of people/households per toilet. This is highlighting either the need to integrate this Census with additional data sources or to collect additional setting and housing domain-specific data.

The development of my home thermal efficiency metric underscores the existing challenges and constraints in the availability and accessibility of housing quality data, even in data-rich settings like London. For instance, the English Housing Survey (EHS) gathers information on housing conditions on a sample of English homes annually. However, access to EHS data requires a long multistep process that takes nearly a year to complete. Moreover, the data are only accessible via the UK Data Service's secure portal which is not equipped for robust analysis (e.g., is missing a number of packages in the R software needed to conduct my planned analyses). Though robust in many ways, limitations of the EPC such as data collection methods and availability of variables, significantly restricted my analysis. This underscores the need for better housing quality data by academic or research institutions, but also governments, for instance by incorporating into part of national surveys, as suggested by Rosenberg and Wilson (Rosenberg and Wilson, 2001). Additionally, better data allow for better and more nuanced measurement of housing quality domains as data availability has a direct impact on the scope of what can be measured. In this present study, the EPC data were able to give information on certain aspects of thermal efficiency but cannot be used, at least independently, to measure thermal comfort.

7.2.2 Home thermal efficiency and health

Beyond the conceptual framing of housing quality and the associated data needs, the London case study I present in this thesis provides a practical example of how a housing quality domain can be measured and the takeaways that can be derived from such analyses. For instance, the lack of clusters of particularly high or low mean LSOA home thermal efficiency across the city indicates the need for

city-wide home thermal efficiency improvements and interventions. It also illustrated a 'double-need' of cities like London, where both the historical and geographical trends (i.e., older homes towards the centre of the city) must be considered in parallel to the socio-economic characteristics of the residents. On one hand, it is important to improve the domestic thermal conditions of older homes, whose residents may be from various socioeconomic backgrounds, as my results showed that the LSOAs with the highest mean home thermal efficiency were primarily in the centre of London which also has the oldest homes. However, on the other hand, government-led support for low-income households via thermal-comfort related interventions (e.g., providing grants for insulation installation) must also continue. In line with my results, other research has also highlighted the complex nature of the interplaying dynamics involved in the home thermal environment (Shrubsole et al., 2014, Sutton-Klein et al., 2021), including the unintended consequences of home improvements, resident behaviour, socioeconomic factors (e.g., fuel poverty, ability to retrofit), tenure and housing age and type. As such, data that could give insight on some of these factors could provide good direction for future research. This could include data on whether a home has undergone any retrofitting (and if so, when and what type), the orientation of the home and the number of windows.

Importantly, domestic thermal efficiency is associated with risk of hospital admissions from all causes (excluding injuries and births), all CVD admissions and all respiratory admissions, even after adjusting for ethnicity, air pollution and smoking. This emphasizes the need for considering health outcomes when building, renovating and retrofitting homes. The impacts of poor thermal efficiency in the home on health that were found in my analysis are consistent with the existing evidence base. For instance, the WHO Housing and Health guidelines (2018) state that home thermal conditions are associated with increased risk of a number of CVD and respiratory conditions via different mechanisms such as inflammation of the lungs and inhibition of circulation. My analysis did not show a statistically significant change in risk for hospital admissions for subpopulations, in most instances. This may suggest that total population-targeted interventions may be the most beneficial.

7.2.2.1 Limitations

While considering the implications of the analyses presented here, it is also important to acknowledge and take limitations of this study into account. My analyses aimed to measure the association between home thermal efficiency and health outcomes and as such do not assess or establish causality. While key covariates that are known to affect both thermal efficiency and health were adjusted for, the possibility of residual confounding cannot be excluded. Additional variables such as resident behaviour, the impact and role of retrofitting, and housing-related variables such as household composition are important factors that may have a potential non-negligible impact of the association

between thermal efficiency and health. Additionally, potential biases such as selection bias, due to the non-random sampling of homes with EPCs, and measurement bias, due to inaccuracies in assessing thermal efficiency or health outcomes, may have impacted the validity of the findings. Future efforts could address these potential sources of bias (e.g., improve EPC data), and alternative study approaches such as longitudinal studies could provide a more comprehensive understanding of underlying mechanisms.

7.3 Future work

The above-discussed implications of this thesis also highlight the need for future work and research in this arena. Many avenues exist to extend and broaden the findings of my thesis. The conceptual framework can be used in different settings to better gauge its adaptability. Importantly, domain indicators could be further refined to better reflect the needs and data availability in different cities. Indicators could be compared across settings and used to create a more standardised tool to measure housing quality domains.

Higher quality data and more research is needed to better evaluate the association between home thermal efficiency and health outcomes. There is a need to foster collaboration across relevant stakeholders to develop ongoing initiatives to collect housing-related data. More robust and granular data would allow for a more accurate measurement of home thermal efficiency and its association to health outcomes, for instance by matching home thermal efficiency and health data at the household or individual level which would remove any ecological fallacy.

The role of age (i.e., children/young adult and elderly populations) in the association between home thermal efficiency and health needs to be further studied as the results from my analysis show a reduction in risk among individuals in LSOAs with worse mean thermal efficiency scores – though these results were mostly not statistically significant. To understand the effects of geography, my analysis could be supplemented by data from other UK cities or even other European cities to gain insight on whether the findings of my analyses are replicated in other settings and at what magnitude. This could potentially highlight how differences or similarities between cities might influence how home thermal efficiency is measured, and its impact on health.

7.4 Conclusion

This thesis comprehensively and critically summarises the existing evidence on housing quality and health to inform decision making on the development of a broad yet comprehensive framework, and the implementation of a case study to define and measure home thermal efficiency in London and its associations with hospital admissions for health outcomes. This thesis primarily uses EPC data, extending its application to the realm of home thermal efficiency and health.

The methods used in this thesis highlight the dire need for robust housing quality data, even in data-rich settings to better inform modelling decisions. The findings presented demonstrate the complexity of measuring phenomena like the home thermal environment, especially where data are not readily available. However, this mirrors the reality in many cities and thus the thesis can serve as a guide to the application of the housing quality and health framework in different settings. The association between housing quality and health are clearly shown in the final analysis, highlighting the need for incorporating epidemiological evidence into the development, implementation and evaluation of housing policies in London and other cities globally. By illuminating the nuanced relationship between housing quality and health, this thesis advocates for a more informed and evidence-driven approach to shaping housing policies which have implications for public health.

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Appendix 9-27. Relative risk (RR) and 95% confidence intervals (95% CI) for IHD admissions among the elderly associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income) 200

Appendix 9-28. Relative risk (RR) and 95% confidence intervals (95% CI) for all asthma admissions associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income) 201

Appendix 9-29. Relative risk (RR) and 95% confidence intervals (95% CI) for asthma admissions among children associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income) 202

Appendix 9-30. Relative risk (RR) and 95% confidence intervals (95% CI) for asthma admissions among adults associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income) 203

Appendix 9-31. Relative risk (RR) and 95% confidence intervals (95% CI) for all LRTI admissions associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income) 204

Appendix 9-32. Relative risk (RR) and 95% confidence intervals (95% CI) for LRTI admissions among children/young adults associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income) 205

Appendix 9-33. Relative risk (RR) and 95% confidence intervals (95% CI) for LRTI admissions among the elderly associated with quintiles of home thermal efficiency (reference category is 'best' thermal

efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income) 206

Appendix 9-34. Relative risk (RR) and 95% confidence intervals (95% CI) for all COPD admissions associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income) 207

Appendix 9-35. Relative risk (RR) and 95% confidence intervals (95% CI) for COPD admissions among the elderly associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income) 208

Appendix 9-36. Relative risk (RR) and 95% confidence intervals (95% CI) for hospital admissions for all health outcomes, all CVD outcomes and all respiratory outcomes associated with quintiles of home thermal efficiency, stratified by quintiles of the IMD income domain 209

Appendix 9-1.MEDLINE and Embase combined search strategy

1	exp housing quality/
2	(hous* quality or hous* condition*1 or hous* deprivation or healthy home*1).mp.
3	exp conceptual framework/
4	exp practice guideline/
5	(framework or guideline or index or definition).mp.
6	public health/
7	exp health/ or exp public health/
8	exp wellbeing/
9	(health or public health or wellbeing).mp.
10	(exp animals/ or nonhumans/) not exp human/
11	1 or 2
12	3 or 4 or 5
13	6 or 7 or 8 or 9
14	11 and 12 and 13
15	14 not 10
16	15 use emczd
17	exp Housing Quality/ or exp Residence Characteristics/
18	(hous* quality or hous* condition*1 or hous* deprivation or healthy home*1).mp.
19	exp Practice Guideline/ or exp Guideline/
20	(framework or guideline or index or definition).mp.
21	exp Health/ or exp Public Health/
22	(health or public health or wellbeing).mp.
23	(exp animals/ or nonhumans/) not exp human/
24	17 or 18
25	19 or 20
26	21 or 22
27	24 and 25 and 26
28	27 not 23
29	28 use medal
30	16 or 29
31	limit 30 to English

Appendix 9-2. Characteristics of studies included in scoping review (highlighted studies are those where health outcomes are not measured)

Authors Year	**Country**	**Sample size**	**Housing quality dimensions**	**Health Outcome** *(where measured)*
Adamkiewicz et al. (2014)	USA	828 individuals	Mold Combustion byproducts index Second hand smoking Chemical exposure (using spray, powders, or foggers or spray air fresheners) Pest (cockroaches, ants, mice, rats or bedbugs) Inadequate ventilation index	Self-reported health status
Aliu and Adebayo (2012)	Nigeria	1,240 individuals	Separate kitchen Tiled bath Flush toilet Room space Number of rooms Structural defects Cross ventilation Sanitation, water, drainage Waste facility	Occurrence of at least one residential quality induced disease or none
Ansarin et al. (2013)	USA	5,545 individuals aged 16 and over	Type of home Number of apartments in the building Age of home Number of rooms in home Time lived in home Whether home was owned or rented Water source and treatment, Allergy component-related questions about the presence of furry animals.	Obstructive sleep apnea syndrome

Anwar et al. (2021)	Canada	293 individuals within 131 households	Number of occupants residing in the house Number of rooms in the house Is smoking permitted in the house Dampness, the presence of visible mold, and the presence of a mildew/moldy or musty odor in the house	Respiratory outcomes: shortness of breath and ever wheeze
Boch et al. (2021)	USA	12,964 children aged 2 years–14 years	Are the following conditions present in the household: "… holes in the walls or ceiling, or cracks wider than the edge of a dime?" "… holes in the floor big enough to catch your foot on?" "… problems with pests such as rats, mice, roaches, or other insects?" "… a toilet, hot water heater, or other plumbing that did not work?"	Poor health status Number of medical visit Hospitalization
Cheung and Mui (2022)	Canada	24,603 individuals aged 60 or older	Living in low-income housing Size of living space (number of bedrooms in the respondent's residence Home maintenance need (only regular maintenance is needed, minor or major repairs are needed) Satisfaction with safety Satisfaction with energy efficiency Satisfaction with accessibility Satisfaction with soundproofing Satisfaction with temperatures during summer and winter Presence of poor indoor air quality Presence of pests Presence of undrinkable water Presence of mold or mildew	General health
De Vries et al. (2018)	Columbia	9656 individuals	Type of toilet (shared or private and (lack of) connection to sewage system) Principal material of floor and walls Electricity supply General access to sewage systems, garbage collection Bath or shower within the house Type of access to water	Anxiety and depression

Dias and de Oliveira (2018)	India	31197 women	Type of flooring Type of toilet facility Cooking fuel Household electrification Glass windows Household assets such as a pressure cooker, telephone, color television, refrigerator, computer, car, and motorcycle/scooter	Contraceptive adoption
Evans (2003)	USA	339 children	Residential crowding (number of people/room), Noise (indoor decibel levels measured over two different, 2-hr periods) Structural quality Clutter and cleanliness Hazards Indoor climate Children's resources (e.g., books, age appropriate toys or games;)	Developmental outcomes
Frisk et al. (2009)	Sweden	49 individuals	Water content Internal moisture supply Mechanically ventilated houses Naturally ventilated houses Carbon dioxide (ppm) Formaldehyde (mg/m3) Nitrogen dioxide (mg/m3) Environmental tobacco smoke House dust mites Pets (cat, dog)	Asthma
Gao et al. (2021)	Africa	88,271 individuals aged 36 to 59 months in 20 Sub-Saharan countries	Access to improved water source Access to improved sanitation facilities Sufficient living area (considered sufficient for household members if no more than 3 people shared the same habitable room) Housing durability (if at least 2 out of 3 of the materials for the walls, roof, and floor were finished)	Early childhood development

Herrin et al. (2013)	Uganda	7096 households	Crowding Independent dwelling (detached or otherwise) Hut Bad roof Bad walls (thatch, straw, or mud and poles, otherwise) Bad water (water source is unprotected (e.g., stream, pond, lake, unprotected well/spring, rain), otherwise Bad toilet (flush toilet, otherwise) Bad lighting (kerosene, wood, paraffin, or gas lantern, or otherwise) Bad cooking	Average days sick
Johnson et al. (2005)	USA	600 households	Landlord repairs Quality of home Year home was built Building materials Central air conditioning Basement Heating source Type of furnace Filter on furnace Indoor temperature Water leaks Pets Cockroaches Pesticide application Car/garage Clothes dryer Weatherproofing	Asthma prevalence, severity, and triggers

Keall et al. (2012)	New zealand	1,660 individuals	Feels a little damp Feels quite damp In shade - partial or substantial House smells musty Any mould in bedrooms/living rooms Unflued gas heater Fungi/mould on joists or bearers No floor insulation Major or minor leaks in roof Ponding of water under house No ceiling insulation No wall insulation	Respiratory symptoms, current smoking behaviour and use of medication for asthma
Kobayashi et al. (2022)	South Africa	4,580 individuals aged ≥40	Construction materials of the main dwelling structure Sources of power for lighting and cooking Source of water and type of sanitation facilities Ownership of livestock Technological amenities, such as a refrigerator, television, telephone, and vehicles	Cognitive health
Marcal (2022)	USA	1,804 households	No broken windows or cracked window panes No open cracks or holes in walls or ceiling No broken plaster or peeling paint Inside of home is adequately lit Inside of home is not crowded Not noticeably cluttered Not dirty/reasonably cleaned Environment inside safe for young children Not overly noisy	Psychological aggression, physical aggression, and neglect due to child maltreatment

Naess et al. (2005)	Sweden	88,159 individuals	Living in blocks/attached house/ flat Tenure Crowding (number people per room) Having telephone Having toilet in the dwelling Having bathroom	Mortality
Orjiakor et al. (2023)	Nigeria	1,674 households	Access to modern roof Access to modern floor Access to modern exterior walls Access to improved toilet Access to improved water source Connection to electricity Access to the internet Ownership of mobile phone Ownership of refrigerator Ownership of television Ownership of radio Ownership of car or other vehicles Ownership of generator Ownership of computer	Risk of food insecurity
Schootman et al. (2009)	USA	352 individuals aged 49–65 years	Cleanliness inside the building, Physical condition of the interior Condition of furnishings Condition of the exterior of the building A global rating	Blood was analyzed for soluble cytokine receptors (interleukin-6, tumor necrosis factor α), C-reactive protein, and adiponectin

Seo and Park (2021)	Republic of Korea	1,308 individuals aged 19 to 34 years	Lighting Soundproof Dampness Ventilation Protection from break-in Protection from natural disaster Protection from fire Sanitation	Mental health (depressive symptoms)
Teare et al. (2020)	South Africa	50 dwellings	Type of roof (roof material, colour, shape) Type of ceiling (none, cement, wood, board) Type of walls (plastered brick, brick, wood, metal sheeting, stone, internal versus external) Type of windows (number, blind, awning, operational, type of glass) Type of floors (cement, linoleum, wood, brick, tiles, sand) Methods used for temperature control (portable fan, ceiling fan, air conditioning) Presence of shade trees (yes/no, number)	temperature and its potential impact on health
Troxel et al. (2020)	USA	634 households	Peeling paint or broken plaster Plumbing that does network Rats or mice, cockroaches Broken locks or no locks on door to unit Broken windows or windows without screens A heating system that does not work	Sleep outcomes: duration, efficiency, quality

Turunen et al. (2017)	Finland	2,674 individuals aged 18 to 75 years	Accessibility of the dwelling and surroundings Accidents (falling /slipping) Air fresheners used in the dwelling Airing the bedding Air traffic noise Asbestos Balcony renovation within the last 5 years Break-in Central heating Cold floors in summer Cold floors in winter Condensation in the windows during winter Draughty in winter Elevated radon concentrations Fireplace in dwelling Food odor in the dwelling Fresh air vents in bedrooms Laundry is dried in the balcony Laundry is dried outside Lighting defects in the dwelling, natural light; in the yard; on the hallways Moisture or mold (Inside or outside) Mold odor in the dwelling No signs of insects in the dwelling Odor in the drinking water; in the dwelling Personality threated when moving in residential area PVC flooring material Roof type Safety systems Satisfied with the dwelling Sauna in the dwelling Scented detergents/cleaners Sewage smell in the dwelling Severe water damage	General Symptoms Eye symptoms Upper respiratory tract symptoms Lower respiratory tract symptoms Respiratory tract infections Difficulties to sleep

			Signs of insects in the dwelling Smoke smell in the dwelling / Smoking in the dwelling (someone) Solar heating Sources of pollen nearby Stuffy air in the dwelling Suitable warm in summer / Suitable warm in winter Toilet water to sedimentation basin Too cold in winter / Too hot in summer Traffic noise disturbance Underdrain repair within last 5 years Use of herbicides, pesticides in the dwelling Washing water to small sewage treatment plant OR closed tank OR sedimentation basin Window renovation Ventilation	
Nriagu et al. (2011)	USA	642 households	Structural (18 items) Moisture/mold (8 items) Electrical (7 items) Ventilation and combustion appliances (6 items) Pest (6 items) Pets (4 items) Fire (6 items) Lifestyle-associated factors (12 items)	NA

Adair et al. (2014)	Canada	55 housing units	Safety/security Natural light Artificial light Utilities-power Indoor air/ventilation Utilities-heating/cooling; water; plumbing Bathroom facilities Structural condition Kitchen/food prep area Kitchen appliances Bedroom/sleeping space Noise Pests Storage space Overall design Laundry	NA
Brkanić (2017)	Croatia	NA	Apartment area Position in building - floor Unit plan and size - layout Condition and design of walls, floors, windows, doors Interior of living room, kitchen, bedroom, and bathroom Living room, kitchen, bedroom, and bathroom size, location, number, and orientation Entrance and hallway Storage Outer spaces - balcony, terrace, garden (existence, size, position) Well-being and environment-friendly design and materials High-tech solutions design style (space and equipment) Sustainability - flexibility and adaptability Ventilation - natural, artificial Noise Comfort (thermal, acoustic)	NA

			Indoor air Condition of lighting/daylight Size and location of windows Window sill level Privacy View	
Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development (2006)	USA	NA	Protection from the elements A thermal environment that will avoid undue heat loss & permit adequate heat loss from the body An atmosphere of reasonable chemical purity Adequate daylight illumination and avoidance of undue daylight glare Direct sunlight Adequate artificial illumination and avoidance of glare Protection from excessive noise Adequate space for exercise and for children to play	NA
Chu et al. (2022)	USA	NA	Indoor air quality, specifically household fuel combustion Dampness and mold Pests and allergens, specifically rodents and cockroaches Lead, specifically lead paint riskHigh indoor temperatures Low indoor temperatures Household crowding, specifically severe crowding Injury hazards, specifically electrical and structural integrity Inadequate water and sanitation Ventilation, specifically building normalized leakage	NA

Iddi et al. (2022)	Africa	15 countries	Main wall Roof Floor materials Type of toilet facility Source of drinking water Type of cooking fuel Presence of electricity	NA
John F. Kain and Quigley (1970)	USA	NA	Overall structural condition General housekeeping Condition of ceilings Condition of walls Condition of floors Condition of lighting Condition of windows	NA
Keall et al. (2010)	England New Zealand	NA	Adequate structural soundness Adequate water supply Adequate sanitary areas and waste disposal Adequate food preparation areas Adequate safety from falls and other injuries Adequate safety from fires, electrocution and explosion: Adequate warmth and dryness Adequate protection from excess heat Adequate lighting and sunlight Adequate control of indoor pollutants Adequate protection from noise Adequate security, privacy and space Addresses energy efficiency Adequate sustainability of water use and waste disposal	NA

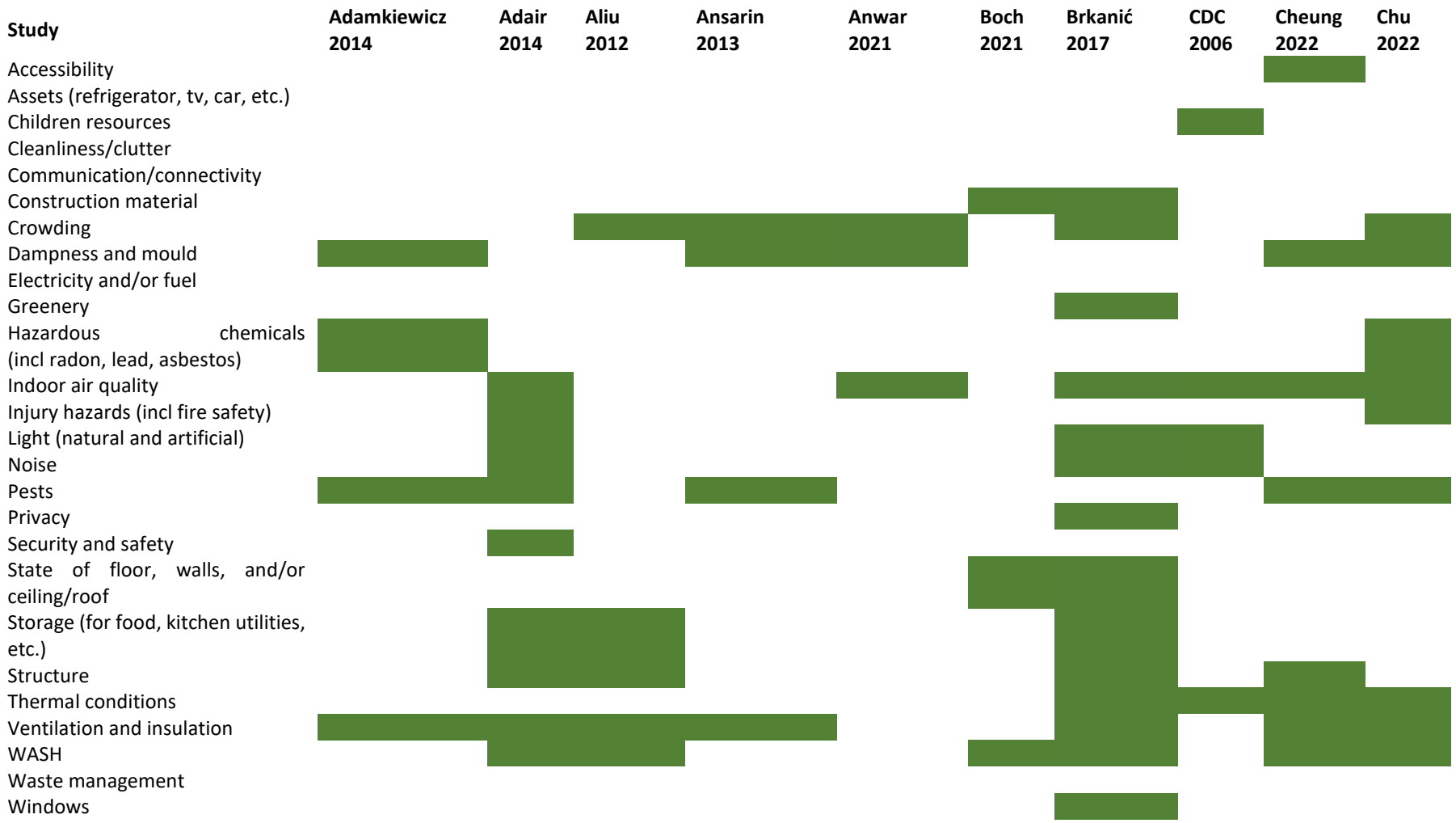
Le et al. (2016)	Vietnam	NA	Location Distance to the current social facilities Evaluation of the master plan of the building General issues in terms of “building design” Movement inside the building (including presence of fire escape) Public spaces of the building Technical areas (including electricity and water supply, waste collection) Structure of spaces inside each apartment/ unit Apartment’s microclimate (including ventilation, illumination, noise) Apartment’s equipment (including fire alarm) Others (including accessibility, security)	NA
Luiz et al. (2009)	Brazil	5,507 Brazilian municipalities	Percentage of households with adequate sewage disposal facilities Percentage of households with adequate waste collection facilities Percentage of households with adequate water supply Percentage of households with average number of people living in each dwelling	NA
National Center for Healthy Housing (2022)	USA	NA	Dry Clean Pest-Free Ventilated Safe Contaminant-Free Maintained Thermally Controlled Accessible Affordable	NA

Nolan and Winston (2011)	Ireland	14,634 individuals 5,836 households	Presence of a bath/shower Presence of central heating Presence of hot water Presence of running water Presence of a toilet Presence of a leaking roof, damp walls etc. or rot in the doors, window frame or floor Presence of room(s) which are too dark or don't have enough light Presence of household durables deprivation (i.e., assets)	NA
Pierse et al. (2020)	New Zealand	895 households	Mold Insulation Floor coverings Curtains Heating Ventilation Draught stopping Crowding	NA
World Health Organization (1967)	Multi	NA	Crowding Privacy Water supply Sanitation (sewage; hygiene) Ventilation Light Protection against excess heat, noise and dampness Appropriate facilities for cooking, dining and storage of food, goods and belongings	NA

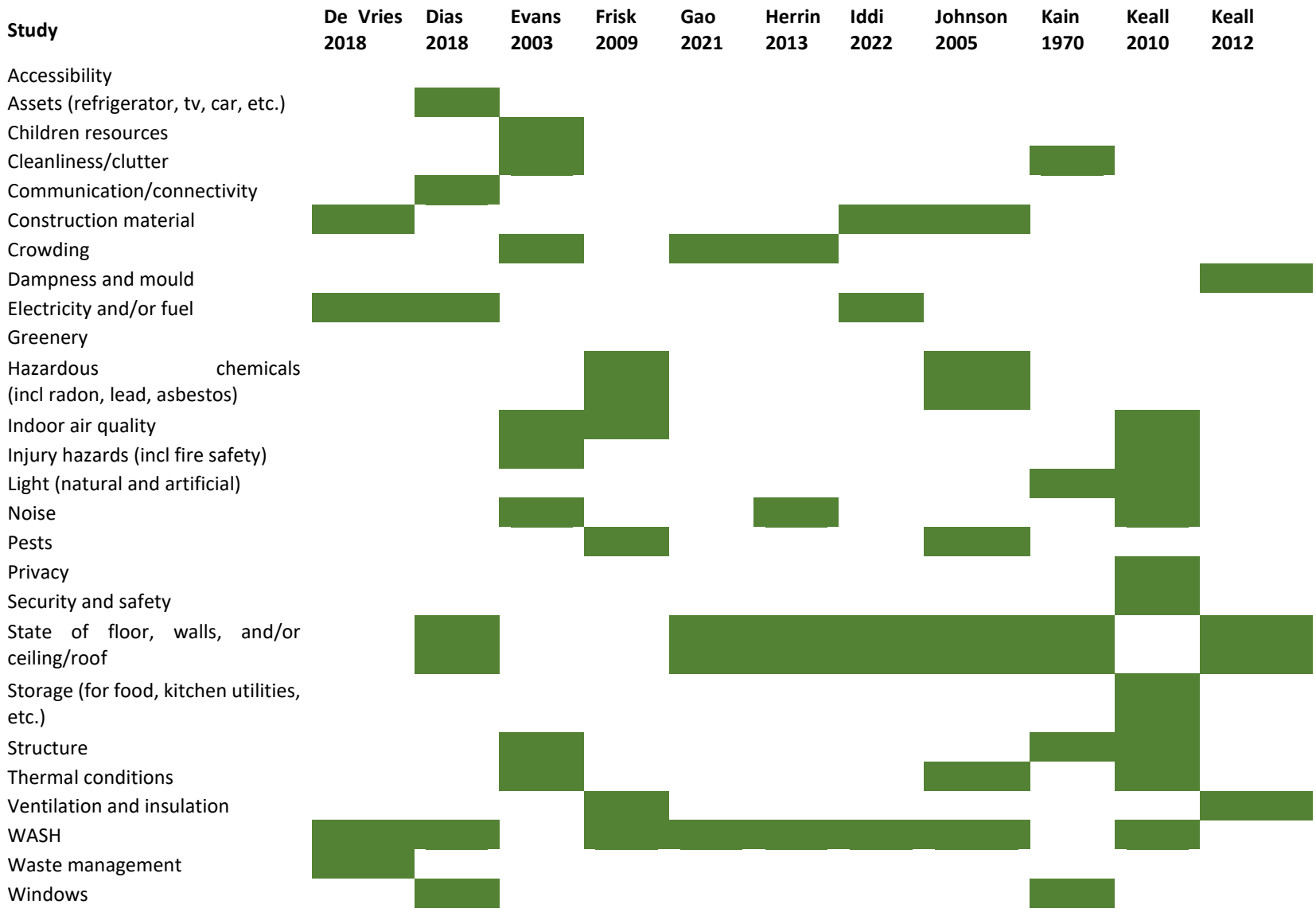
World Health Organization (1989)	Multi	NA	Safe water supply Sanitary excreta disposal Disposal of solid wastes Drainage of surface water Personal and domestic hygiene Safe food preparation Structural safeguards against disease transmission Structural features and furnishing Indoor air pollution Chemical safety	NA
World Health Organization (2018)	Multi	NA	Inadequate living space (crowding) High/low indoor temperatures Injury hazards in the home Accessibility Water quality Air quality Tobacco smoke Noise Asbestos Lead Radon	NA

NA: Not available/not applicable

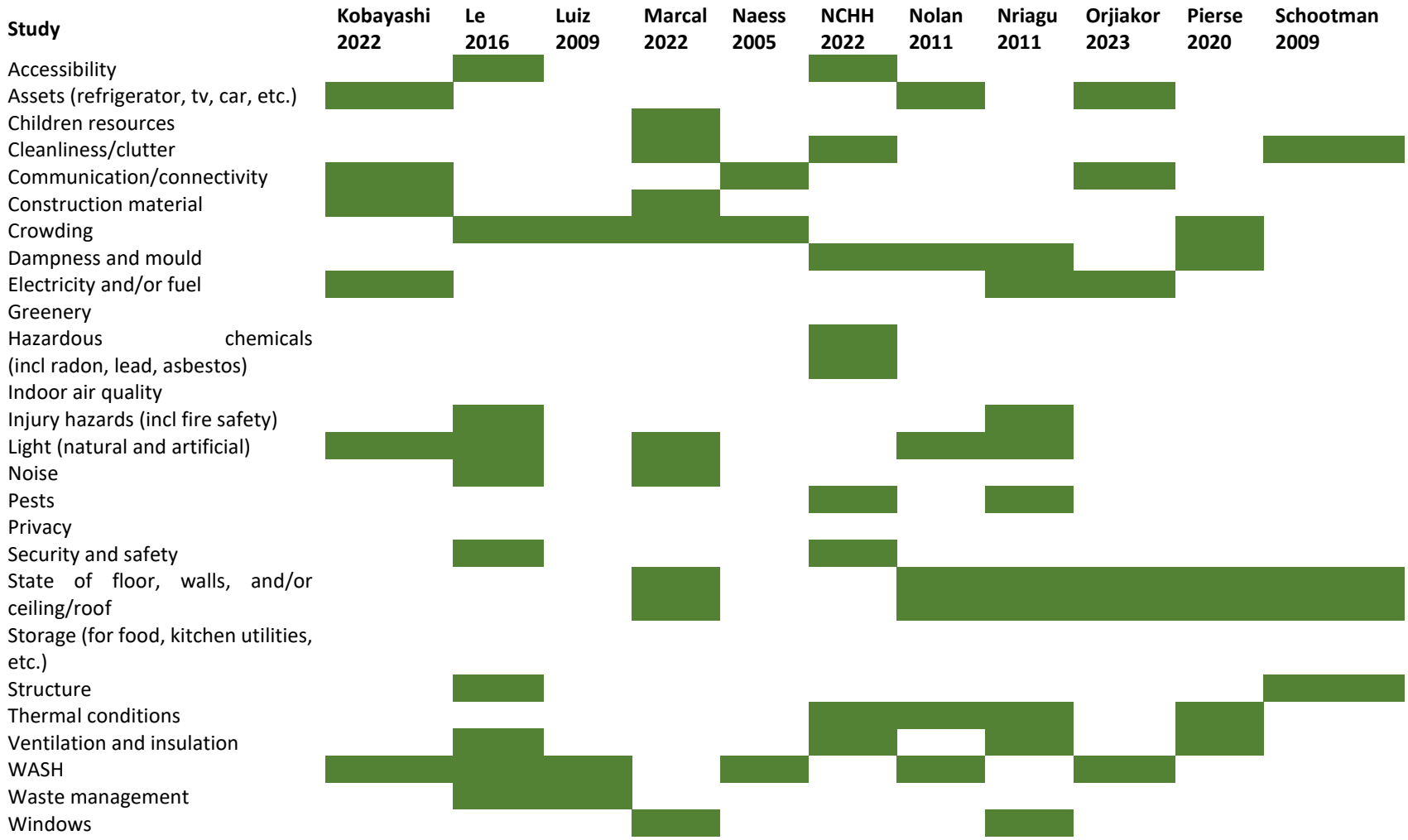
Appendix 9-3. List of housing domain by study, for studies included in scoping review



List of housing domain by study, for studies included in scoping review [cont.]



List of housing domain by study, for studies included in scoping review [cont.]



List of housing domain by study, for studies included in scoping review [cont.]

Study	Seo 2021	Teare 2020	Troxel 2020	Turunen 2017	WHO 1967	WHO 1989	WHO 2018	Total
Accessibility				■			■	5
Assets (refrigerator, tv, car, etc.)								4
Children resources								3
Cleanliness/clutter								5
Communication/connectivity								4
Construction material		■	■					9
Crowding					■	■	■	16
Dampness and mould	■			■	■		■	14
Electricity and/or fuel								6
Greenery		■						2
Hazardous chemicals (incl radon, lead, asbestos)				■		■		7
Indoor air quality						■		10
Injury hazards (incl fire safety)	■			■			■	9
Light (natural and artificial)	■			■	■			13
Noise	■			■	■			11
Pests			■	■				10
Privacy					■			3
Security and safety	■		■	■				7
State of floor, walls, and/or ceiling/roof		■		■				17
Storage (for food, kitchen utilities, etc.)					■	■		6
Structure						■		10
Thermal conditions	■	■	■	■	■		■	17
Ventilation and insulation	■			■	■			16
WASH	■		■	■	■	■		25
Waste management					■	■		5
Windows			■					6

Appendix 9-4. Variables available in London data sources, by domain

Domain	Relevant and available variables	London data source
Thermal comfort	• Type of central heating appliance • Type of heating fuel	• Census • English Housing Survey (EHS) Physical Survey • Energy Performance Certificate
	• Property construction year	• EHS Physical Survey • EHS Questionnaire • Energy Performance Certificate
	• Number of heated rooms	• Energy Performance Certificate
	• Household composition	• Census
	• Number of (bed)rooms	• Census • Energy Performance Certificate
	• Description of floor, wall, roof • Type of ventilation • Type of window glazing • Proportion of windows that are multiple glazed	• Energy Performance Certificate
Dampness and mould	• Type of central heating appliance • Type of heating fuel	• Census • Energy Performance Certificate • EHS Physical Survey
	• Property construction year	• EHS Physical Survey • EHS Questionnaire • Energy Performance Certificate

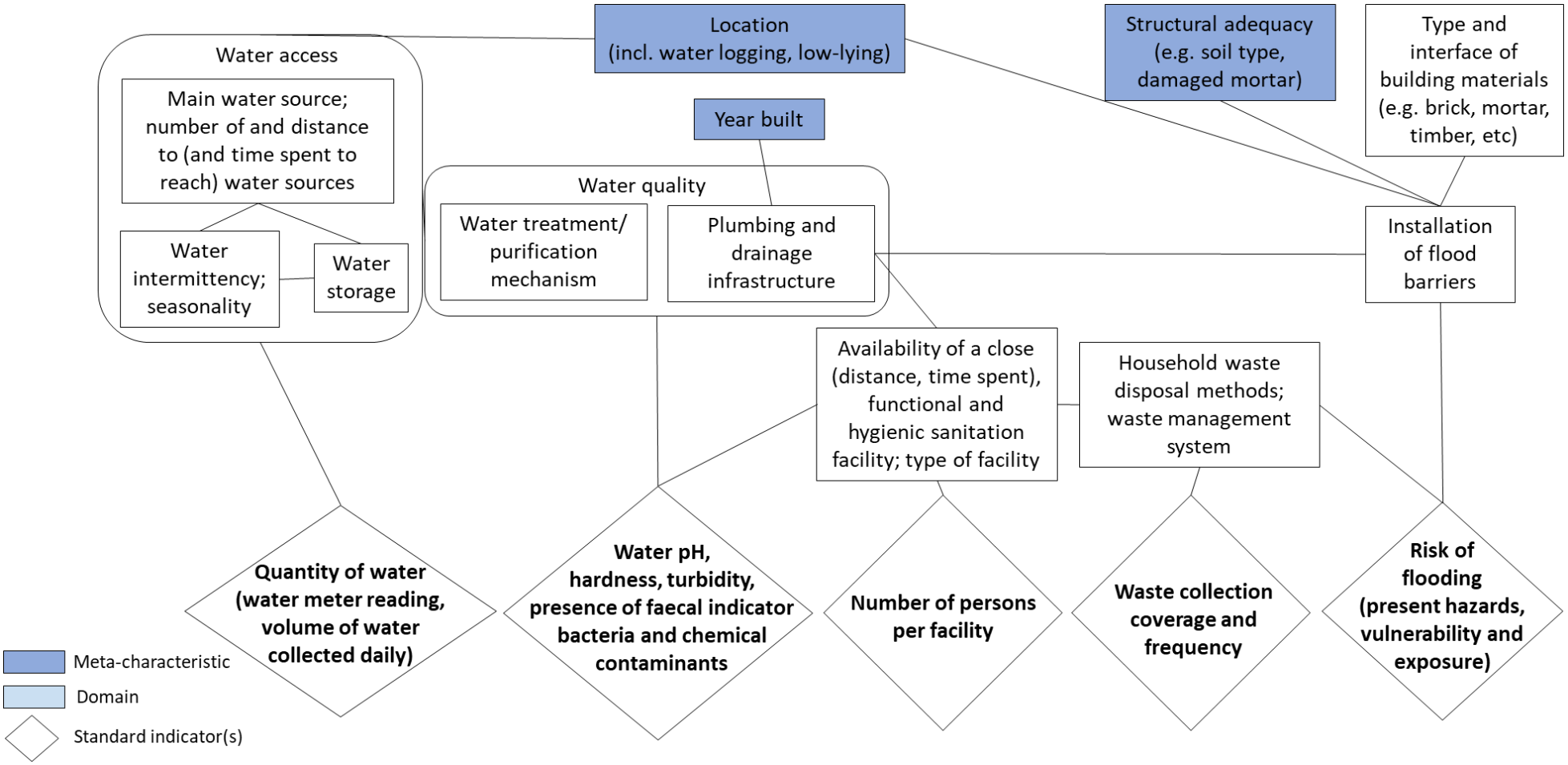
	• Insulation present in walls, roofs, floors • Presence of trickle vents • Inadequate room or appliance ventilation • Presence of functioning extractor fan	• EHS Physical Survey • Energy Performance Certificate
	• Ability to keep comfortably warm in home	• EHS Questionnaire • EHS Physical Survey
	• Condition of walls, ceiling, roof • Building/construction material • Availability of a balcony • Evidence of rising (ground level) damp, penetrating (higher level) damp, or serious condensation/ mould growth	• EHS Physical Survey
	• Occupant expression of problems with condensation, damp, or mould in home	• EHS Questionnaire
Water and sanitation (incl. flooding & waste management)	• Property construction year	• EHS Physical Survey • EHS Questionnaire • Energy Performance Certificate
	• Building/construction material • Mains drainage present and functional • Hot and cold water • Working sink • Working bath/shower • Working bathroom	• EHS Physical Survey
Pests, allergens, and disease vectors	• Building/construction material • Condition of walls, ceiling, roof • Presence of litter/rubbish around house • Evidence of traps or chemicals • Other visual evidence • Evidence of mice or rats • Occupants told inspector about pests	• EHS Physical Survey
	• Presence of carbon monoxide detector	• EHS Questionnaire

Air quality/ pollution in the home	• Presence of smoke detector	• EHS Physical Survey
	• Condition of walls, ceiling, roof, foundation • Availability of a balcony	• EHS Physical Survey
	• Insulation present in walls, roofs, floors • Presence of trickle vents • Inadequate room or appliance ventilation • Presence of functioning extractor fan • Number of open fireplaces	• EHS Physical Survey • Energy Performance Certificate
	• Type of central heating appliance • Type of heating fuel	• EHS Physical Survey • Energy Performance Certificate • Census
Exposure to chemicals, hazardous materials	• Property construction year	• Energy Performance Certificate • EHS Physical Survey • EHS Questionnaire
	• Condition of walls, ceiling, roof, foundation	• EHS Physical Survey
Noise pollution	• Noise from intrusive industry • Noise from heavy traffic • Noise from motorways/main roads • Noise from railway/aircraft noise • Presence of functioning extractor fan(s) • Building/construction material • Wall thickness	• EHS Physical Survey
	• Noisy neighbours in this area	• EHS Questionnaire
	• Flat building height • Flat storey	• Energy Performance Certificate
	• Window glazing	• EHS Physical Survey • Energy Performance Certificate
Lighting	• Flat building height • Flat storey	• Energy Performance Certificate
	• Availability of a balcony • Safe and functional electrical system • Inadequate natural light	• EHS Physical Survey

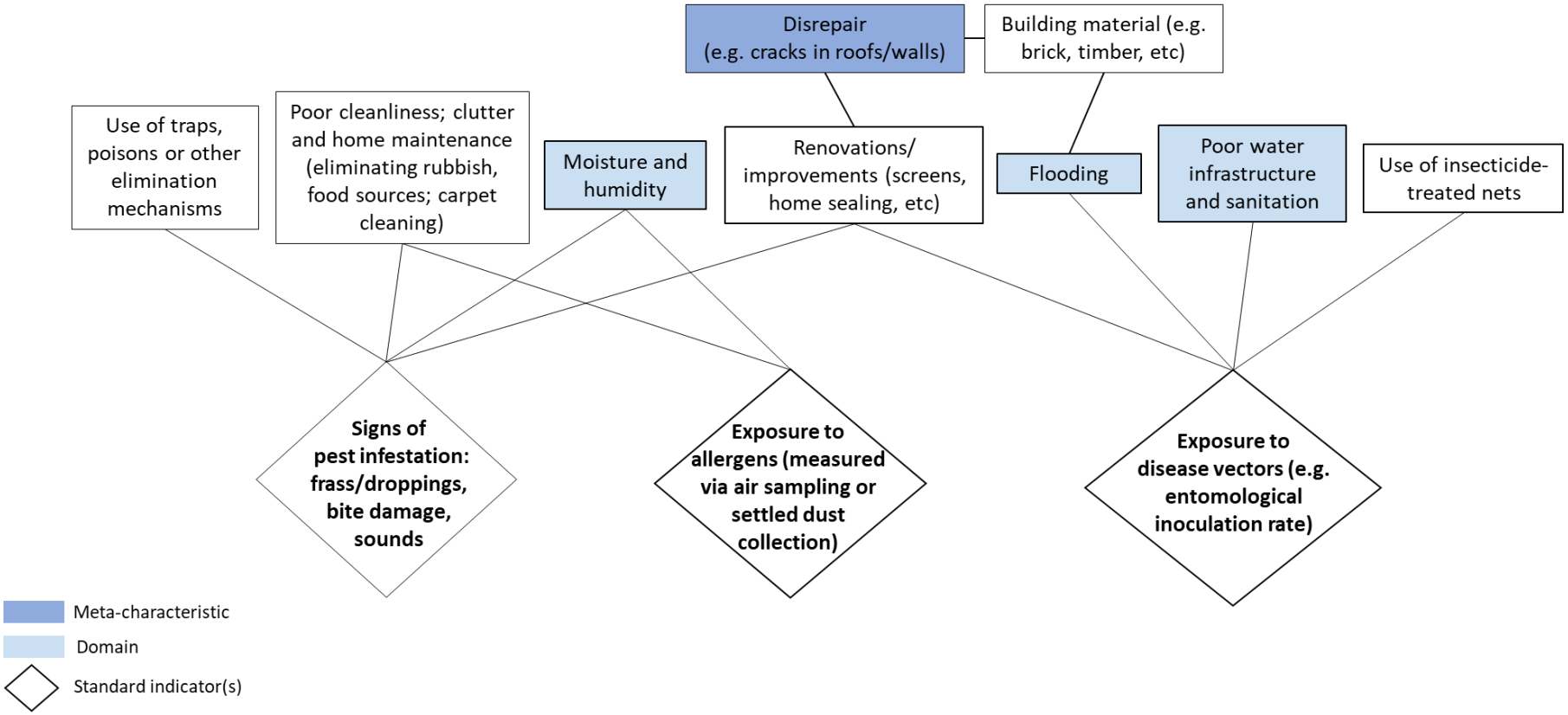
	• Inadequate artificial light	
	• Proportion of low energy lighting in fixed outlets	• EHS Physical Survey • Energy Performance Certificate
Overcrowding	• Number of (bed)rooms	• EHS Physical Survey • EHS Questionnaire • Energy Performance Certificates • Census
	• Number of people in household	• EHS Physical Survey • EHS Questionnaire • Census
	• Household composition • Occupancy rating	• Census
Injury hazards/ home safety	• Number of open fireplaces	• EHS Physical Survey • Energy Performance Certificate
	• Building/construction material • Condition of floors, stairs, ceiling, roof • Availability of a balcony, garage • Safe and functional electrical/gas system • Risk of falling • Risk of fire, explosion	• EHS Physical Survey
	• Property construction year • Use of a chip pan to cook • If used biomass fuel used, what type • Presence of carbon monoxide detector • Presence of smoke detector • Presence of fire blanket, fire extinguisher, fire door, fire escape/wide opening windows] • Adaptations for disabled	• EHS Physical Survey • EHS Questionnaire
Security/ personal safety	• Property type (detached, semi-detached, or terrace)	• EHS Physical Survey • EHS Questionnaire • Energy Performance Certificates • Census

	• Security measures (door, windows, alarm)	• EHS Physical Survey • EHS Questionnaire
	• Flat building height • Flat storey	• Energy Performance Certificate
	• Risk of entry by intruders	• EHS Physical Survey
Privacy/isolation	• Property type (detached, semi-detached, or terrace)	• EHS Physical Survey • EHS Questionnaire • Energy Performance Certificates • Census
	• Availability of a balcony	• EHS Physical Survey
	• Security measures: door • Security measures: windows • Security measures: alarm • Adaptations for disabled	• Physical Survey • EHS Questionnaire
	• Shared rooms and facilities	• EHS Physical Survey • EHS Questionnaire • Census
Communication and connectivity	• Internet access at home	• EHS Questionnaire

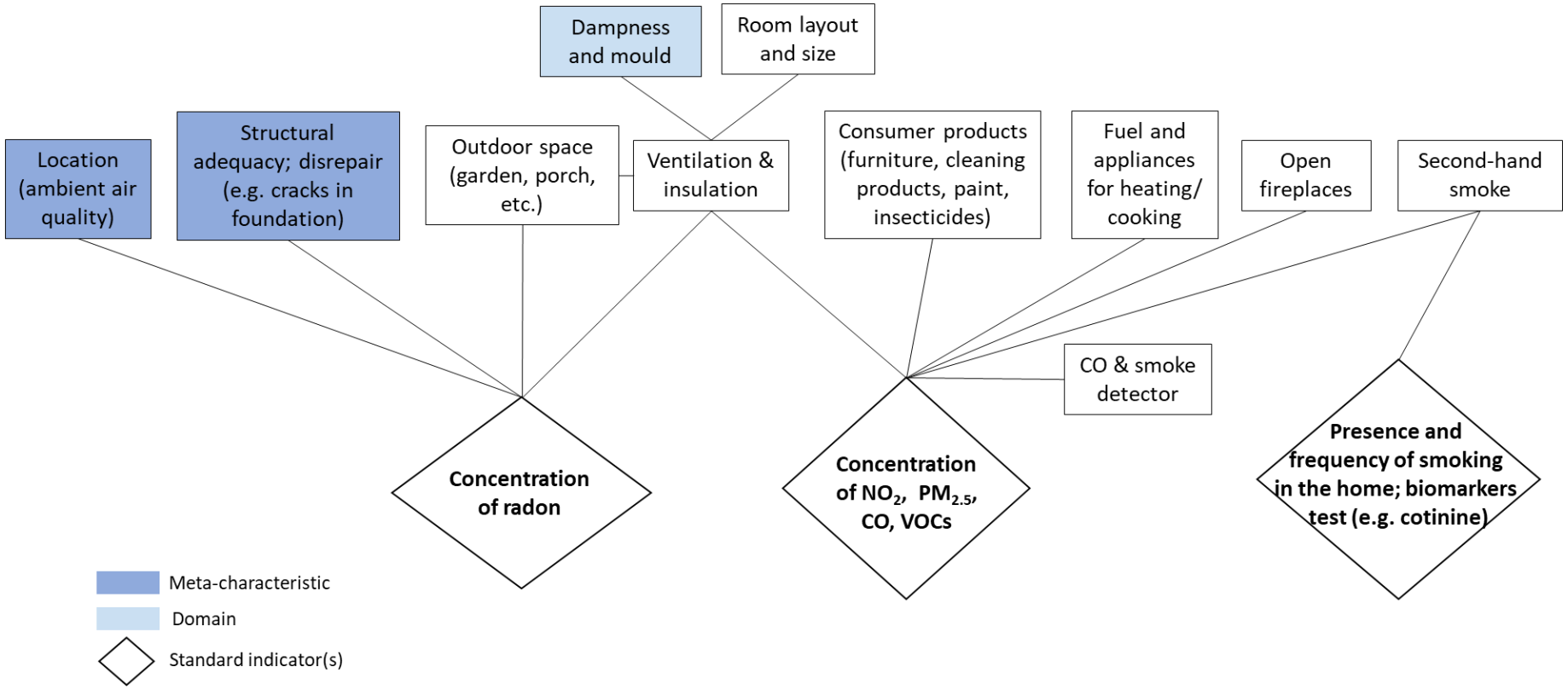
Appendix 9-5. Water and sanitation (incl. flooding and waste mgmt.) domain diagram



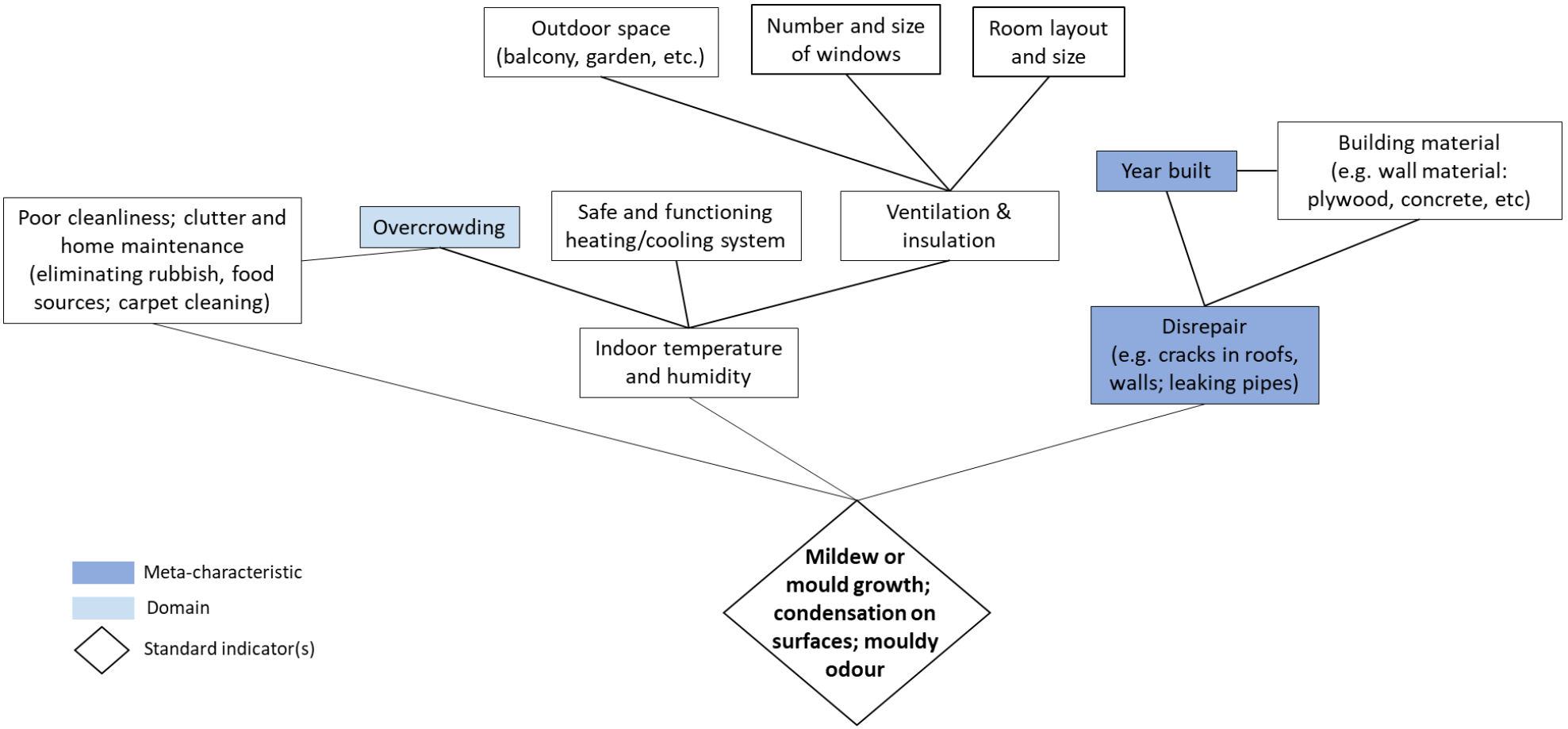
Appendix 9-6. Pests, allergens, disease vectors domain diagram



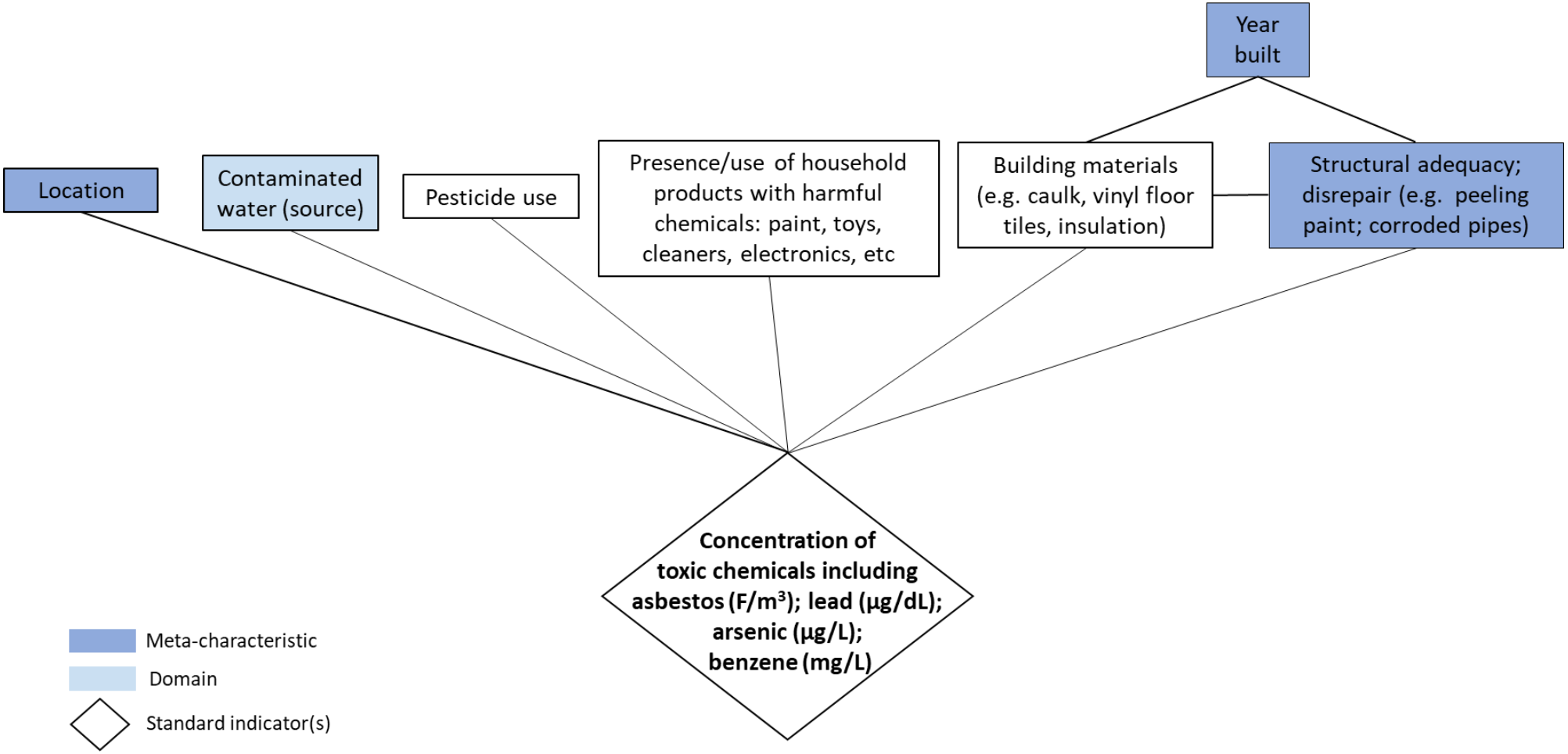
Appendix 9-7. Air quality/pollution in home domain diagram



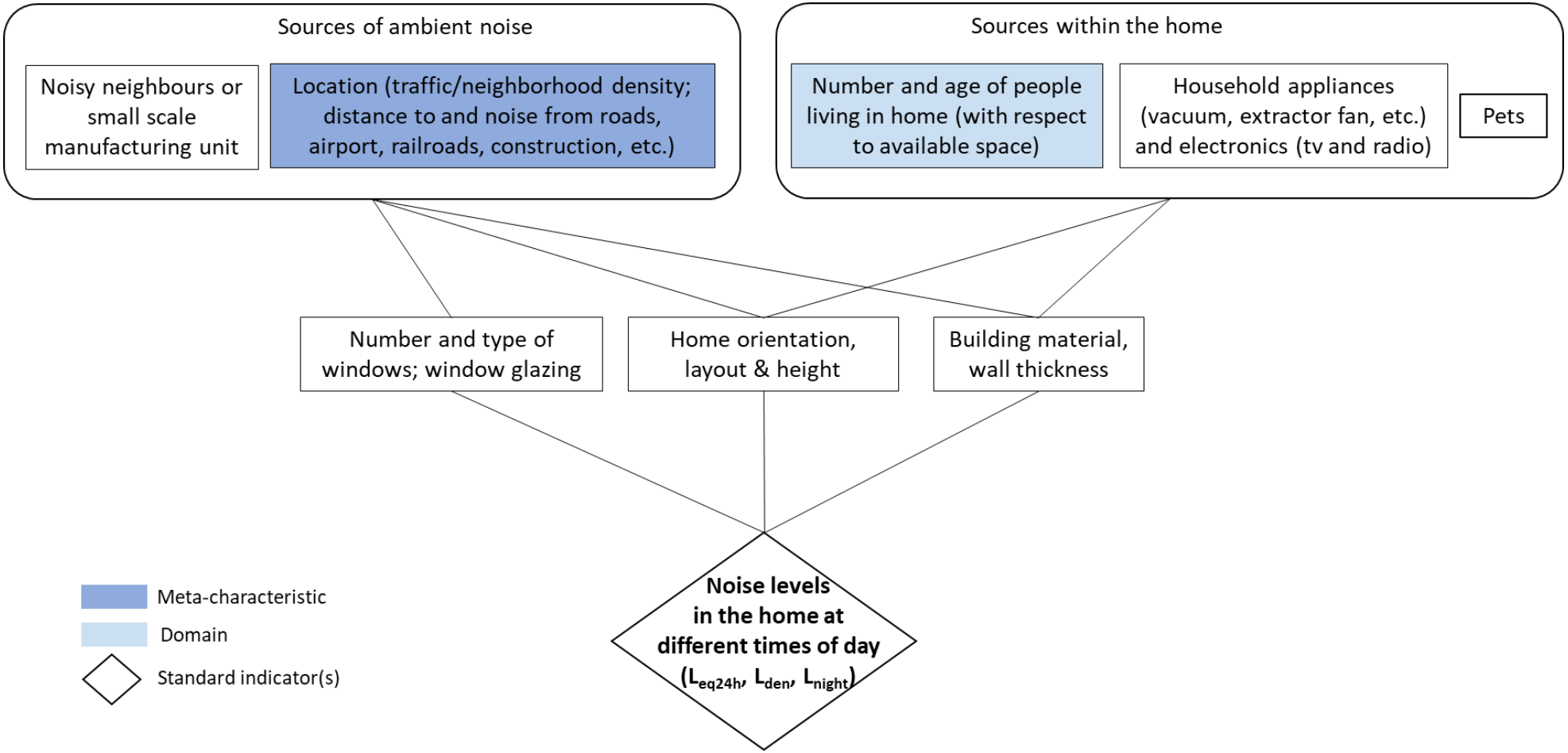
Appendix 9-8. Dampness and mould domain diagram



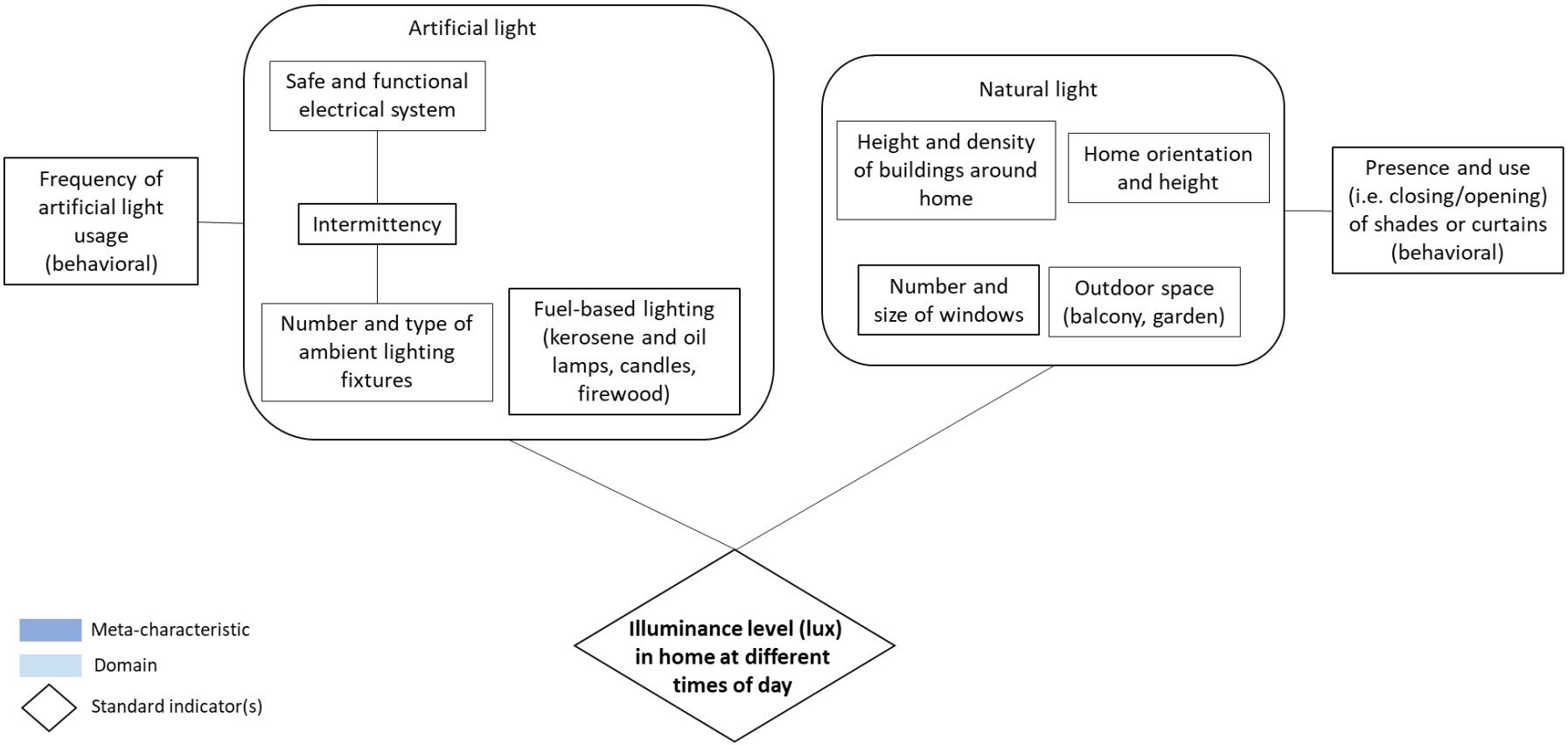
Appendix 9-9. Exposure to chemicals, hazardous materials domain diagram



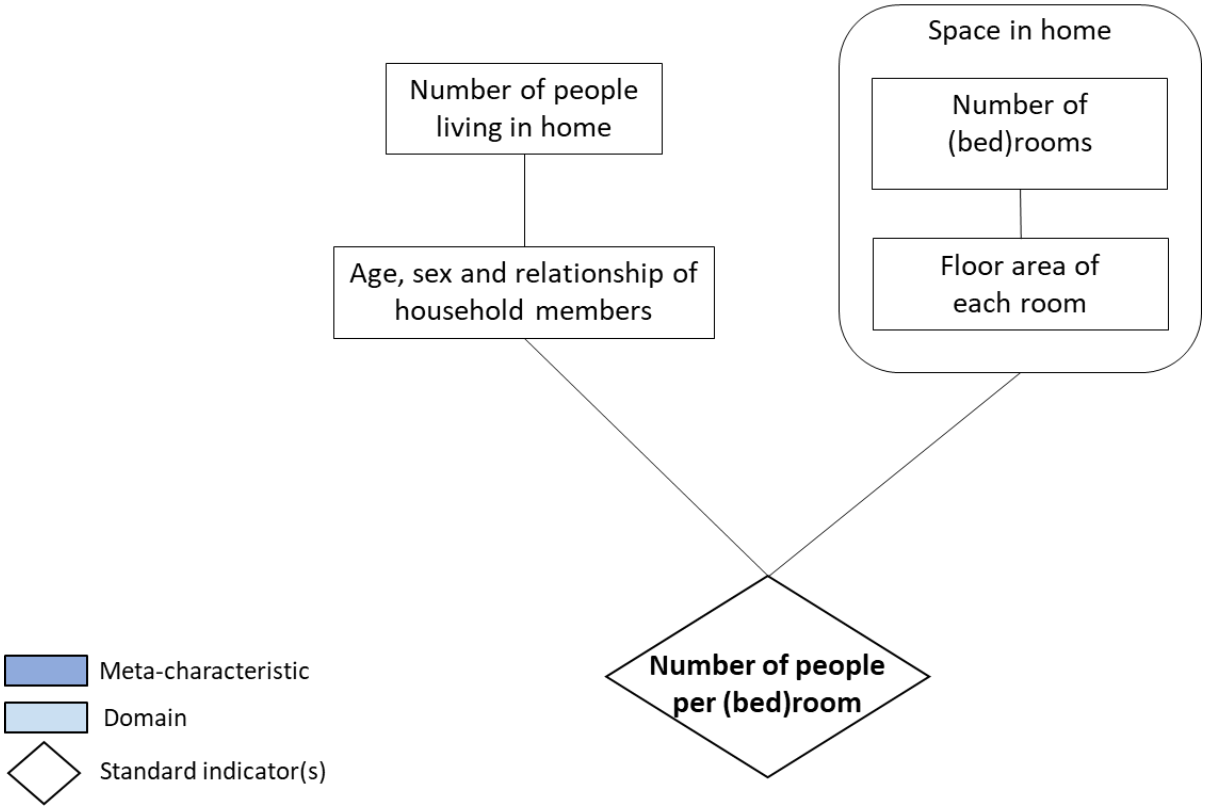
Appendix 9-10. Noise pollution domain diagram



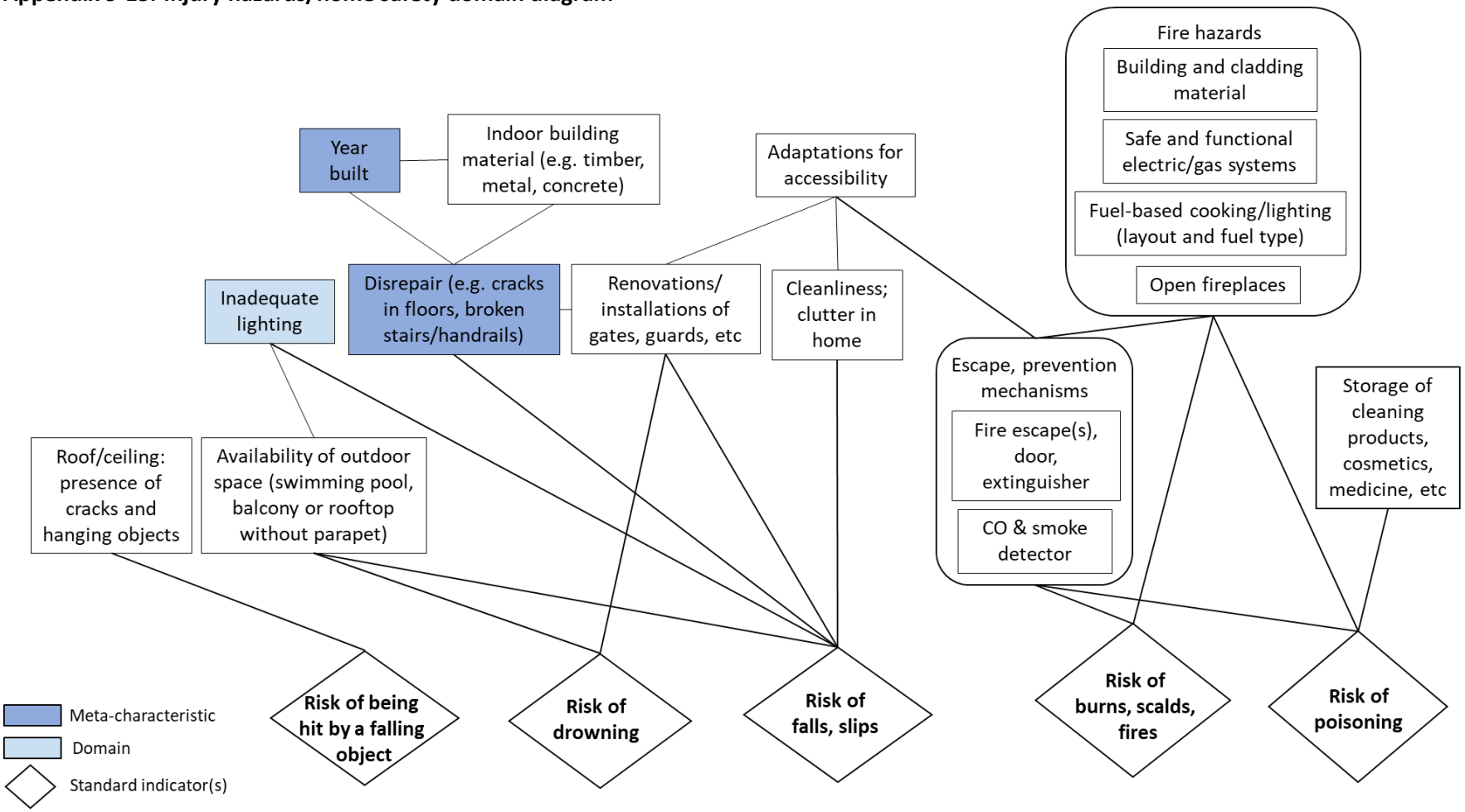
Appendix 9-11. Lighting domain diagram



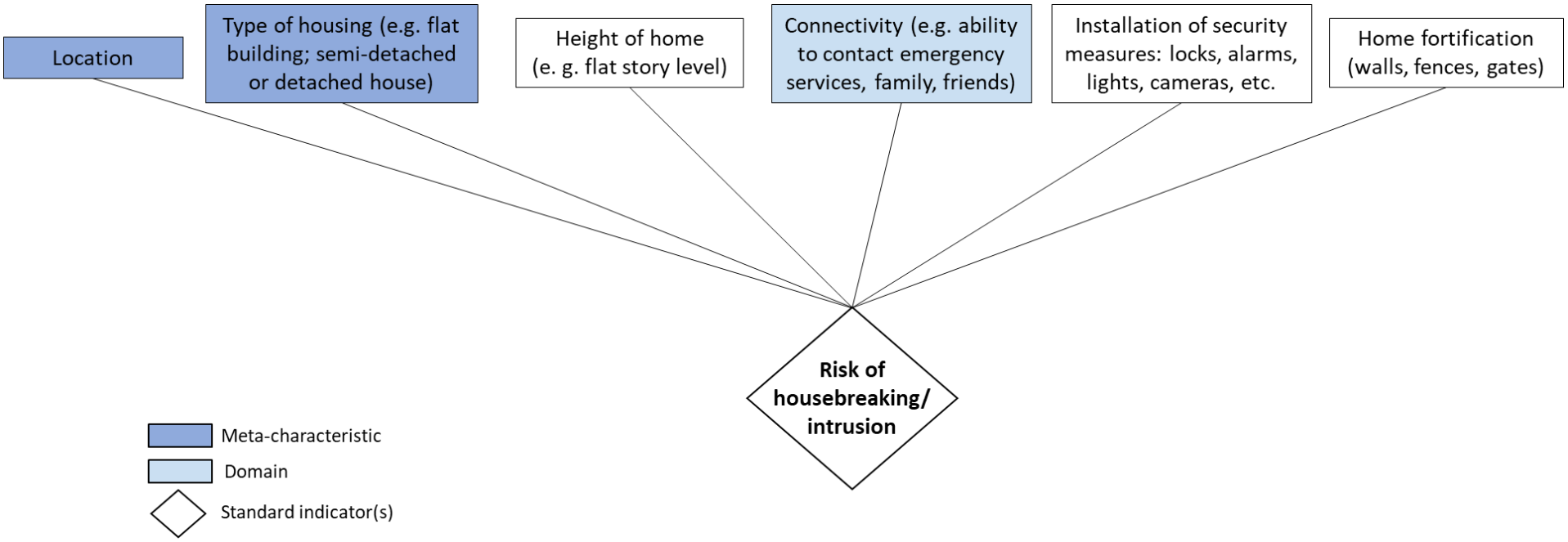
Appendix 9-12. Overcrowding domain diagram



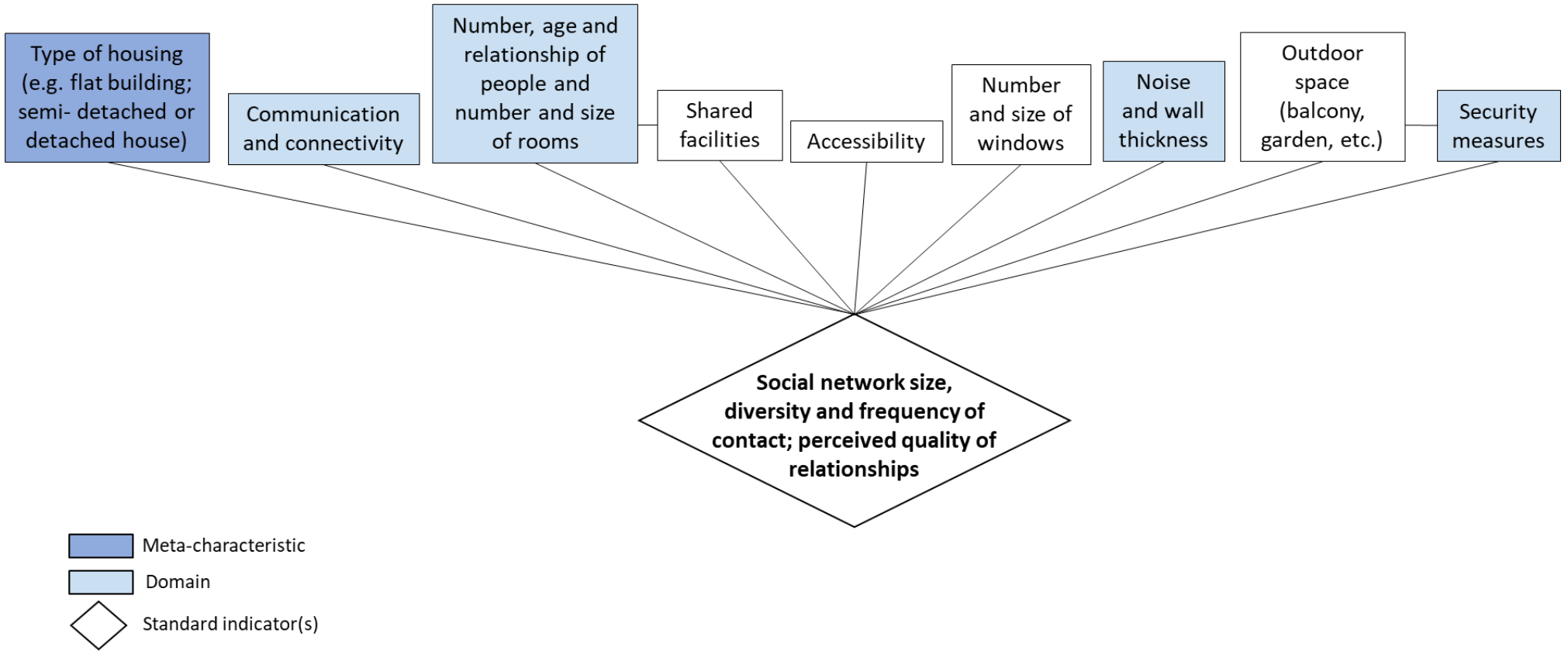
Appendix 9-13. Injury hazards/home safety domain diagram



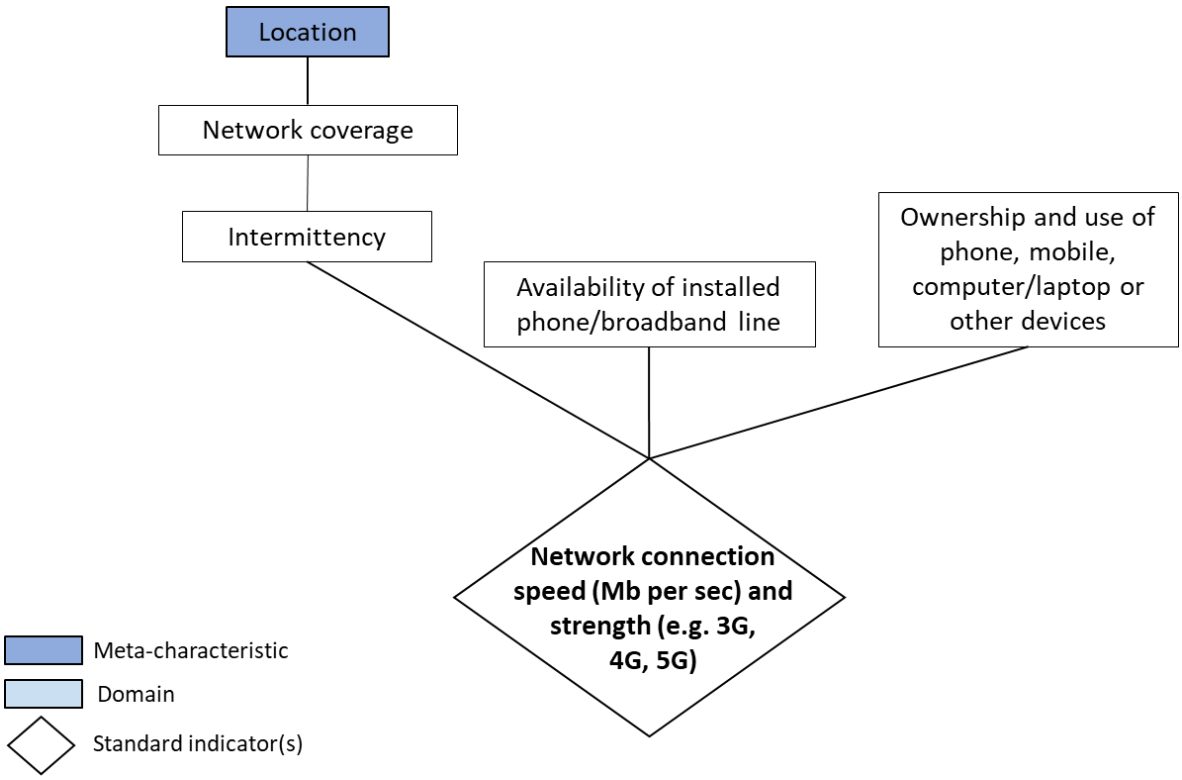
Appendix 9-14. Security/personal safety domain diagram



Appendix 9-15. Privacy/isolation domain diagram



Appendix 9-16. Communication and connectivity domain diagram



Appendix 9-17. Variable list: Energy Performance Certificates

Variable name	Variable description
LMK_KEY	Individual lodgement identifier.
ADDRESS1	First line of the address
ADDRESS2	Second line of the address
ADDRESS3	Third line of the address
POSTCODE	The postcode of the property
BUILDING_REFERENCE_NUMBER	Unique identifier for the building
CURRENT_ENERGY_RATING	Current energy rating converted into a linear 'A to G' rating (where A is the most energy efficient and G is the least energy efficient)
POTENTIAL_ENERGY_RATING	Estimated potential energy rating converted into a linear 'A to G' rating
CURRENT_ENERGY_EFFICIENCY	Based on cost of energy, i.e. energy required for space heating, water heating and lighting [in kWh/year] multiplied by fuel costs. (£/m²/year where cost is derived from kWh).
POTENTIAL_ENERGY_EFFICIENCY	Summary of the potential environmental efficiency of the property feature
PROPERTY_TYPE	Describes the type of property such as House, Flat, Mansion, Maisonette etc. This is actually the type differentiator for Property but only a limited number of property types, notably Apartment and Apartment Block, have any specific characteristics and warrant their own definition.
BUILT_FORM	The building type of the Property e.g., Detached, Semi-Detached, Terrace etc. Together with the Property Type, the Build Form produces a structured description of the property
INSPECTION_DATE	The date that the inspection was actually carried out by the energy assessor
LOCAL_AUTHORITY	Office for National Statistics code. Local authority area in which the building is located.
CONSTITUENCY	Office for National Statistics code. Parliamentary constituency in which the building is located.
COUNTY	County in which the building is located (where applicable)
LODGEMENT_DATE	Date lodged on the Energy Performance of Buildings Register

TRANSACTION_TYPE	Type of transaction that triggered EPC. For example, one of: marketed sale; non-marketed sale; rental; not sale or rental; assessment for Green Deal; following Green Deal; FIT application; none of the above; RHI application; ECO assessment. Where the reason for the assessment is unknown by the energy assessor the transaction type will be recorded as 'none of the above'. Transaction types may be changed over time.
ENVIRONMENT_IMPACT_CURRENT	The Environmental Impact Rating. A measure of the property's current impact on the environment in terms of carbon dioxide (CO_2) emissions. The higher the rating the lower the CO_2 emissions. (CO_2 emissions in tonnes / year)
ENVIRONMENT_IMPACT_POTENTIAL	The potential Environmental Impact Rating. A measure of the property's potential impact on the environment in terms of carbon dioxide (CO_2) emissions after improvements have been carried out. The higher the rating the lower the CO_2 emissions. (CO_2 emissions in tonnes / year)
ENERGY_CONSUMPTION_CURRENT	Estimated total energy consumption for the Property in a 12 month period. Value is Kilowatt Hours per Square Metre (kWh/m²)
ENERGY_CONSUMPTION_POTENTIAL	Estimated potential total energy consumption for the Property in a 12 month period. Value is Kilowatt Hours per Square Metre (kWh/m²)
CO2_EMISSIONS_CURRENT	CO_2 emissions per year in tonnes/year.
CO2_EMISS_CURR_PER_FLOOR_AREA	CO_2 emissions per square metre floor area per year in kg/m²
CO2_EMISSIONS_POTENTIAL	Estimated value in Tonnes per Year of the total CO_2 emissions produced by the Property in 12 month period.
LIGHTING_COST_CURRENT	GBP. Current estimated annual energy costs for lighting the property.
LIGHTING_COST_POTENTIAL	GBP. Potential estimated annual energy costs for lighting the property after improvements have been made.
HEATING_COST_CURRENT	GBP. Current estimated annual energy costs for heating the property.
HEATING_COST_POTENTIAL	GBP. Potential annual energy costs for lighting the property after improvements have been made.
HOT_WATER_COST_CURRENT	GBP. Current estimated annual energy costs for hot water
HOT_WATER_COST_POTENTIAL	GBP. Potential estimated annual energy costs for hot water after improvements have been made.
TOTAL_FLOOR_AREA	The total useful floor area is the total of all enclosed spaces measured to the internal face of the external walls, i.e. the gross floor area as measured in accordance with the guidance issued from time to time by the Royal Institute of Chartered Surveyors or by a body replacing that institution. (m²)
ENERGY_TARIFF	Type of electricity tariff for the property, e.g., single.

MAINS_GAS_FLAG	Whether mains gas is available. Yes means that there is a gas meter or a gas-burning appliance in the dwelling. A closed-off gas pipe does not count.
FLOOR_LEVEL	Flats and maisonettes only. Floor level relative to the lowest level of the property (0 for ground floor). If there is a basement, the basement is level 0 and the other floors are from 1 upwards
FLAT_TOP_STOREY	Whether the flat is on the top storey
FLAT_STOREY_COUNT	The number of Storeys in the Apartment Block.
MAIN_HEATING_CONTROLS	Type of main heating controls. Includes both main heating systems if there are two.
MULTI_GLAZE_PROPORTION	The estimated banded range (e.g., 0% - 10%) of the total glazed area of the Property that is multiple glazed.
GLAZED_TYPE	The type of glazing. From British Fenestration Rating Council or manufacturer declaration, give as one of; single; double; triple.
GLAZED_AREA	Ranged estimate of the total glazed area of the Habitable Area.
EXTENSION_COUNT	The number of extensions added to the property. Between 0 and 4.
NUMBER_HABITABLE_ROOMS	Habitable rooms include any living room, sitting room, dining room, bedroom, study and similar; and also a non-separated conservatory. A kitchen/diner having a discrete seating area (with space for a table and four chairs) also counts as a habitable room. A non-separated conservatory adds to the habitable room count if it has an internal quality door between it and the dwelling. Excluded from the room count are any room used solely as a kitchen, utility room, bathroom, cloakroom, en-suite accommodation and similar; any hallway, stairs or landing; and also any room not having a window.
NUMBER_HEATED_ROOMS	The number of heated rooms in the property if more than half of the habitable rooms are not heated.
LOW_ENERGY_LIGHTING	The percentage of low energy lighting present in the property as a percentage of the total fixed lights in the property. 0% indicates that no low-energy lighting is present.
NUMBER_OPEN_FIREPLACES	The number of Open Fireplaces in the Property. An Open Fireplace is a fireplace that still allows air to pass between the inside of the Property and the outside.
HOTWATER_DESCRIPTION	Overall description of the property feature
HOT_WATER_ENERGY_EFF	Energy efficiency rating. One of: very good; good; average; poor; very poor. *
HOT_WATER_ENV_EFF	Environmental efficiency rating. One of: very good; good; average; poor; very poor. *

FLOOR_DESCRIPTION	Overall description of the property feature
EFF FLOOR_ENERGY_EFF	Energy efficiency rating. One of: very good; good; average; poor; very poor. *
EFF FLOOR_ENV_EFF	Environmental efficiency rating. One of: very good; good; average; poor; very poor. *
WINDOWS_DESCRIPTION	Overall description of the property feature
WINDOWS_ENERGY_EFF	Energy efficiency rating. One of: very good; good; average; poor; very poor. *
WINDOWS_ENV_EFF	WINDOWS. Environmental efficiency rating. One of: very good; good; average; poor; very poor. *
WALLS_DESCRIPTION	Overall description of the property feature
WALLS_ENERGY_EFF	Energy efficiency rating. One of: very good; good; average; poor; very poor. *
WALLS_ENV_EFF	Environmental efficiency rating. One of: very good; good; average; poor; very poor. *
SECONDHEAT_DESCRIPTION	Overall description of the property feature
SHEATING_ENERGY_EFF	Energy efficiency rating. One of: very good; good; average; poor; very poor. *
SHEATING_ENV_EFF	Environmental efficiency rating. One of: very good; good; average; poor; very poor. *
ROOF_DESCRIPTION	Overall description of the property feature
ROOF_ENERGY_EFF	Energy efficiency rating. One of: very good; good; average; poor; very poor. *
ROOF_ENV_EFF	Environmental efficiency rating. One of: very good; good; average; poor; very poor. *
MAINHEAT_DESCRIPTION	Overall description of the property feature
MAINHEAT_ENERGY_EFF	Energy efficiency rating. One of: very good; good; average; poor; very poor. *
MAINHEAT_ENV_EFF	Environmental efficiency rating. One of: very good; good; average; poor; very poor. *
MAINHEATCONT_DESCRIPTION	Overall description of the property feature
MAINHEATC_ENERGY_EFF	Energy efficiency rating. One of: very good; good; average; poor; very poor. *
MAINHEATC_ENV_EFF	Environmental efficiency rating. One of: very good; good; average; poor; very poor. *

LIGHTING_DESCRIPTION	Overall description of property feature. Total number of fixed lighting outlets and total number of low-energy fixed lighting outlets
LIGHTING ENERGY EFF LIGHTING_ENERGY_EFF	Energy efficiency rating. One of: very good; good; average; poor; very poor. *
EFF LIGHTING_ENV_EFF	Environmental efficiency rating. One of: very good; good; average; poor; very poor. *
MAIN_FUEL	The type of fuel used to power the central heating e.g., Gas, Electricity
WIND_TURBINE_COUNT	Number of wind turbines; 0 if none.
HEAT_LOSS_CORRIDOOR	Flats and maisonettes only. Indicates that the flat contains a corridor through which heat is lost. Heat loss corridor, one of: no corridor; heated corridor; unheated corridor
UNHEATED_CORRIDOR_LENGTH	The total length of unheated corridor in the flat. Only populated if flat or maisonette contains unheated corridor. If unheated corridor, length of sheltered wall (m^2).
FLOOR_HEIGHT	Average height of the storey in metres.
PHOTO_SUPPLY	Percentage of photovoltaic area as a percentage of total roof area. 0% indicates that a Photovoltaic Supply is not present in the property.
SOLAR_WATER_HEATING_FLAG	Indicates whether the heating in the Property is solar powered.
MECHANICAL_VENTILATION	Identifies the type of mechanical ventilation the property has. This is required for the RdSAP calculation.
ADDRESS	Field containing the concatenation of address1, address2 and address3. Note that post code is recorded separately.
LOCAL_AUTHORITY_LABEL	The name of the local authority area in which the building is located. This field is for additional information only and should not be relied upon: please refer to the Local Authority ONS Code.
CONSTITUENCY_LABEL	The name of the parliamentary constituency in which the building is located. This field is for additional information only and should not be relied upon: please refer to the Constituency ONS Code.
CERTIFICATE_HASH	Unique, cryptographic hash of a set of fields from the certificate. Can be used to uniquely identify a certificate in the downloads and the API. Note that these may change in the future, but will be consistent within a single session.

* On actual energy certificate shown as one to five star rating.

Appendix 9-18. Exploring multiplicity within EPC data

Upon my exploration of the EPC data, I found that some addresses had multiple EPCs in a year, which may have been for a valid (e.g., re-inspection after home improvements) or invalid (e.g., errors) reason. It is, however, impossible to determine whether the multiple EPCs are valid solely based on the data.

As visible in Figure A.1, a small portion of addresses have multiple EPCs in a given year (3% on average across study period). For instance, there are 312,608 EPCs lodged in 2009. Among these, 97% (n = 294,922) had a unique address (i.e., one EPC per address). Of the 17,686 EPCS with a duplicate address, 8,321 addresses were present in 2 EPCs and 321 addresses were present in more than 2 EPCs.

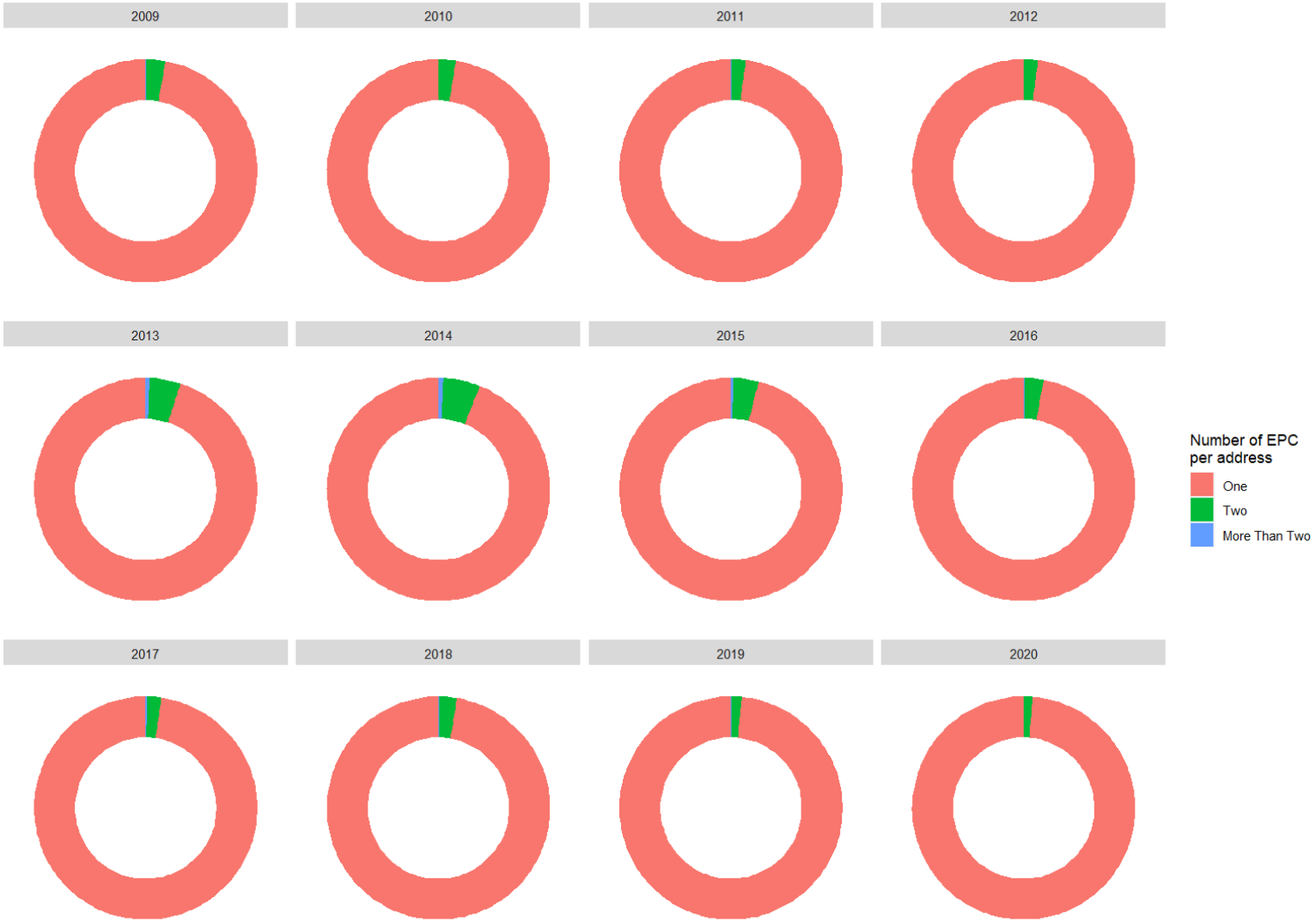


Figure A.1. Number of EPCs per address, 2009-2020

A closer exportation into this subset of the data gives insight on the differences among the multiple EPCs. For instance, in 2009 there are four addresses that have eight or more EPCs within the year. Collectively, these addresses account for 49 EPCs in 2009 alone (Figure A.2). In some instances, a single address has 8 EPCs all with the same inspection and lodgement date (Address 1 in Figure C-2.2), but in many instances the inspection and lodgement date vary – sometimes by weeks.



Figure A.2. Addresses with 8 or more EPCs in 2009

One outlier is Address 2, which has 24 EPCs. However, when reviewing the data for this address, the dwelling has three floors – each with 8 EPCs (Figure A.3). While the address information on the EPC doesn't make it clear, one could presume that they are likely to be different housing units as separate EPCs were necessary. Moreover, the patterns observed in the insulation variables also indicate that these are different dwellings. 'Dwelling' is indicated as the type of roof insulation for the ground and 1st floor, but not the 2nd floor. 'Dwelling' is also indicated as the type of floor insulation for the 1st and 2nd floors. As such, the data present a multi-flat building. This should have been accounted for by the inspectors when lodging the address information into the EPC database. Variables one would expect to be similar across the flats such as the tenure (social rent), property type (flat), and construction period (1976-1982) are indeed consistent across the 24 EPCs.

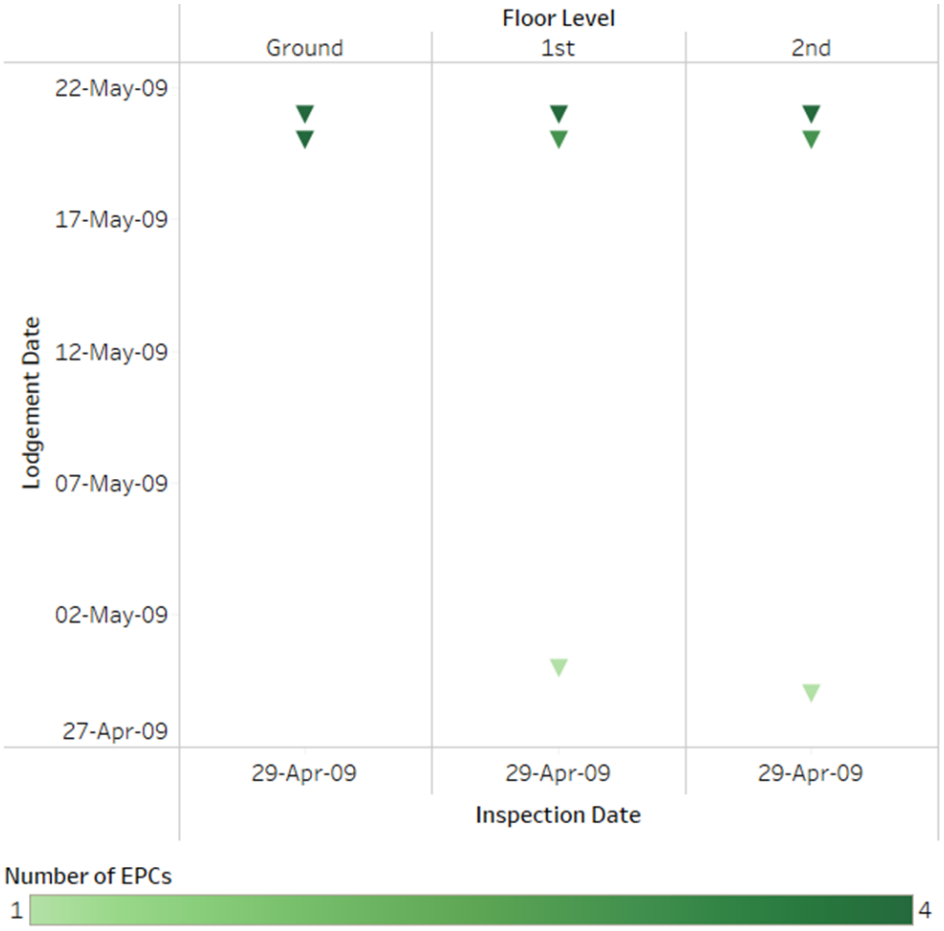


Figure A.3. Distribution of EPCs by floor level for a single address with 24 EPCs in 2009

Address 2 is also unique because despite the EPCs being lodged over a period of days, all of the EPCs indicate that the inspection itself all happened on a single day. In most EPC multiplicity cases, both the inspection and lodgement dates vary. This is noteworthy as it seems that the latter EPCs generally show better performance. There are numerous reasons that this could be. One hypothesis is that the homeowners conducted renovations on the home in between the two dates and had the home re-inspected. This could be the case especially if the homeowners planned to sell the home. Another hypothesis is simply that there was an error in the information initially logged since the EPC data cannot be altered once it has been lodged on the register. Though other hypotheses may be equally true. Upon contact, the data holders confirmed that an address may have more than one EPC for valid (such as re-inspection after home improvements) or invalid reasons (errors). As it is impossible to know whether the multiple EPCs are valid simply based on the data, for my analyses I use the most recent EPC for an address in each year.

Appendix 9-19. Variable list: UK Census (2011)

Variable name	Variable description
Own vs Rent	Categorical variable with following categories: ▪ Owns outright ▪ Owns with a mortgage or loan ▪ Part-owns and part-rents (shared ownership) ▪ Rents (with or without housing benefit) ▪ Lives here rent-free
Who is the landlord (if rent)	Categorical variable with following categories: ▪ Housing association, housing co-operative, charitable trust, registered social landlord ▪ Council or local authority ▪ Private landlord or letting agency ▪ Employer of a household member ▪ Relative or friend of a household member ▪ Other
Type of accommodation	Categorical variable with following categories: ▪ Detached whole house or bungalow ▪ Semi-detached whole house or bungalow ▪ Terraced whole house or bungalow (including end-terrace) ▪ A flat, maisonette or apartment that is in a purpose-built block of flats or tenement ▪ A flat, maisonette, or apartment that is part of a converted or shared house (including bed-sits) ▪ A flat, maisonette, or apartment that is in a commercial building (for example, in an office building, hotel, or over a shop) ▪ A caravan or other mobile or temporary structure
If self-contained accommodation	Categorical variable with following categories: ▪ Yes ▪ No, one or more rooms are shared with another household
Number of rooms	▪ Continuous variable 01-99
Number of bedrooms	▪ Continuous variable 00-99
Number of people living in the home	▪ Continuous variable 01-30
Type of central heating	Categorical variable with following categories: ▪ No central heating

	▪ Gas central heating ▪ Electric (including storage heaters) central heating ▪ Oil central heating ▪ Solid fuel (for example wood, coal) central heating ▪ Other central heating ▪ Two or more types of central heating ▪ No code required
Household type	Categorical variable with following categories: ▪ Married couple household with dependent child(ren) ▪ Married couple household with no dependent children ▪ Same-sex civil partnership couple household with dependent child(ren) ▪ Same-sex civil partnership couple household with no dependent children ▪ Cohabiting couple (Opposite sex) household with dependent child(ren) ▪ Cohabiting couple (Opposite sex) household with no dependent children ▪ Cohabiting couple (Same sex) household with dependent child(ren) ▪ Cohabiting couple (Same sex) household with no dependent children ▪ Lone parent household with dependent child(ren) ▪ Lone parent household with no dependent children ▪ One person household ▪ Multi-person household all student ▪ Multi-person household other ▪ No code required
Occupancy rating	Categorical variable with following categories: ▪ 0 the household has the number of bedrooms recommended by the 'bedroom standard' ▪ -1 or less: the household has at least one bedroom too few for the number and composition of people living in the household ▪ +1: indicates that a household has one bedroom more than is recommended for the number and composition of people living in the household ▪ +2 or more: indicates that a household has two or more bedrooms more than is recommended for the number and composition of people living in the household
Household composition	Categorical variable with following categories: ▪ One person household: Aged 65 and over ▪ One person household: Other ▪ One family only: All aged 65 and over ▪ One family only: Married couple: No children

	▪ One family only: Married couple: One dependent child ▪ One family only: Married couple: Two or more dependent children ▪ One family only: Married couple: All children non-dependent ▪ One family only: Same-sex civil partnership couple: No children ▪ One family only: Same-sex civil partnership couple: One dependent child ▪ One family only: Same-sex civil partnership couple: Two or more dependent children ▪ One family only: Same-sex civil partnership couple: All children non-dependent ▪ One family only: Cohabiting couple: No children ▪ One family only: Cohabiting couple: One dependent child ▪ One family only: Cohabiting couple: Two or more dependent children ▪ One family only: Cohabiting couple: All children non-dependent ▪ One family only: Male lone parent: One dependent child ▪ One family only: Male lone parent: Two or more dependent children ▪ One family only: Male lone parent: All children non-dependent ▪ One family only: Female lone parent: One dependent child ▪ One family only: Female lone parent: Two or more dependent children ▪ One family only: Female lone parent: All children non-dependent ▪ Other household types: With one dependent child ▪ Other household types: With two or more dependent children ▪ Other household types: All full-time students ▪ Other household types: All aged 65 and over ▪ Other household types: Other ▪ No code required
Tenure of household	Categorical variable with following categories: ▪ Owned: Owned outright ▪ Owned: Owned with a mortgage or loan ▪ Shared ownership (part owned and part rented) ▪ Social rented: Rented from council (local authority) ▪ Social rented: Other social rented ▪ Private rented: Private landlord or letting agency ▪ Private rented: Employer of a household member ▪ Private rented: Relative or friend of household member ▪ Private rented: Other ▪ Living rent free ▪ No code required

Appendix 9-20. Cases exceed population data

When merging the ONS population data with the health data, there are instances where the number of admissions is greater than the population count for each LSOA-age-sex group. In the data, there are 4835 LSOAs, 17 age categories (i.e., 5-year age group from 0 to 80+) and 2 sexes. Thus, the total number of LSOA-age-sex groups is 164,390.

In the data for all hospital admissions (excluding injuries and births), the above-described problem is found in a subset of 297 LSOA-age-sex groups (0.18%*). These combinations are across 246 unique LSOAs. 73% of these combinations were among males, and 27% among females. These combinations were most common in the oldest age group (Figure A.4), with 76% occurring in the 80+ age group.

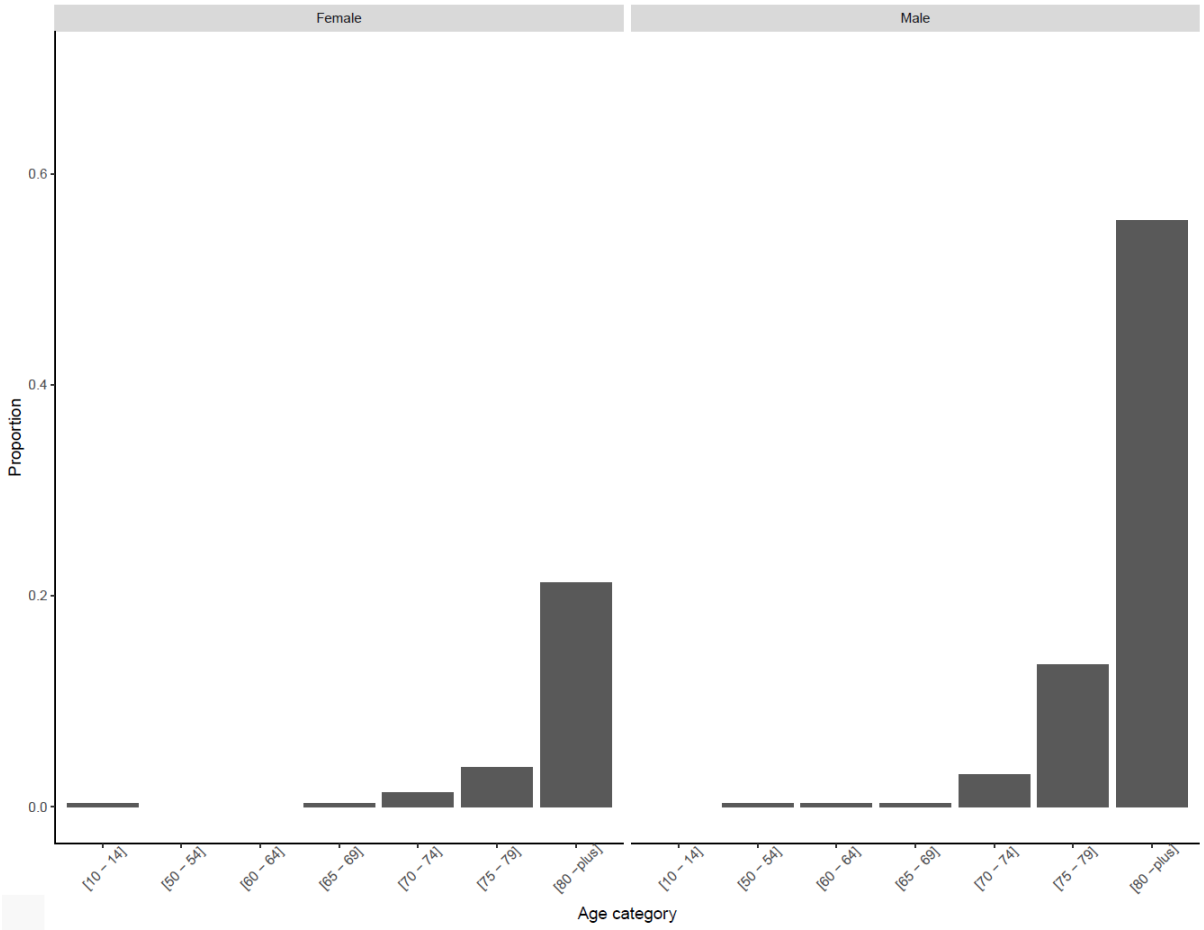


Figure A.4. Count of instances where the number of admissions is greater than the population count for each LSOA-age-sex group

The difference between the number of cases and population ranges between 1 and 31 The most frequent difference is 1 (n=103). About 80% (n=237) of these combinations have a difference of 5 or less between the cases and population counts.

In order to assess the impact on the standardised rate, different scenarios to deal with this issue were considered. The scenarios considered were:

1. Setting cases = 0
2. Setting cases = population
3. Setting population = cases
4. Dropping rows with this issue

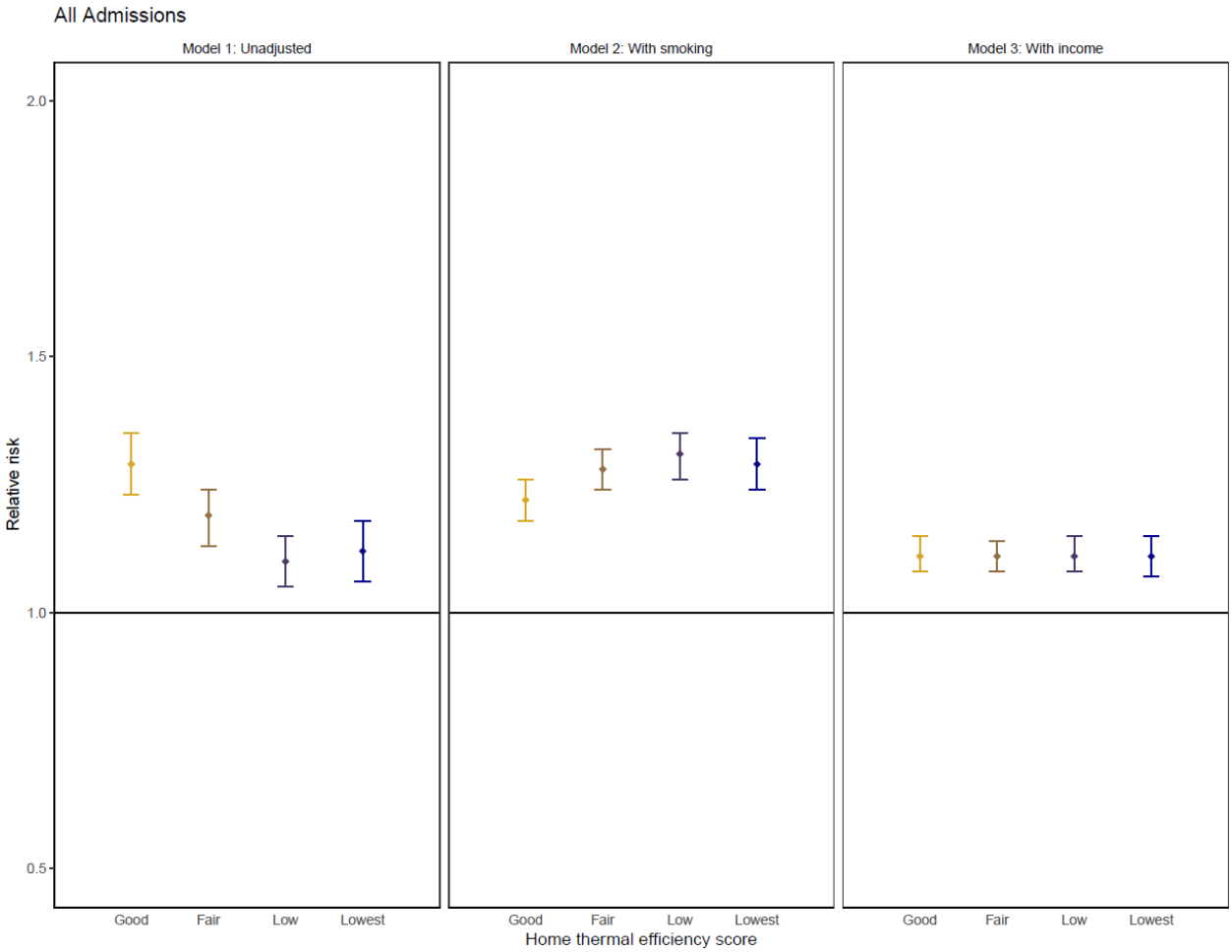
In each instance, the age- and sex-standardised rate was calculated for each LSOA. The mean of the LSOA standardised rates is presented below in Table A.1 as the overall London age- and sex-standardised rate in order to compare across the scenarios.

Table A.1. Mean of the LSOA standardised rates by scenario

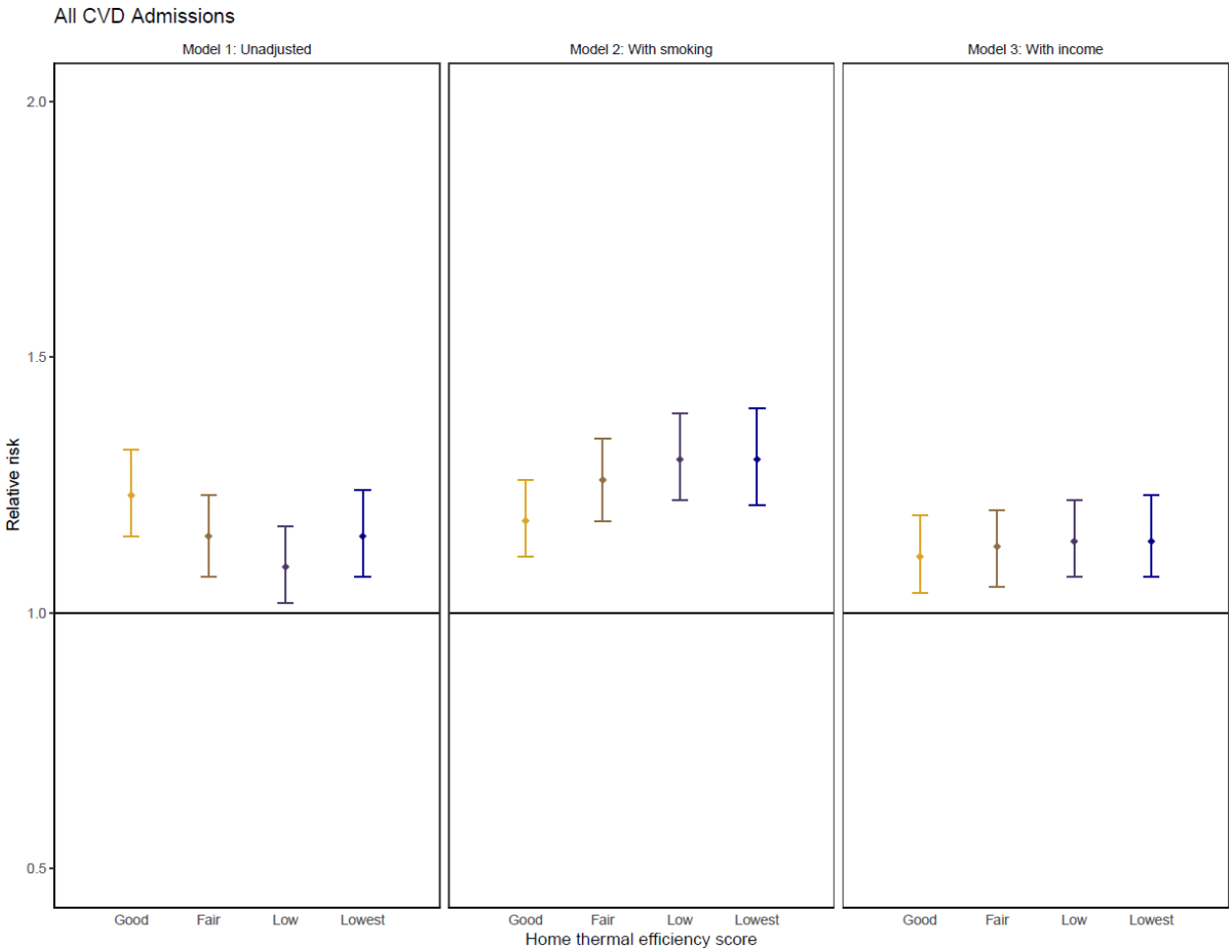
Scenario	Standardised rate
1	0.1065118
2	0.1074506
3	0.107585
4	0.1069308

The difference between the standardised rates across the four scenarios was modest. As such, I conclude that there is not a significant difference between them. However, since population data are estimated and the HES data can be assumed to be complete, I set the population to the number of cases in the instances where the population was less than the number of admissions for a given LSOA-age-sex groups (i.e., scenario 3).

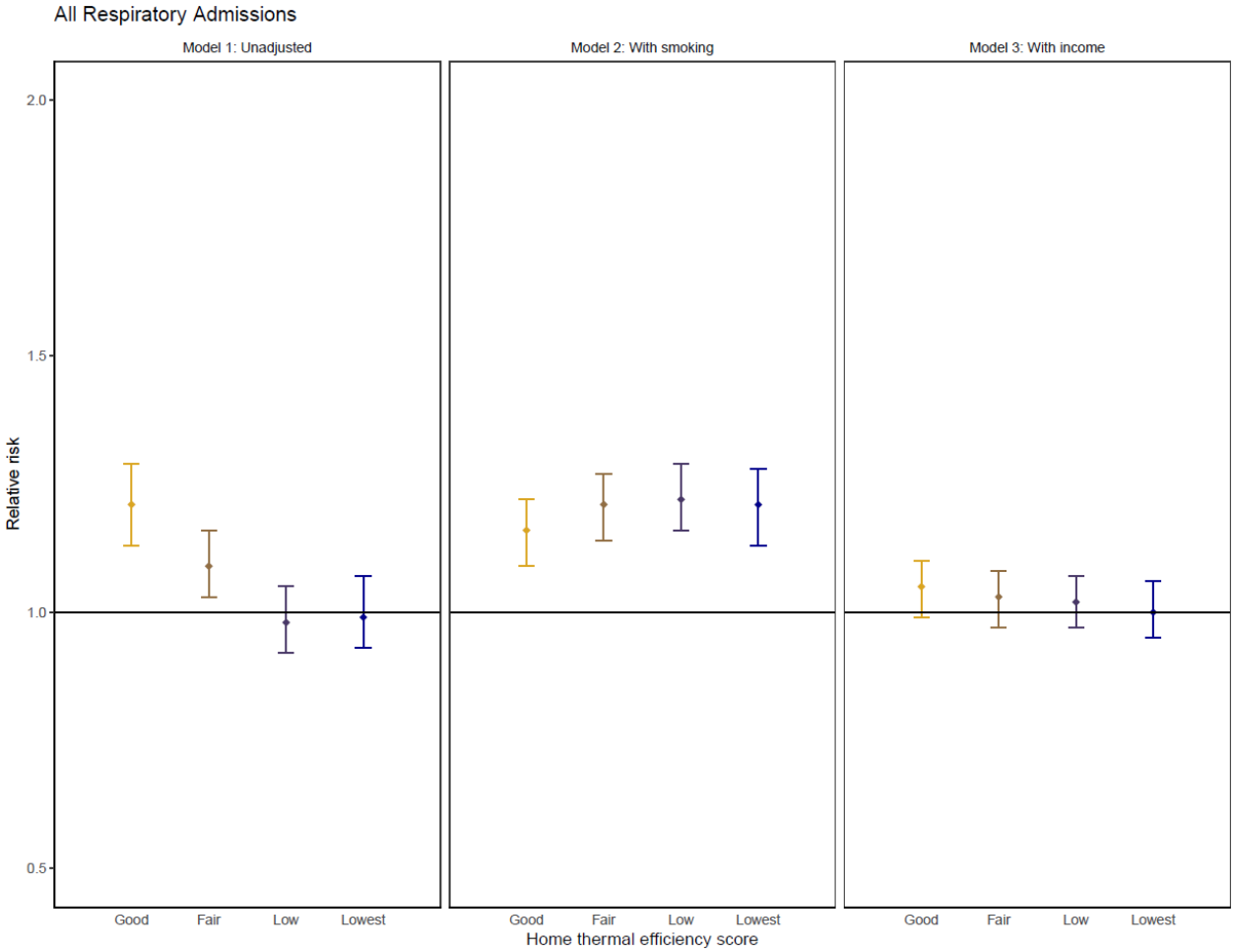
Appendix 9-21. Relative risk (RR) and 95% confidence intervals (95% CI) for hospital admissions from all health outcomes associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income)



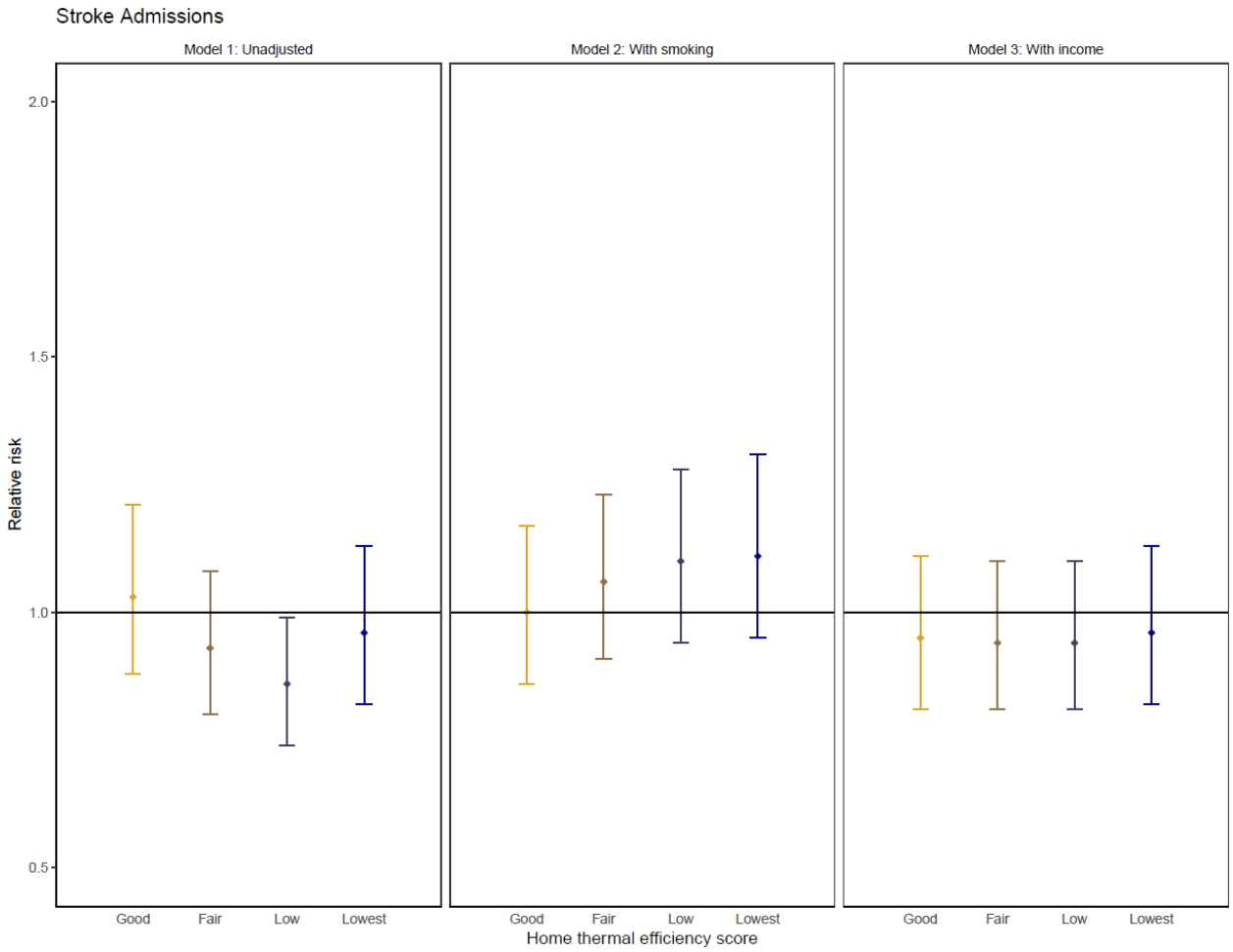
Appendix 9-22. Relative risk (RR) and 95% confidence intervals (95% CI) for all CVD-related hospital admissions associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income)



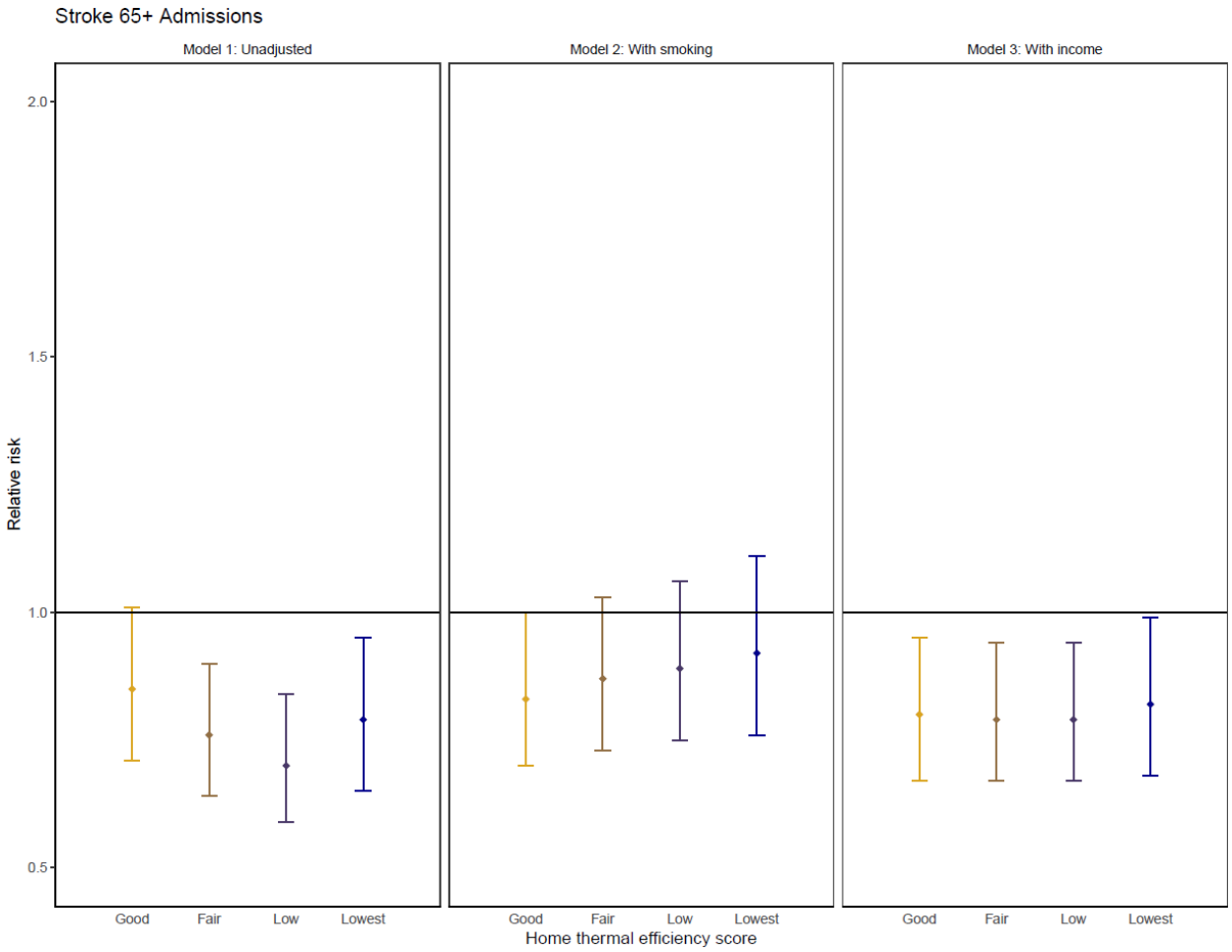
Appendix 9-23. Relative risk (RR) and 95% confidence intervals (95% CI) for all respiratory-related hospital admissions associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income)



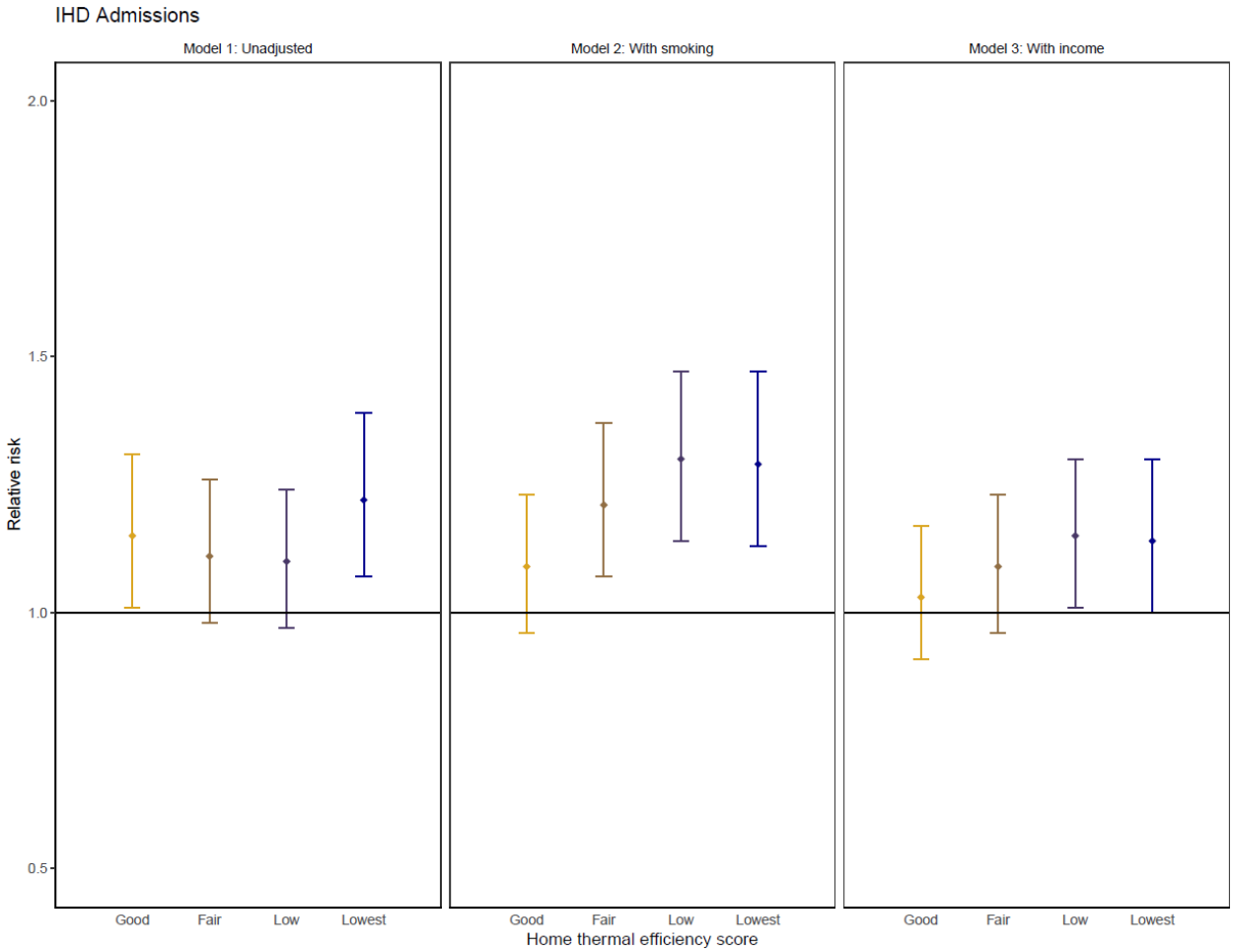
Appendix 9-24. Relative risk (RR) and 95% confidence intervals (95% CI) for all stroke admissions associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income)



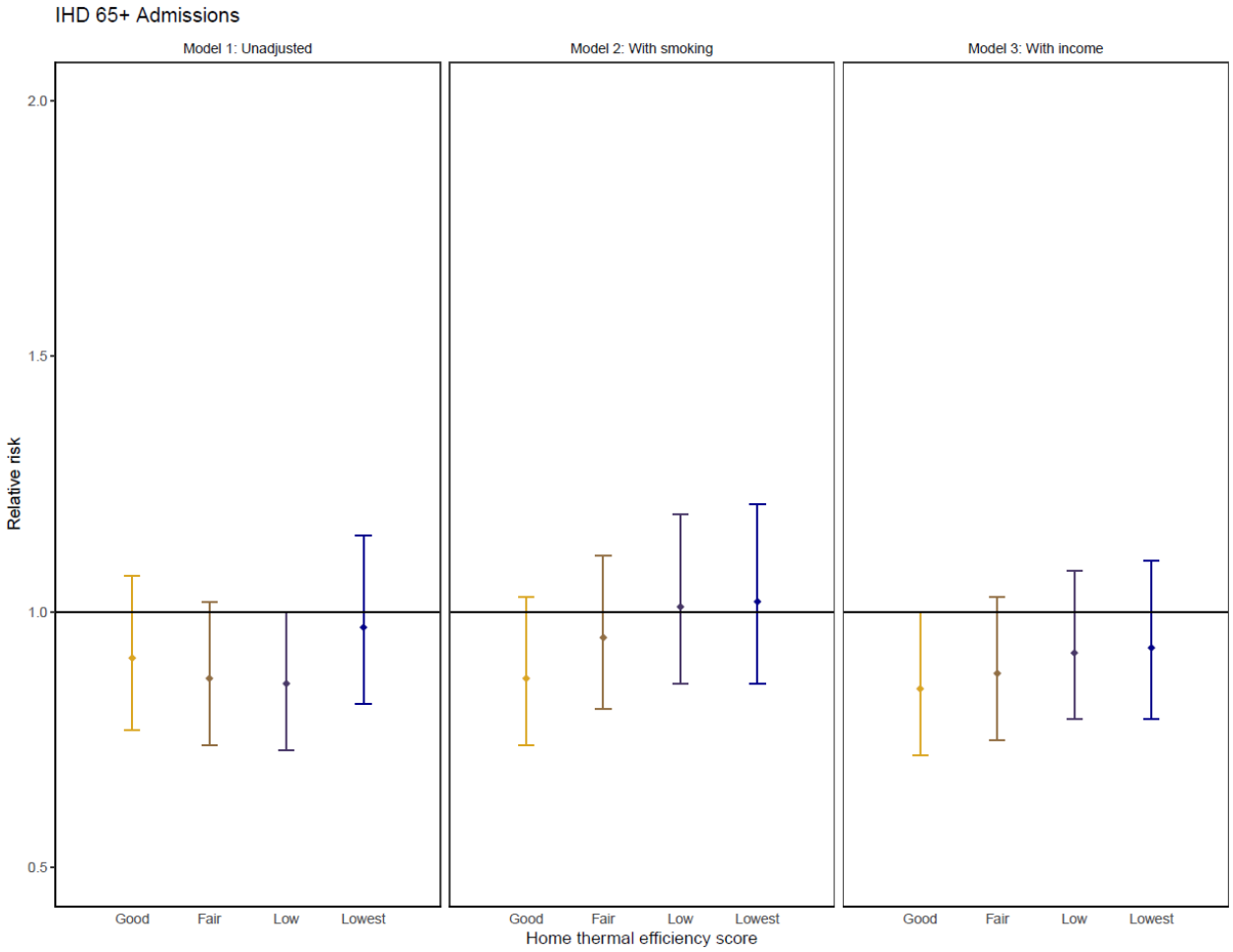
Appendix 9-25. Relative risk (RR) and 95% confidence intervals (95% CI) for stroke admissions among the elderly associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income)



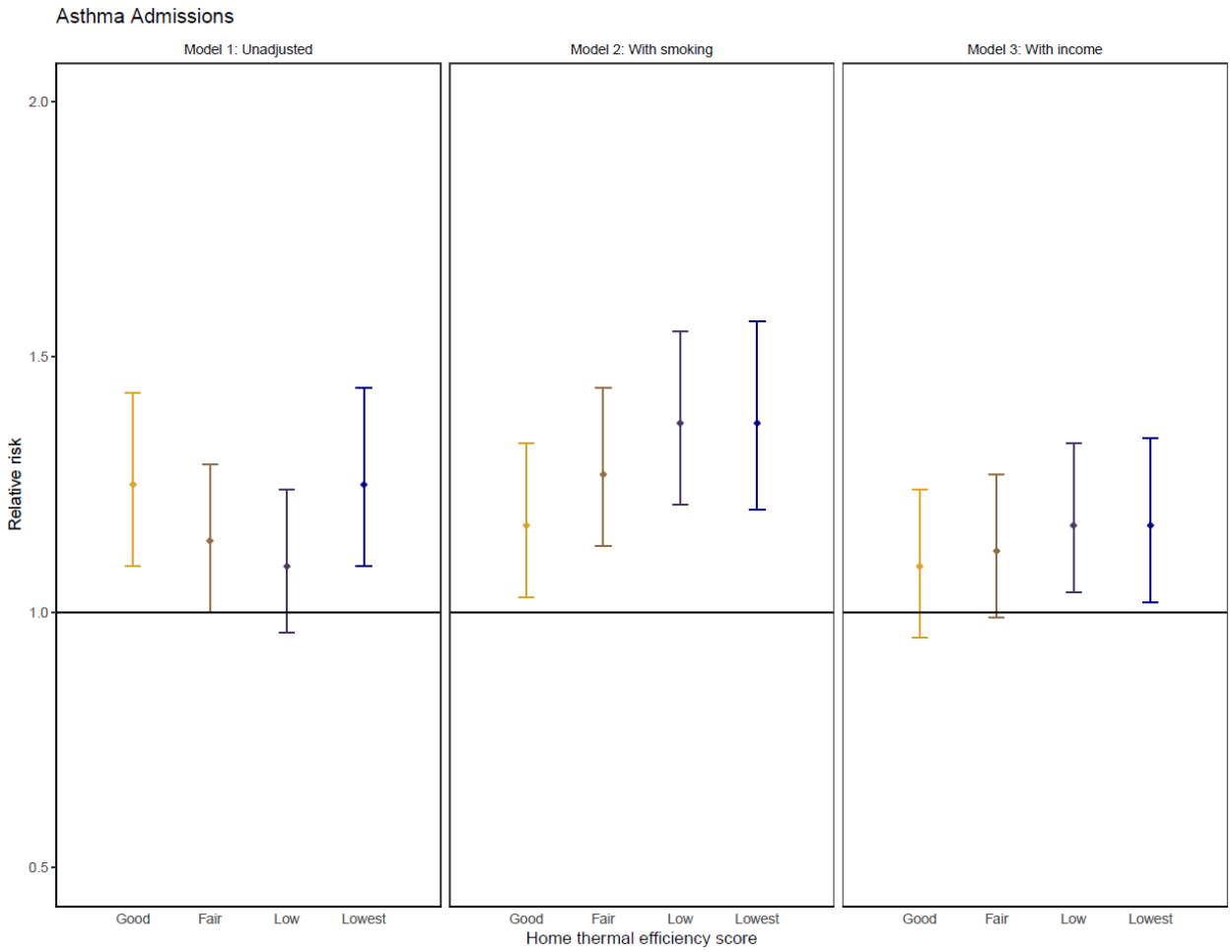
Appendix 9-26. Relative risk (RR) and 95% confidence intervals (95% CI) for all IHD admissions associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income)



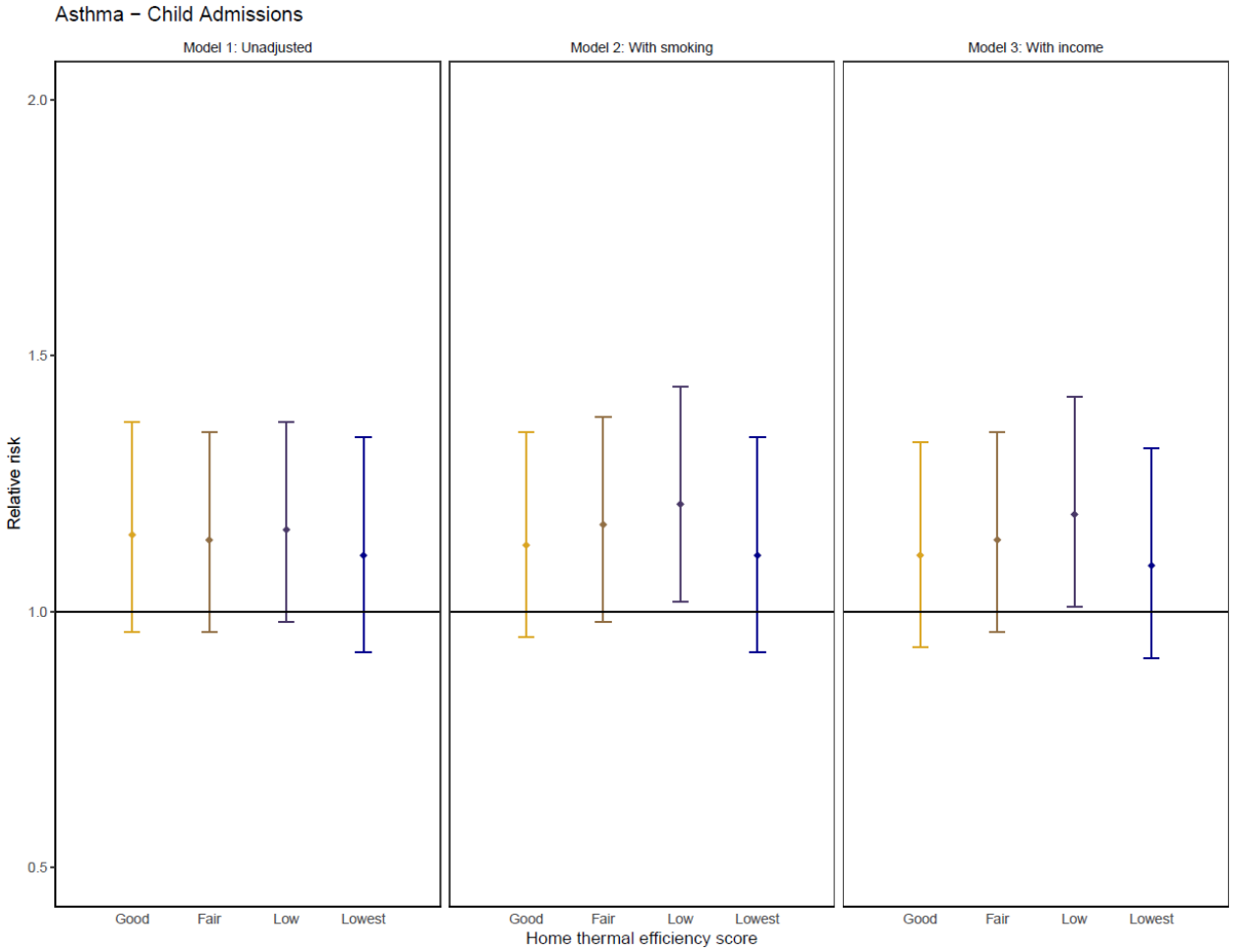
Appendix 9-27. Relative risk (RR) and 95% confidence intervals (95% CI) for IHD admissions among the elderly associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income)



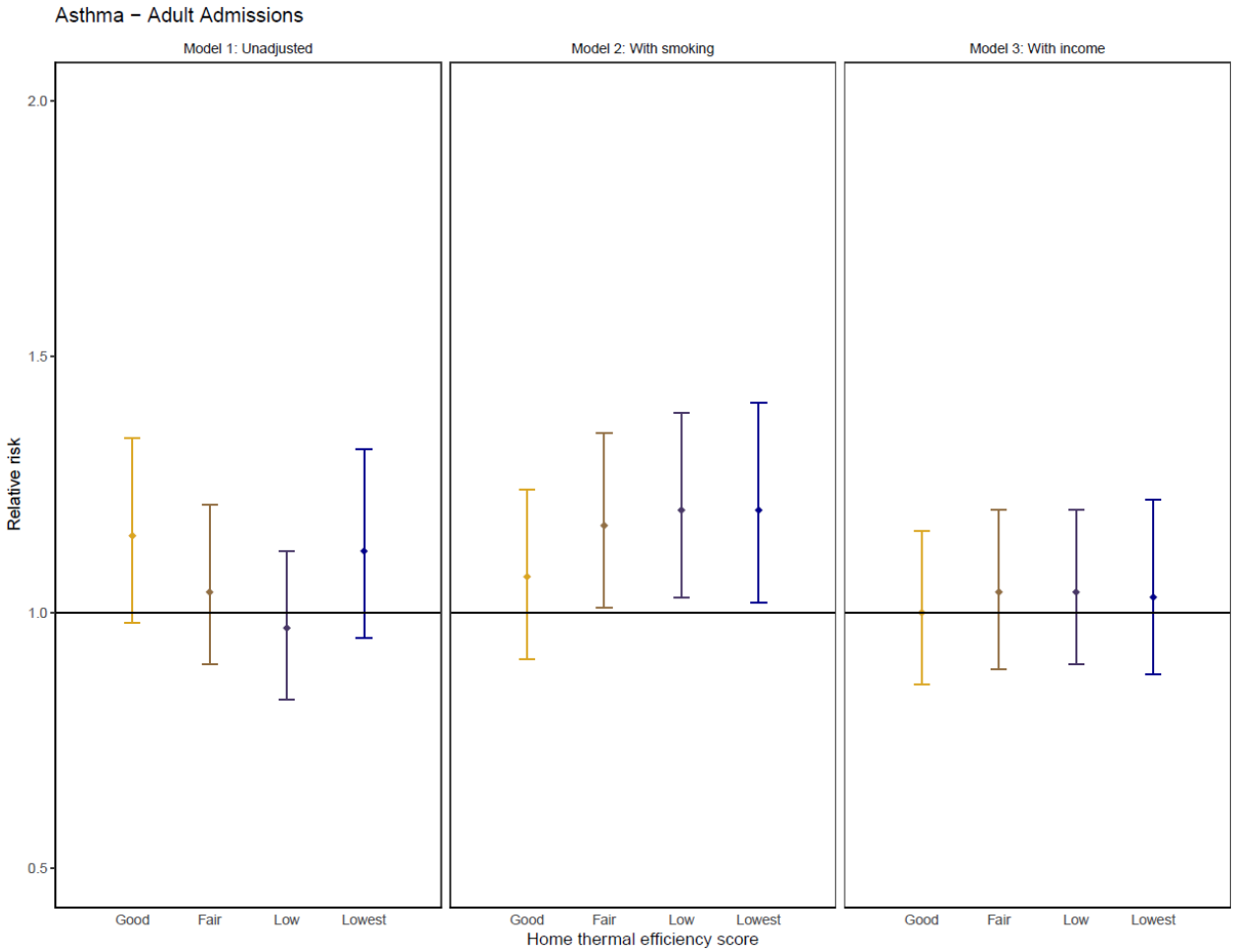
Appendix 9-28. Relative risk (RR) and 95% confidence intervals (95% CI) for all asthma admissions associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income)



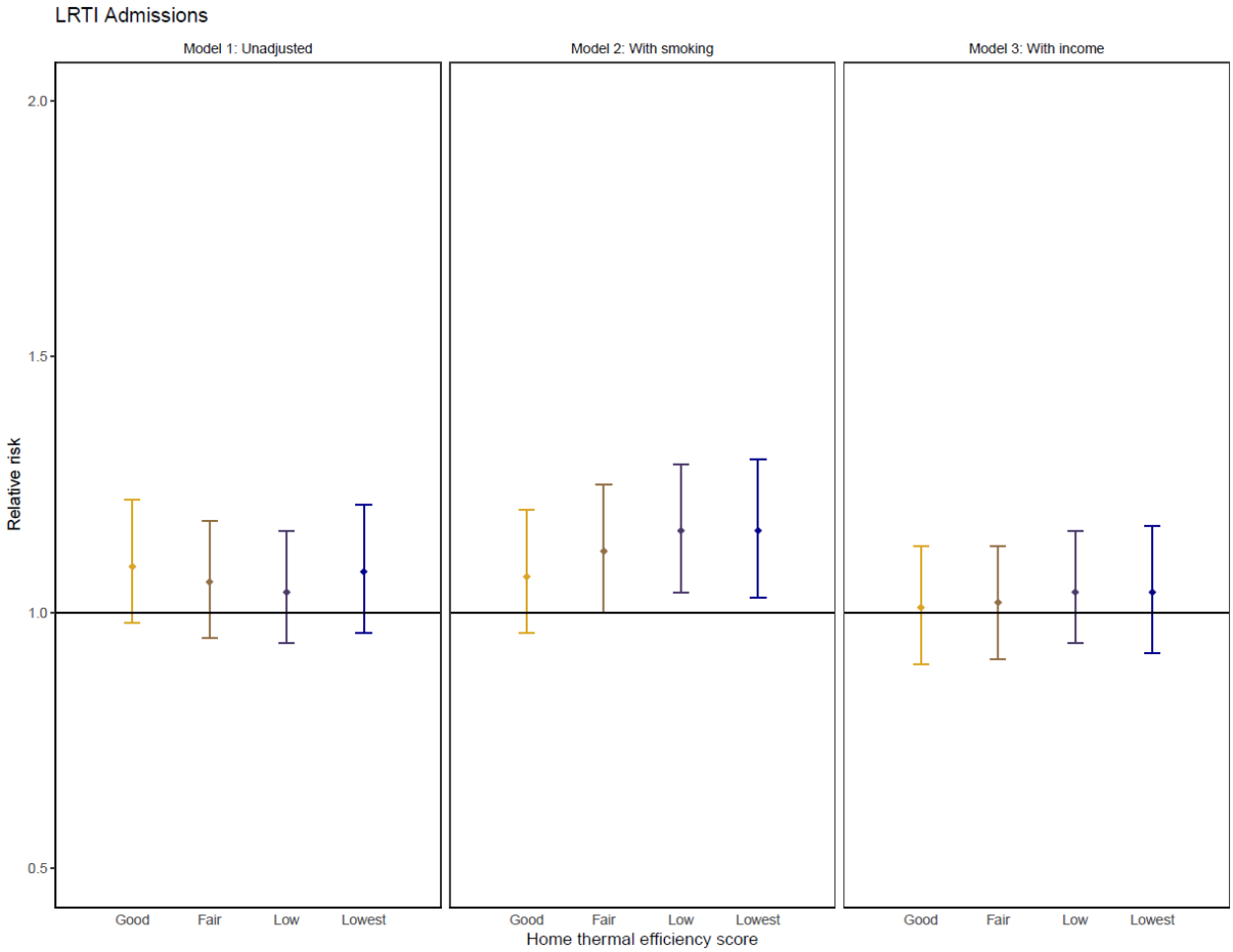
Appendix 9-29. Relative risk (RR) and 95% confidence intervals (95% CI) for asthma admissions among children associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income)



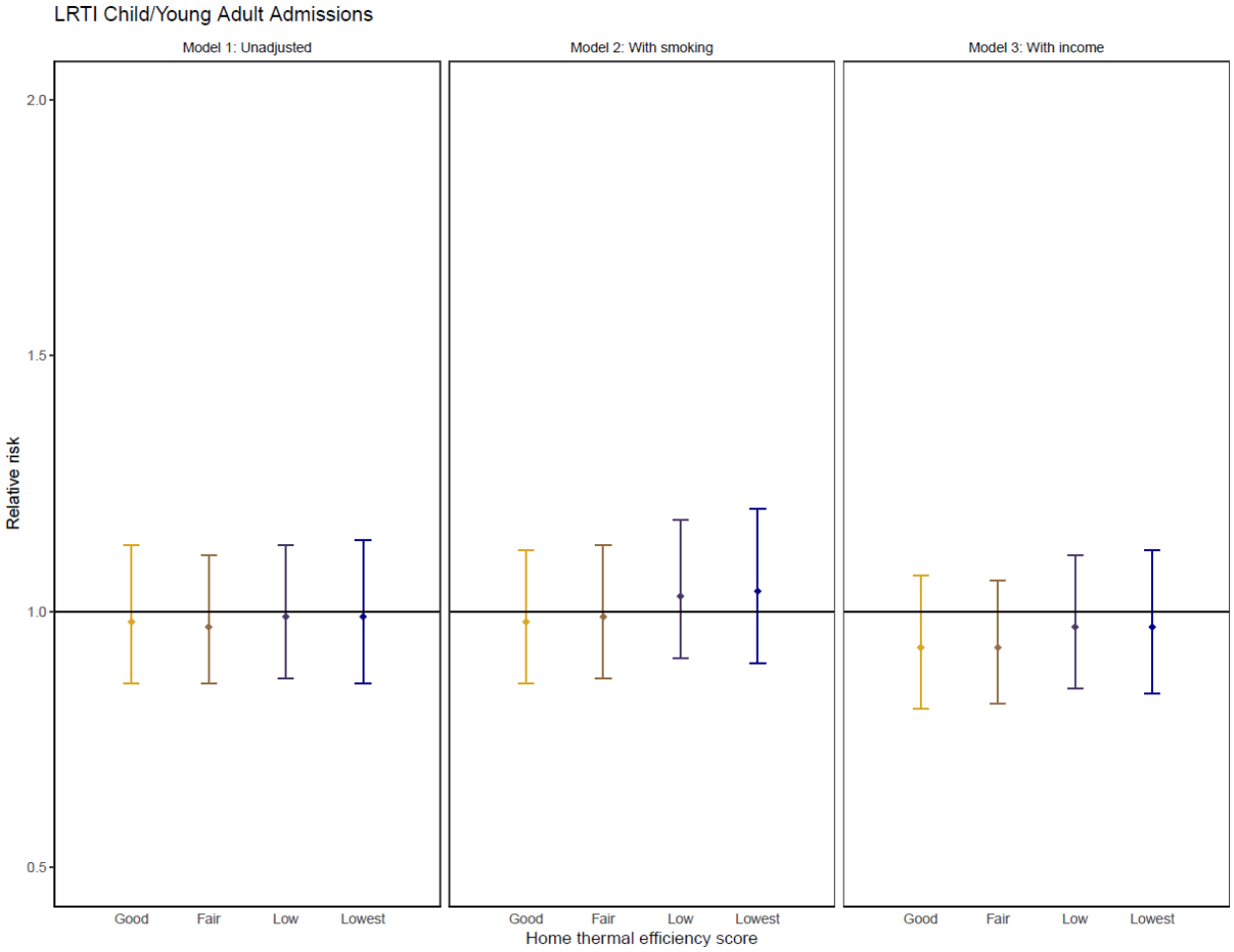
Appendix 9-30. Relative risk (RR) and 95% confidence intervals (95% CI) for asthma admissions among adults associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income)



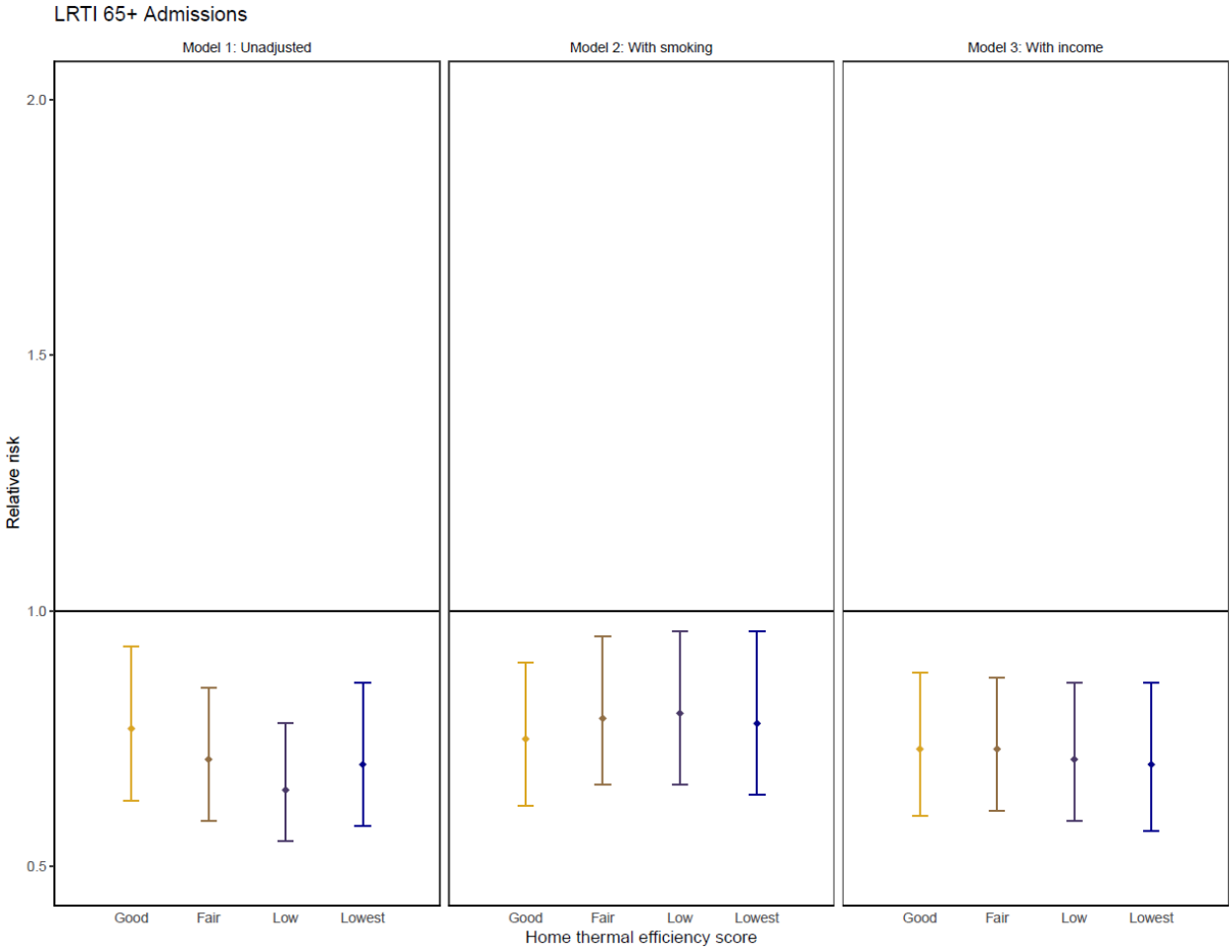
Appendix 9-31. Relative risk (RR) and 95% confidence intervals (95% CI) for all LRTI admissions associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income)



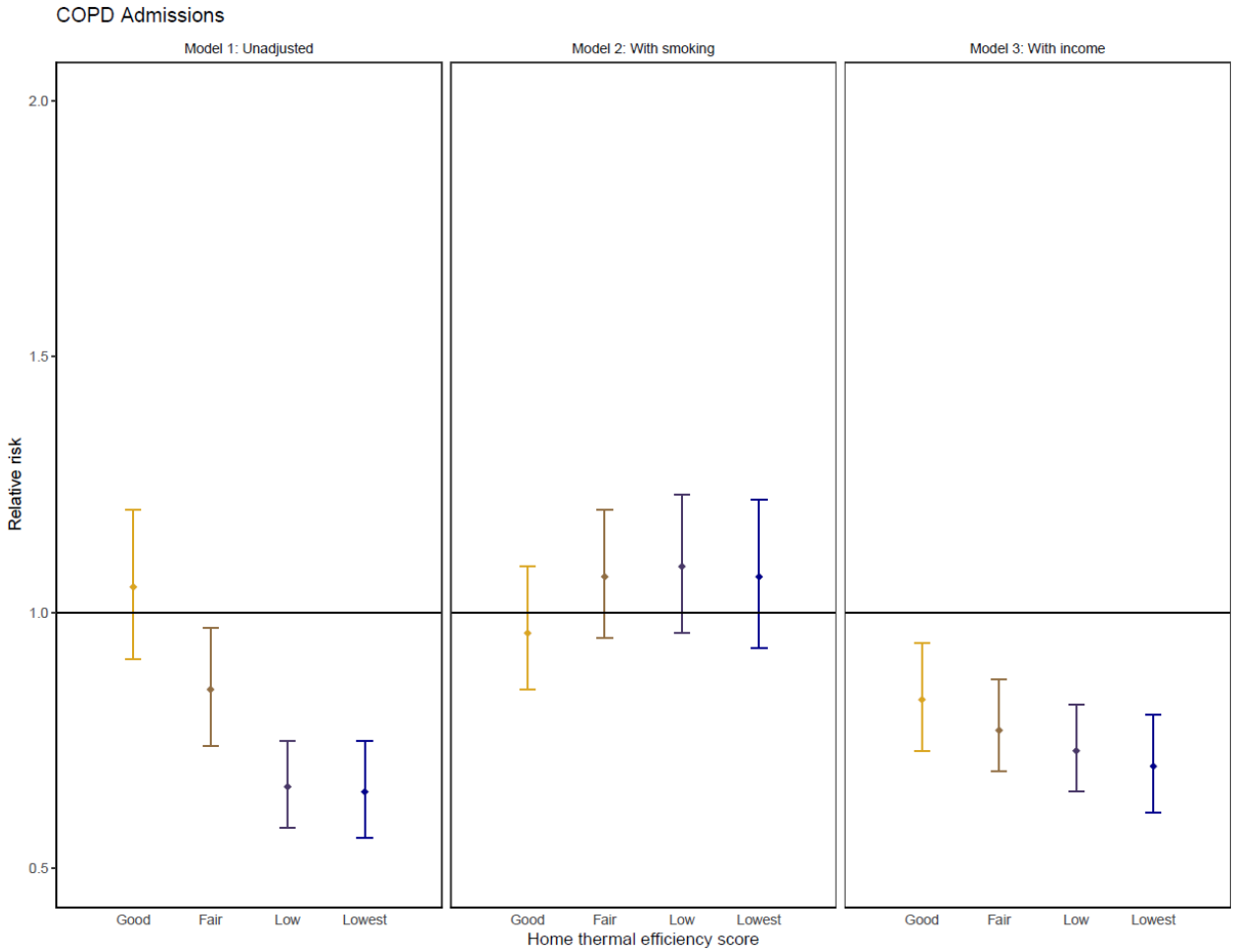
Appendix 9-32. Relative risk (RR) and 95% confidence intervals (95% CI) for LRTI admissions among children/young adults associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income)



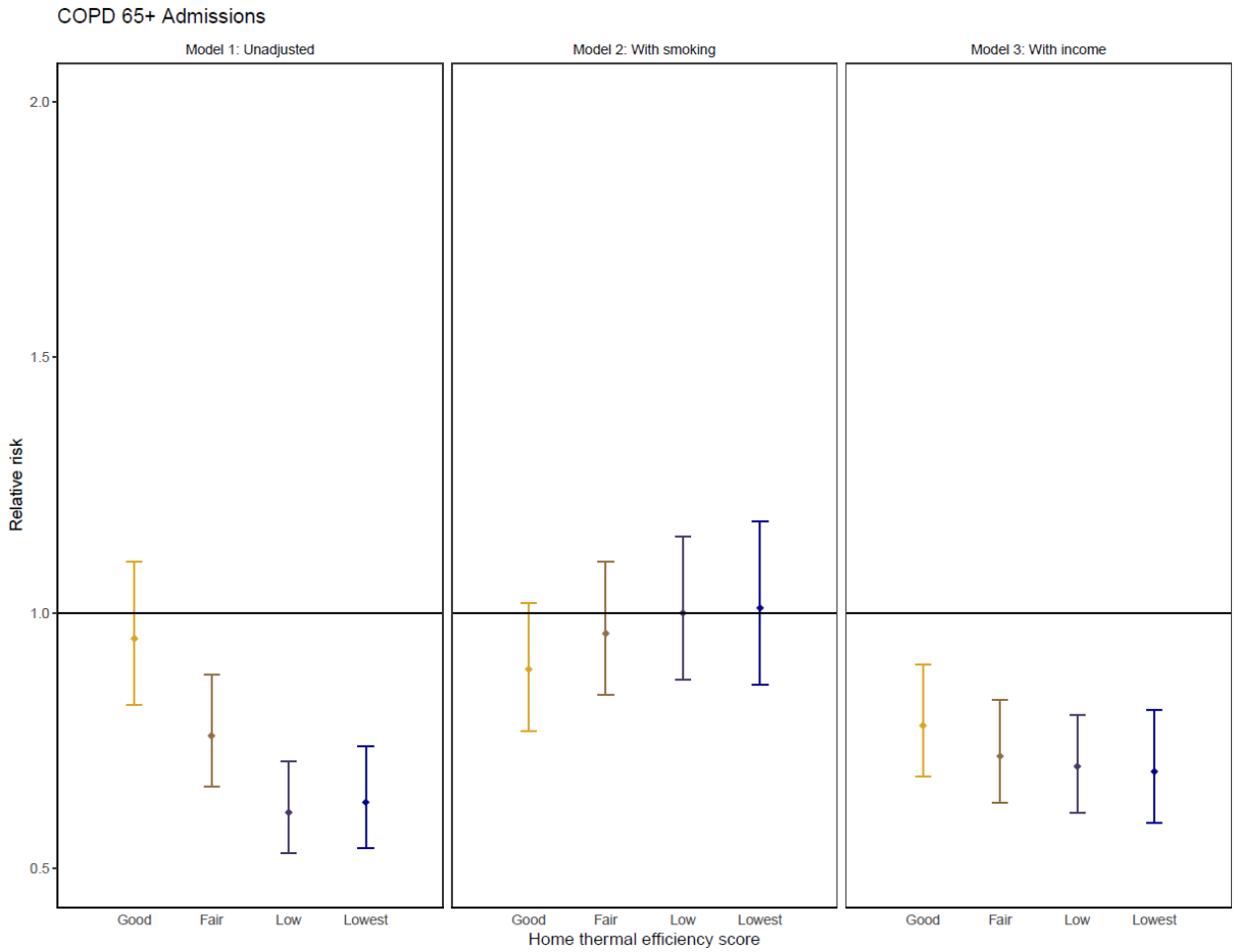
Appendix 9-33. Relative risk (RR) and 95% confidence intervals (95% CI) for LRTI admissions among the elderly associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income)



Appendix 9-34. Relative risk (RR) and 95% confidence intervals (95% CI) for all COPD admissions associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income)



Appendix 9-35. Relative risk (RR) and 95% confidence intervals (95% CI) for COPD admissions among the elderly associated with quintiles of home thermal efficiency (reference category is 'best' thermal efficiency score) for Model 1 (unadjusted), Model 2 (adjusted for ethnicity, air pollution and smoking), and Model 3 (adjusted for ethnicity, air pollution and income)



Appendix 9-36. Relative risk (RR) and 95% confidence intervals (95% CI) for hospital admissions for all health outcomes, all CVD outcomes and all respiratory outcomes associated with quintiles of home thermal efficiency, stratified by quintiles of the IMD income domain

All admissions (excluding births and injuries)										
	Income quintile 1		**Income quintile 2**		**Income quintile 3**		**Income quintile 4**		**Income quintile 5**	
	RR	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**
Best	1	1.00	1	1.00	1	1.00	1	1.00	1	1.00
Good	1.14	(1.01, 1.28)	1.01	(0.92, 1.12)	1.18	(1.10, 1.27)	1.14	(1.08, 1.21)	1.05	(0.99, 1.12)
Fair	1.26	(1.14, 1.40)	1.19	(1.09, 1.30)	1.16	(1.08, 1.24)	1.15	(1.10, 1.21)	1.07	(1.01, 1.14)
Low	1.31	(1.18, 1.46)	1.23	(1.13, 1.35)	1.17	(1.09, 1.26)	1.17	(1.11, 1.23)	1.05	(0.98, 1.12)
Lowest	1.34	(1.19, 1.50)	1.24	(1.12, 1.37)	1.19	(1.10, 1.29)	1.16	(1.09, 1.22)	1.03	(0.95, 1.10)
All CVD admissions										
	Income quintile 1		**Income quintile 2**		**Income quintile 3**		**Income quintile 4**		**Income quintile 5**	
	RR	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**
Best	1	1.00	1	1.00	1	1.00	1	1.00	1	1.00
Good	1.25	(0.95, 1.63)	1.01	(0.82, 1.24)	1.18	(0.99, 1.42)	1.24	(1.11, 1.38)	0.99	(0.88, 1.13)
Fair	1.39	(1.09, 1.77)	1.17	(0.97, 1.41)	1.21	(1.02, 1.43)	1.25	(1.13, 1.39)	1.03	(0.91, 1.17)
Low	1.47	(1.15, 1.88)	1.23	(1.02, 1.49)	1.27	(1.07, 1.50)	1.28	(1.15, 1.43)	1.03	(0.91, 1.18)
Lowest	1.54	(1.19, 1.99)	1.22	(0.99, 1.50)	1.27	(1.06, 1.52)	1.27	(1.13, 1.42)	1.07	(0.93, 1.23)
All respiratory admissions										
	Income quintile 1		**Income quintile 2**		**Income quintile 3**		**Income quintile 4**		**Income quintile 5**	
	RR	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**	**RR**	**95% CI**
Best	1	1.00	1	1.00	1	1.00	1	1.00	1	1.00
Good	1.21	(0.96, 1.54)	0.97	(0.81, 1.15)	1.04	(0.90, 1.19)	1.09	(1.00, 1.19)	1.04	(0.94, 1.14)
Fair	1.43	(1.16, 1.76)	1.17	(1.00, 1.38)	1.02	(0.90, 1.16)	1.06	(0.97, 1.15)	1.04	(0.95, 1.15)
Low	1.50	(1.21, 1.86)	1.21	(1.03, 1.43)	1.04	(0.91, 1.18)	1.07	(0.98, 1.16)	1.00	(0.90, 1.10)
Lowest	1.58	(1.26, 1.99)	1.17	(0.98, 1.41)	1.03	(0.90, 1.19)	1.04	(0.95, 1.15)	0.98	(0.88, 1.10)