Simulating indoor air quality in London hospitals: A building-based bottom-up method

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Abstract. Healthcare premises are energy-intensive buildings, and their operation and performance are critical to healthcare delivery and the protection of patients. A key step towards ensuring people's wellbeing and facilitating recovery is establishing the distributions of indoor air pollutants and temperature, and associated exposures in hospitals. Microenvironment pollutant concentrations are determined by the generation of indoor sources of pollution and the penetration of outdoor air to the indoors. In hospitals, the conditions for air pollution are typically highly controlled to deliver clean environments; however, building ventilation systems may still be subject to harsh external environments that impact on indoor environmental conditions. The aim of this study is to enhance understanding of how building operations and energy efficiency improvements will impact indoor hospital environments whilst reducing potential harmful pollutant exposures and energy demand. To achieve this, the ventilation conditions and corresponding $PM_{2.5}$ penetration of London hospitals were simulated. The baseline data of building stock physics (building types, construction periods, floor levels, room functions, total floor area and energy performance ratings) for hospitals were aggregated from the building typologies and room functions of the London 3DStock model to analyse the effect of built configurations on air ventilation and pollutant transfer using the CONTAM tool. The simulation results show that recently built or retrofitted hospital buildings are more airtight and energy-efficient but also need to carefully maintain intentional ventilation and filtration to ensure adequate air quality conditions to prevent the ingress of outdoor-sourced air pollutants. The simulations also show that COVID operating procedures may greatly increase airflow and a corresponding need for additional air filtration to meet guidance on pollution levels.

Keywords. Indoor Air Quality, Healthcare Premises, Optimization and Modelling, Building Envelope, CONTAM.
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1. Introduction

The UK's 2050 climate target of net zero carbon emissions [1] prompts the urgent need for building retrofits to improve building energy efficiency and reduce carbon emissions, especially in public buildings. To reduce the heat loss, requires the improvement of the building envelope which will significantly modify ventilation characteristics, such as air tightness. As a result, research and policy interest in Indoor Air Quality (IAQ) and the potential health impacts of indoor air pollutant exposure has been gradually increasing in recent years. When estimating indoor air quality, both the infiltration of outdoor air pollutants and building air exchange play significant roles [2].

The healthcare sector has been estimated to be responsible for 4 to 5% of the carbon footprint and about a fifth of public sector emissions in England [3]. Actions of the healthcare sector will be instrumental in delivering the Net Zero Strategy (NZS) by 2050. Although the National Health Service (NHS) has made significant progress in reducing carbon emissions by 26% between 1990 and 2019 [4], to-date the pace of improvement is insufficient to meet the 2050 target. Therefore, there must be an acceleration of related work to deliver a net zero healthcare sector. Hospitals are energy-intensive buildings, but their operation and performance are critical to healthcare delivery and the protection of patients. A key step towards ensuring people's wellbeing and facilitating recovery is establishing the distributions of indoor air pollutants and temperature, and associated exposure in hospitals. However, there are significant knowledge gaps around the impact of building retrofits on IAQ within UK healthcare premises, and more generally their indoor environmental conditions are not well described.

This study aims to understand the impact of building physics and energy performance on air penetration rates for ventilation prediction and indoor air quality modelling in London healthcare buildings. London healthcare premises were retrieved from a 3-dimensional model of London, providing the opportunity to develop bottom-up physics-based models to simulate indoor air quality and energy demand. Hospitals, surgeries, clinics, and health centres (including dentists) were modelled, and offices and wards in the premises were focused upon as they are the main room types where people spend time in hospitals.

CONTAM 3.2 was employed to simulate IAQ in London healthcare buildings. CONTAM, as a well-validated multizone indoor air quality and ventilation analysis computer program, created by the National Institute of Standards and Technology (NIST) of the U.S. Department of Commerce, can determine: (1) airflows; (2) indoor contaminant concentrations; (3) personal exposure to indoor air pollution [5]. To-date only a few studies have applied CONTAM to healthcare environments [6, 7, 8] and the modelling outputs of these studies were mainly for a single building, which may be difficult to generalise across multiple spaces in multiple buildings. Moreover, previous studies, using either computational fluid dynamics (CFD) simulation [9, 10] or a modelling approach based on in-situ measurements [11] to estimate hospital ventilation, were also from very specific cases. This study employing bottom-up large-scale building modelling of healthcare premises provides an innovative way to address the limitation of generalisation by using information aggregated from across London.

2. Method

2.1 3DStock: aggregation of healthcare environments in London

The London 3DStock model, which was developed by a team at the UCL Energy Institute led by Professor Philip Steadman, is a method for modelling London's whole building stock. Great Britain Ordnance Survey digital maps, commercial property taxation data from the Valuation Office Agency (VOA), and Light Detection and Ranging (LiDAR) data from the UK Environment Agency were assembled into a 3D model [12]. The characteristics of individual domestic, non-domestic and mixed-use premises in all 33 boroughs of the Greater London area and the floor-by-floor activities, room-level sub-activities and floor areas from the VOA's non-domestic premises surveys were held in a PostgreSQL database. This large dataset has been mainly used in analysing and estimating population-level energy demand [13, 14]. In this research, for simulating indoor air quality based on energy performance and building characteristics, 3DStock was used to aggregate basic building characteristics of existing healthcare buildings in London. Simple archetypes representing healthcare building typologies in different construction periods were proposed, based on the aggregation.

The building information extracted from the 3DStock model for CONTAM model development were building types; construction periods; floor levels; room functions; floor areas and energy performance ratings. The classes of each building characteristic are listed below:

(1) Building type: Four typical building types were used, which are Detached, Semi-detached, End-terrace and Mid-terrace forms. These types refer to the attachment of a building to other buildings, and are not a reference to residential use. Those without a record of building type, were denoted 'N/A'.

(2) Construction period: Four periods were used to present the building age, which are Pre-1914, 1918-1939, 1945-1980, Post-1980. Those without a record of construction year, were denoted 'N/A'.

(3) Floor level: Floor level was recorded for each premises in 3DStock up to the fiftieth floor. Numbers 0 to 50 denote ground floor to fiftieth floor. Basements, lower ground floors and mezzanines are also identified. Those without a record of floor level, were denoted 'N/A'.

(4) Room function: Detailed sub-activities within each premises are provided in 3DStock, largely based on the VOA's sub-activity classification system. In this research, healthcare sub-activities are grouped into 14 types: Consulting Room; Facilities (such as x-ray rooms, computer rooms); Kitchen (including staff/mess/common rooms and tea points); Office; Reception (including lobby, hall and porch); Retail Zone; Storage (including file/ report rooms; Surgery (including dental surgeries); Toilet (including changing area, shower rooms, restrooms); Treatment Room (including clinics); Waiting Room (free space excluding reception area); Ward (including pre-/post-surgery rooms); Utility Room (such as garages, cleaning rooms); Other (Including mix-used rooms and rooms hard to classify).

(5) Floor area of sub-activity was recorded in square metres (m^2) in 3DStock. In this research, healthcare premises were rounded to show the statistics of different bands of building total floor area.

(6) Energy performance: 3DStock contains records for Energy Performance Certificates (EPCs), which are a theoretical energy performance indicator based on the building and the standardised use of its fixed services (heating,

lighting etc.). EPCs grade performance from 'A' (best) to 'G' (worst). Where the premises do not have an EPC, a 'virtual EPC' (vEPC) has been created, based on nearby premises with similar non-EPC derived characteristics. To cope with mixed-use buildings, 3DStock also aligns and aggregates non-domestic EPCs and vEPCs to their domestic equivalents [9], presenting as "rvEPCs" for healthcare premises with a scale of 1 to 100 from the worst to the best energy performance. Henceforth, rvEPCs are simply denoted as EPCs. This provides a metric applicable across all building types in the stock and a general idea of energy performance, but it is not 100% accurate.

Depending on the building statistics, basic models were created to simulate ventilation and penetration of outdoor air pollution indoors in CONTAM by estimating building air exchange rates (Air Changes per Hour, ACH) for each archetype.

2.2 CONTAM: simulation of ventilation and air pollution in London healthcare environments

CONTAM determines room-to-room airflows driven by exterior wind pressure, buoyancy effect of indoor-outdoor temperature difference and intentional mechanical ventilation. In hospitals, the conditions for air pollution are typically highly controlled to deliver clean environments; however, building ventilation systems may still be subject to harsh external environments that impact on indoor environmental conditions. This work includes both unintentional infiltration and intentional ventilation to simulate hour-by-hour indoor $PM_{2.5}$. Here, indoor-sourced $PM_{2.5}$ was ignored and only outdoor-sourced $PM_{2.5}$ was assumed to affect indoor microenvironment pollutant concentrations.

The U.S. Department of Energy defined sixteen reference buildings, and CONTAM models of the 16 reference buildings were created to support physics-based airflow calculations and indoor air quality analysis [15]. Two types of reference building of healthcare environments have been identified: hospital and outpatient health care. These were further classified into subtypes based on the construction year, pre-1980, post-1980 and newly built after 2004. In this research, only the type "hospital" was applied for simplicity, and parameters in CONTAM libraries and building variables were adjusted accordingly for London healthcare buildings. For alignment with the construction years of healthcare premises in 3Dstock, only pre-1980 and post-1980 CONTAM models were used. Summer weather was set as the warmest July and winter weather as the coldest January, according to the UK typical meteorological status [16]. Based on the typical meteorology features, hourly airflows, and time-average ventilation rates and indoor $PM_{2.5}$ were subsequently simulated in the building form of hospital environments for January and July in the Pre-1980 and Post-1980 reference buildings.

Figure 1 from NIST Technical Note 1734 shows the layout of floors in a hospital where (a) patient rooms (wards) and (b) offices are located [12]. The ambient environment surrounding the building was set following the weather file converted from Typical Meteorological Year 2 (TMY2) in London for transient analysis. The zones in CONTAM sketchpad were assigned with the aggregate floor areas by room use type, construction periods and energy performance. According to the Chartered Institute of Building Services Engineers recommendations, the workplace temperature was set at 18 °C in hospitals [17] and the ward was set at 20 °C. Other settings were kept default when running simulations. The single patient room 8 at the top-left corner in figure 1 (a) and the single office 3 at the top-left corner in figure 1 (b) were the target rooms to be modelled in this research.

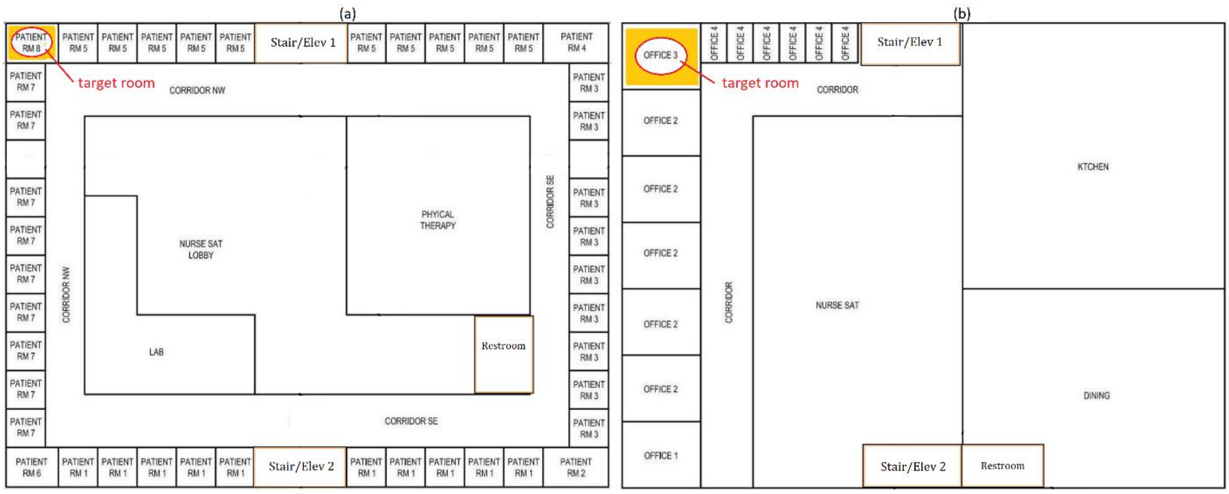

Fig. 1 - Layout of floors in hospitals where (a) wards and (b) offices are located on (adapted from [15]).

CONTAM was also used to estimate room-to-room indoor infiltration of $PM_{2.5}$ concentrations only originating from the environment surrounding the building, which were investigated under the pollution scenario related to the London Average Air Quality Levels. Indoor sources of $PM_{2.5}$ were not considered in this study at this stage. The London Average Air Quality Levels, available from the London Datastore for the period 01/01/2008 – 31/07/2019, shows background and roadside average pollutant levels (ug/m^3) for $PM_{2.5}$ by hour of day per month [18]. This research used the 2019 London mean background $PM_{2.5}$ levels. The contaminant species properties of $PM_{2.5}$ were set with a molecular weight of 8 kg/kmol, diffusion coefficient 2×10^{-5}-m^2/s and specific heat 1000 J/kgK, and a sink of $PM_{2.5}$ was set in each room in the deposition rate model with the deposition rate 0.19 per hour for transient simulation. Other settings of Contaminant Numerics in CONTAM models, including Linear Contaminant Solver, CVODE Non-Linear Contaminant Solver, Convergence for Cyclic Simulations and 1D Options, were kept as default settings.

The COVID-19 pandemic has shown the importance of indoor air quality and ventilation controls, especially in facilities where reducing viral exposure is required, such as hospitals. COVID-19 guidance from UK Health Security Agency [19] was examined in an attempt to evaluate the impacts on indoor pollution level. However, as the guidance is only general in nature and contains no information on proposed rates of ventilation/infiltration, the effects of the guidance could not be evaluated.

3. Results and discussion

3.1 3DStock model aggregation results

The 3DStock model can provide information regarding the distribution of building types, building physics and room features of healthcare buildings in London. The Sankey diagram in Figure 2 illustrates the breakdown of room-level healthcare premises in London by building archetype, storey count, room use, room area, floor level, and construction period. The majority of London healthcare premises were found in mid-terrace and detached buildings of less than four storeys. Office, Surgery, Storage, Toilet and Consulting rooms were the top five room uses, which were found mainly at ground and first floor level. Very few activities were found higher than the fifth floor. Most of these rooms were no more than 20 m^2 and located in the buildings built before 1940 or with no construction year record.

In all, 11,028 room-level units of healthcare premises were present in the building dominated by non-domestic activities in the 3DStock model and Table 1 summarises their energy performance in different construction periods. Most London healthcare premises are EPC grade D (44%) or grade E (27.9%), and EPC grade D dominates all construction periods. The mode of EPC grades was D within the 3DStock samples, which is the same for England's existing properties as found in the Live tables on Energy Performance of Buildings Certificate [20]. It was also found post-1980 healthcare premises have better energy performance than other periods, with more EPC grade B and C than EPC grade E, F, and G. Other periods have higher percentages of EPC grade E, F, and G than EPC grade B and C. This could also suggest that the more recently built hospital premises, modelled in the research, might have higher airtightness and less leaky building envelopes bringing better energy performance.

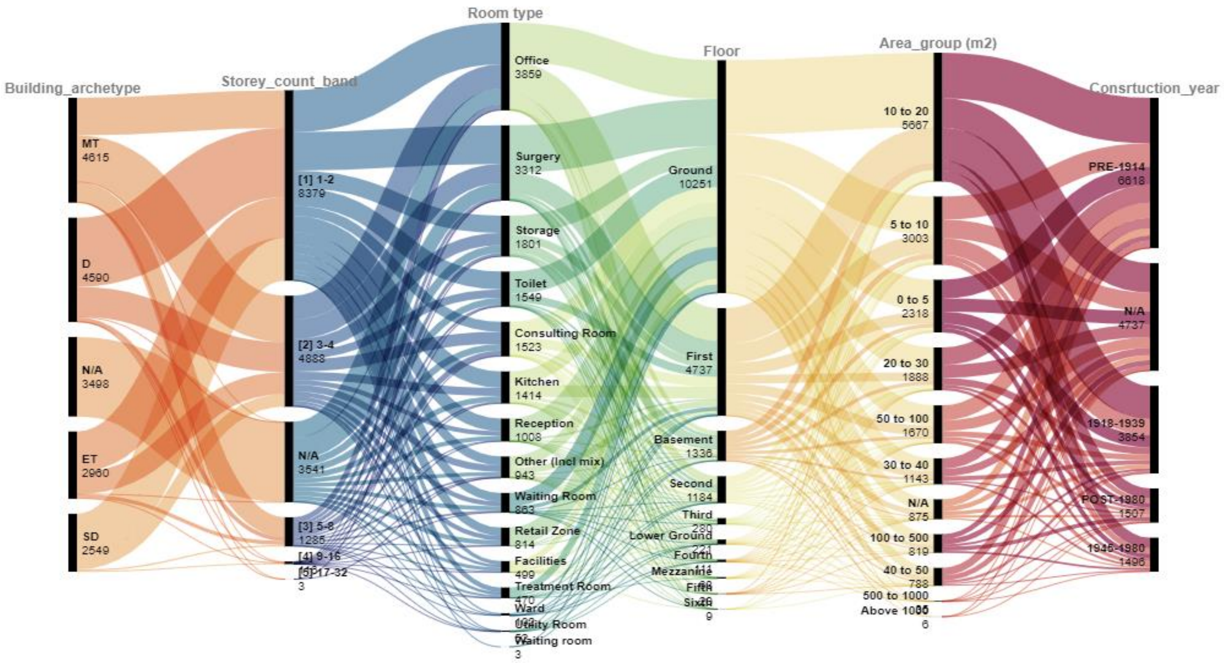

Fig. 2 - Sanky diagram of London healthcare premises created by RAWGraphs data visualization framework [21].

Tab. 1 - Energy performance of London healthcare premises in different construction periods.

EPC Periods	A N(%)	B N(%)	C N(%)	D N(%)	E N(%)	F N(%)	G N(%)	N/A N(%)	Total N(%)
N/A	1 (0.0)	42 (0.4)	172 (1.6)	351 (3.2)	192 (1.7)	115 (1.0)	52 (0.5)	91 (0.8)	1016 (9.2)
PRE-1914	0 (0.0)	92 (0.8)	482 (4.4)	1984 (18.0)	1472 (13.3)	325 (2.9)	93 (0.8)	398 (3.6)	4846 (43.9)
1918-1939	0 (0.0)	27 (0.2)	189 (1.7)	1601 (14.5)	938 (8.5)	144 (1.3)	85 (0.8)	80 (0.7)	3064 (27.8)
1945-1980	0 (0.0)	6 (0.1)	117 (1.1)	516 (4.7)	291 (2.6)	58 (0.5)	28 (0.3)	56 (0.5)	1072 (9.7)
POST-1980	0 (0.0)	137 (1.2)	173 (1.6)	401 (3.6)	180 (1.6)	24 (0.2)	50 (0.5)	65 (0.6)	1030 (9.3)
Total	**1 (0.0)**	**304 (2.8)**	**1133 (10.3)**	**4853 (44.0)**	**3073 (27.9)**	**666 (6.0)**	**308 (2.8)**	**690 (6.3)**	**11028 (100)**

3.2 CONTAM model simulation results

Based on the 3DStock aggregate information, CONTAM building layouts were adjusted for hospitals in pre-1980 and post-1980 buildings. Table 2 shows the mean floor area per room use type in two periods, which were input to CONTAM zone floor area for each room use type. For example, the mean office floor area in pre-1980 is 37m^2 and in post-1980 is 72m^2. Using the table, it was found that all room types except for the Facilities rooms are more spacious in post-1980 buildings than in pre-1980 buildings.

Tab. 2 - The mean floor area of different room use types in pre-1980 and post-1980 healthcare premises.

Year Room type	Pre-1980 Area (m^2)	Post-1980 Area (m^2)	N/A Area (m^2)	Total % of N	Total Area (m^2)
Consulting Room	33	37	55	8.4	39
Facilities	14	12	22	2.7	17
Kitchen	10	11	11	7.8	10
Office	37	72	47	21.2	43
Reception	20	37	25	5.5	23
Retail Zone	23	71	27	4.5	26
Storage	12	19	13	9.9	13
Surgery	34	75	35	18.2	37
Toilet	4	6	7	8.5	5
Treatment Room	20	32	26	2.6	23
Utility Room	6	12	10	0.3	8
Waiting Room	18	35	23	4.8	21
Ward	39	128	33	0.6	47
Other (Incl mix)	37	117	52	5.2	52
Total	**26**	**54**	**32**	**100**	**30**

Figure 3, below, is the example of simulated airflow rate distribution of the target patient room (ward) of pre-1980 hospitals, during 1st January to 7th January. Sixteen grey lines indicate the balanced airflows through all airflow paths coming from outdoors (positive values) and blowing out of (negative values) the room. The red line is the sum of all sixteen flow rates, and the sum was used to estimate the air exchange of a room. In wintertime, the maximum ventilation rate in the pre-1980 hospital ward was 351.0 m^3/h at 8 am on 3rd January, which gives 2.1 ACH after being divided by the volume of the ward 166.5 m^3. For summertime, the maximum ventilation rate of the pre-1980 hospital ward was 132.7 m^3/h at 1pm on 22nd July and lead to 0.8 ACH. Comparing to the results of the post-1980 hospital, larger ward floor areas lead to lower air change rate, 0.6 ACH in winter and 0.2 ACH in summer. As for the offices in hospitals, the maximum air change rates from an airflow path were: 5.5 ACH in winter and 2.6 ACH in summer in the pre-1980 hospitals and 1.7 ACH in winter and 0.8 ACH in summer in the post-1980 hospitals. It was found the air change rates in the post-1980 hospitals are less than half those in the pre-1980 hospitals. The average ACH in an office was higher than in a ward, 2 – 4 times depending on the time of day and month of the year.

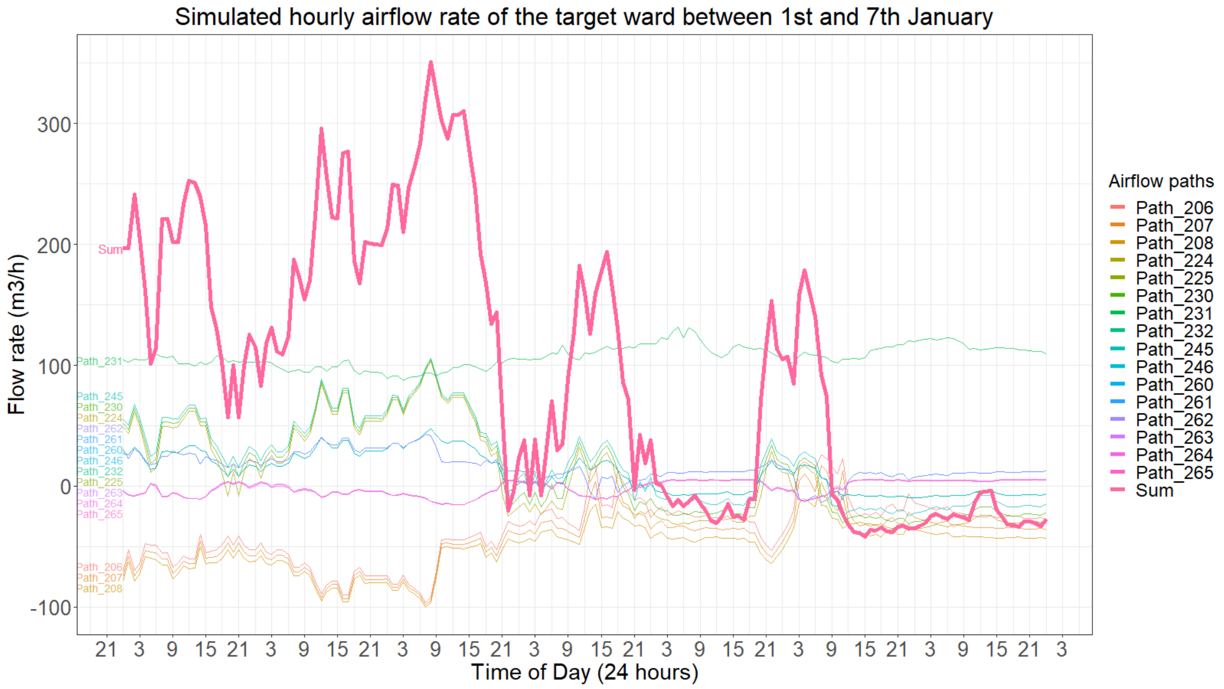

Fig. 3 - Simulated airflow rate of the target patient room of London hospitals between 1st January and 7th January. Sixteen lines stand for the balanced airflows through all airflow paths coming from outdoors and blowing out the room.

With different levels of ventilation rate resulting from conditioned simulation, air pollutants from outdoors are accumulated and removed at a different pattern for each room in healthcare environments. In this research, transient concentrations of $PM_{2.5}$ (μg/m³) in each room are simulated based on the temporal resolution of transient weather data and transient contaminant data, which are both on an hourly basis.

Figure 4 shows the example of simulated hourly $PM_{2.5}$ concentration of the target office and ward in the pre-1980 hospitals from 1st January to 7th January and 1st July to 7th July respectively. It was found, in wintertime, offices (10.9 – 15.2 μg/m³) and wards (11.1 – 15.8 μg/m³) both have higher indoor $PM_{2.5}$ concentrations than the WHO air quality guideline for $PM_{2.5}$, 10 μg/m³ annual mean (WHO 2006) in the pre-1980 hospitals, while in summertime the $PM_{2.5}$ for the office (8.3 – 9.5 μg/m³) and for the ward (8.4 – 9.6 μg/m³) are both lower than the WHO air quality guideline. As for the post-1980 hospitals, the overall indoor $PM_{2.5}$ concentrations are close to, but slightly lower than, the ones in the pre-1980 hospitals: in wintertime the offices are 10.9 – 15.2 μg/m³ and the wards are 11.1 – 14.9 μg/m³; in summertime the offices are 7.9 – 9.5 μg/m³ and the wards are 8.4 – 9.4 μg/m³.

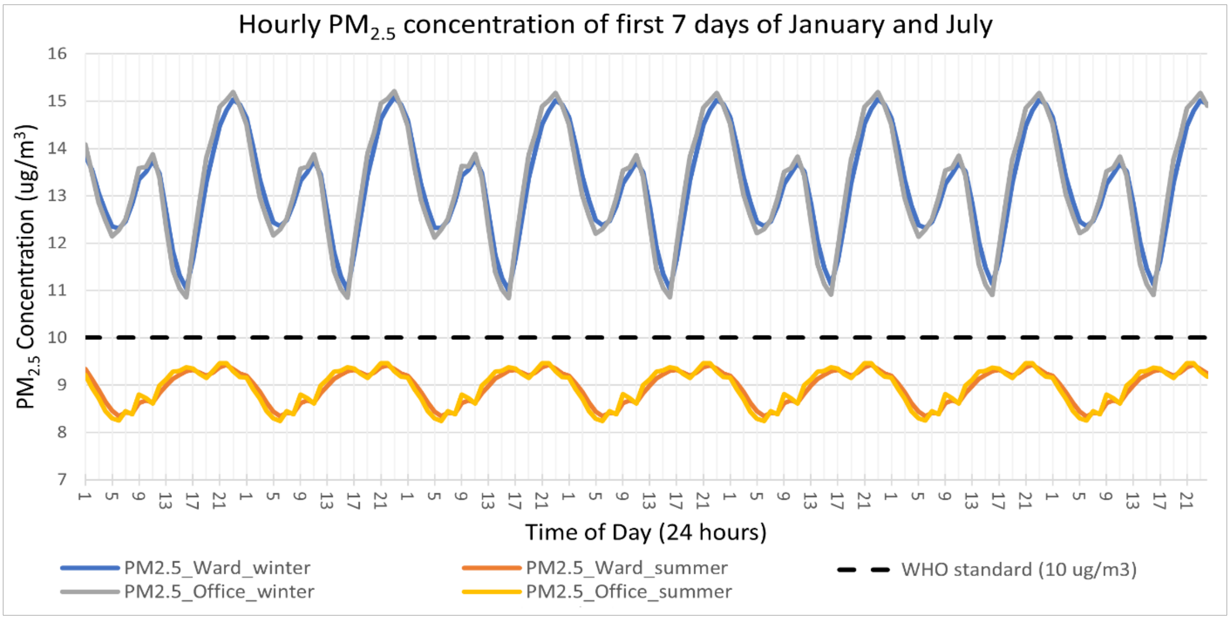

Fig. 4 - Hourly $PM_{2.5}$ concentration of the target office and patient rooms in the pre-1980 hospitals during 1st to 7th January and 1st to 7th July. The dashed line shows the WHO air quality guideline for $PM_{2.5}$, 10 μg/m³ annual mean.

3.3 Discussion

The air change rate of the hospital zones was shown to be affected by not only external ambient conditions in different seasons but also by building features, spatial configuration, floor area, construction year and energy-related features. However, both the 3DStock and CONTAM models are still under development, so some building characteristics were not available in 3DStock and were assumed in the simulations; for example, the space arrangement of rooms. The simulation results of London hospital models presented here indicate the air change rate is lower in post-1980 premises than in the pre-1980 premises, which implies recently built or retrofitted buildings are both more airtight and more energy efficient, as would be hoped from the evolution of Building Regulations.

The observed association between simulated indoor $PM_{2.5}$ concentrations and ventilation rate in rooms also implies the importance of both external ambient conditions and building characteristics. Wintertime weather, with a high ventilation rate, may increase the risk of people being exposed to the outdoor-sourced $PM_{2.5}$ moving indoors, but a recently built or retrofitted building with more airtightness and an appropriate operating schedule of openings could, on the contrary, lower the risk. Also, mechanical ventilation may further limit the penetration of outdoor $PM_{2.5}$ to the indoors. Our results show low ventilation may decrease indoor $PM_{2.5}$ exposure from outdoor $PM_{2.5}$, but the airtightness may prevent indoor-sourced $PM_{2.5}$ (which were not considered in this study but should be included in the future) from flowing out through openings. On the contrary, during the COVID-19 pandemic, the UK Health Security Agency guidance asks to keep fresh air coming into homes and workspaces through both natural and mechanical ventilation, which may lead to more outside-sourced $PM_{2.5}$ exposure. Therefore, a filtering system or air-purifying device might reduce both $PM_{2.5}$ and virus exposure.

DOE CONTAM models of reference buildings provide us with an opportunity to apply London settings to develop London hospital models, applicable to similar spaces across entire portfolios of buildings. However, the feasibility of DOE models, designed for the U.S. healthcare environments, still need to be examined when the representative information becomes available in the 3DStock or from other building stock surveys, in the future.

4. Conclusion

The deterioration of indoor air quality, due to increasingly airtight buildings (assumed to result from improved construction quality), may cause adverse exposure to indoor air pollutants, so we need to enhance our understanding of how improvement to energy efficiency-related features affects indoor air quality. This study contributes knowledge of how building physics and energy-related features interact in terms of airflow ventilation and penetration by outdoor air pollutants. Furthermore, the method is applied at the individual room or building scale across an entire building stock, providing a high-level but relatively detailed model, without the need for individual surveys. As more information becomes available, the large-scale inventories of healthcare buildings can provide an opportunity for bottom-up indoor air quality modelling to eliminate indoor air pollutants.

5. Acknowledgement

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Data Statement

The datasets generated during and/or analysed during the current study are not available because data licence agreements do not allow publication of the raw data but the authors will make every reasonable effort to publish them in near future.