Energy Research & Social Science 87 (2022) 102472

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

The office of the future: Operational energy consumption in the post-pandemic era

Eirini Mantesi *, Ksenia Chmutina, Chris Goodier

School of Architecture, Building and Civil Engineering, Loughborough University, Leicestershire LE11 3TU, UK

ARTICLE INFO

Keywords:
Future office
Activity-based workspace design
COVID-19
Hybrid working model
Energy efficient workspace

ABSTRACT

As a result of COVID-19 and in order to combat the spread of the virus, work-from-home and remote working has become a widely accepted practice in professional settings globally. It is widely known that we are currently experiencing a highly transient period in terms of how we define work. Office work is progressively becoming more collaborative, modern workforce more mobile, and office occupancy more dynamic. As flexible working evolves, it becomes apparent that the role of workspace is also changing. So will the occupancy patterns and operation of office building. Using a mixed-method approach, this paper explores the future of offices, considering flexible working model and investigates the operational energy consumption of UK office buildings in the post-pandemic era. Previous research has shown that office buildings are one of the five largest sectors in the building stock in terms of energy consumption. The results of this study demonstrate that by embracing emerging transitions in hybrid working model and activity-based workspace environments, the energy demand in the office building sector could fall below pre-COVID-19 levels, with significant energy savings reaching up to 50% energy reduction in comparison to the pre-pandemic situation.

1. Introduction

A review into the history of offices illustrates how office design has always been led by dynamic changes in society [1]. Across the world, work-from-home (WFH) has been rising steadily for over a decade [2–4], peaking suddenly in spring 2020 due to the COVID-19 pandemic, when almost overnight, the world's offices emptied [5]. The governments' restrictions imposed internationally to fight COVID-19 advised (and in many cases, mandated) people to stay in their homes and triggered the largest ever 'experiment' of home working [6]. Online platforms and technology-enabled solutions facilitated – at least temporarily - the full transition of white-collar working activities from office-based to remote, home-based working [7]. Now as we see buildings, cities and countries reopening, it is important not to lose focus on *flattening the curve* for energy use and CO_2 emissions, as a way to tackle climate change.

Office buildings are one of the five largest building stock sectors in energy consumption, requiring 27.6GWh/year in the UK and 68% of total non-domestic electricity use [8]. The commercial and real estate sector consumes 40% of global energy annually and accounts for more than one third of carbon emissions [9]. London alone has 300 million ft^2 of office space, producing approximately 3 million tonnes of CO_2 annually [9].

Energy use in office buildings has seen a considerable rise in recent years [10] due to the expansion in office floor space and the increase in building utilisation (affecting heating and lighting demand) [10], the prolonged occupancy hours, the significant growth in information technology [11], and the extensive use of air-conditioning [12] (often operated beyond occupants' control). Although this trend is partly offset by considerable improvements in building envelope efficiency [11], evidence shows that small power and ICT equipment [13] and lighting [14] account for a significant proportion of energy end-use [15]. In many offices, especially open plan ones, lights often remain on even when the space is no longer being used [11]. Masoso et al. [16] conducted a monitoring study of five office buildings and revealed the "*shocking quantities of energy being wasted during non-occupied hours in commercial buildings*" [16,p.1], with more energy used out of hours (56%) than during working hours (44%) due to occupants leaving lighting and equipment on at the end of the day. Space cooling is also cited as a significant cause of energy use in offices [1,10,13]. Uncontrolled solar gains due to extensive glazing facades, higher internal gains due to increased use of IT equipment, and poorly controlled artificial lighting can all cause overheating and result in increased cooling

* Corresponding author at: School of Architecture, Building and Civil Engineering, Epinal Way, Loughborough University, Leicestershire LE11 3TU, UK.
E-mail address: e.mantesi@lboro.ac.uk (E. Mantesi).

https://doi.org/10.1016/j.erss.2021.102472
Received 18 June 2021; Received in revised form 11 December 2021; Accepted 17 December 2021
Available online 13 January 2022

demand in the workspace [1].

An increasing amount of research published in current literature has focused on the operational energy consumption in office buildings and more specifically on the energy-relevant interaction of occupants with buildings [17–25]. Other studies have analysed various aspects of human-building interactions, focussing primarily on the socio-psychological factors that affect energy-saving behaviours in the workplace [20,26,27]. It is now widely acknowledged that the traditional view of building engineering, which focussed solely on technical aspects of building technologies, is not adequate to predict the actual energy use in the sector [17,25]. Human behaviour significantly affects building performance and energy consumption [24].

The evolving new working practices due to digitalisation, in conjunction with anticipated changes in working model as a consequence of the pandemic, are expected to significantly affect the design and operation of offices and consequently the human-building interaction. Understanding occupancy patterns in future offices is crucial during this transient period in which the meaning of the office work is changing rapidly. COVID-19 acted as a catalyst and accelerated pre-existing trends such as the rise of remote working. Pre-COVID-19 studies have shown that the number of workstations being used in an office is usually around 50% to 60% of the notional population within a building [28,29], translating to 3.5 million tonnes of unnecessary CO_2 emissions from New York and London alone [9]. Preliminary research on the impact of remote working on energy consumption conducted after the pandemic outbreak [30] has shown that if those who primarily work in an office were able to work from home (worldwide) at least one day per week, it would save 1% of global oil consumption per year. Despite the expected rise in residential energy consumption, research shows that the overall impact of remote working on the global CO_2 emissions would be an annual decline of 24 million tonnes [30].

What is seen as "normal" in office operation is evolving and this has both technical and social dimensions that can influence the prospects for achieving energy efficiency. A significant opportunity is presented to assess solutions on how to "redefine" the office of the future to support the evolution of flexible working patterns, while simultaneously promoting more energy efficient office buildings. To achieve this, a fundamental question needs to be answered first: *How will the future workplace change in the post-pandemic era due to flexible working and how will this affect its energy performance?* The study presented in this paper *aims to provide new insights on the workplace of the future and to explore the impact of flexible working patterns on the operational energy consumption of office buildings in the post-pandemic era.*

1.1. Historical evolution of workspace

The first corporate office was the London headquarters of the British East India Company [1699–1774] [31] but it was not until the beginning of the industrial revolution that the modern office was created [32]. The invention of railways, telegraph, telephones and typewriters, moved the office away from the factory and into business premises [31,33], economic activity and manufacturing gathered in city and town centres. A number of ancillary professions "flourished on the back of heavy industry" [5]. The extended use of steel, combined with the invention of elevators, introduced the skyscrapers as a symbol of power [33], and office blocks were built reaching up, designating the gradual disconnection of workspace's relationship to the city. The introduction of air-conditioning in the 1930s and fluorescent lighting in the 1940s resulted in deep plan structures, since building design was no longer limited by natural lighting and ventilation [1,34]. The need for intense supervision and micro-management as a driver for 'productivity' led to a new type of unpartitioned, open-plan office, where rows of desks and equipment were arranged as to accommodate numerous people working efficiently in the given area [31]. Work became the frame of life and office became the fabric of work.

Two distinct types of offices developed over the years [1,31–33]: the "corridor" or "cellular" office, and the "open-plan" office. Between 1950s and 1960s, the Schnelle brothers in Germany introduced a third typology of office type, the "Burolandschaft" design or "landscape" office. The landscape office was a typology based around human interaction and human-centred design [31].

Over the last decades, the introduction of laptops, WiFi and mobile phones promoted the emerging patterns of agile and flexible working. Reflecting on the changing working practices, and as an effort to accommodate the needs of current workforce, an increasing number of organisations are adopting more flexible and adaptable office design solutions. Adaptability in architecture refers to the capacity of buildings to accommodate substantial change and it has been characterised as a very useful design concept often associated to improved environmental performance (more efficient use of space, increased longevity, improved operating performance) [35]. Flexibility is a term often correlated to adaptability and refers to the ability of a building to continuously adapt its space layout and even its structure to evolving needs [36]. A flexible workspace can therefore be defined as a "multi-functional" space, designed to accommodate the requirements and to support the different tasks that take place in the building. Activity-based workplace (ABW) design is an approach to office design that embraces the concept of space flexibility. ABW suggests replacing rows of desks with WiFi and shared spaces for informal breakouts, formal meetings and quite concentration zones [31]. The idea of ABW design was first introduced by the architect Robert Luchetti in the late 1980s, who defined a series of different locations that office workers could use for various activities. It was a human-centric and idealistic approach to office design, which later became distorted and misunderstood as a synonymous to hot-desking [37]. Nevertheless, the basic concept of ABW design involves much more than just desk-sharing. ABW environments provide office workers with a variety of indoor workspaces purposively designed to accommodate different tasks, enabling people to move frequently during the day, choosing the right place to develop their daily activities [38–40]. The principles of ABW concept are gradually shifting the core idea of office design from "amount of space" per person to the "kind of space" per person, where the aim is to promote autonomy, flexibility, efficiency, knowledge sharing and to facilitate collaboration, solidarity, and interaction among co-workers. Despite the different benefits of flexible – ABW environments, they are commonly misinterpreted as simply a cost-saving exercise that organisations employ to increase occupancy densities and reduce the associated cost of their real estate portfolio [37,40]. The combination of unassigned desks and extreme densities are found to be some of the biggest reasons why some people do not want to go to the office [41].

Contemporary offices have repeatedly been criticised in the literature as being associated with high levels of distraction, emotional exhaustion and poor employees' performance [29,42–46]. However, the recent WFH experience, imposed by COVID-19, brought to the surface the urgent need to make office buildings more habitable, humane, and safe. Office buildings are a product of their time and the people who occupy them [31]. As Duffy successfully noted in his book [32,p.216], "*the meaning of the working environment cannot be taken for granted in times of change, because the office is such a precise mirror of attitudes*". Therefore, the office building is an entity that should be easily adaptable over time, able to accommodate the businesses' and employees' changing demands. History have shown that our cities and buildings have always been influenced by disease outbreaks. The modern street grid was attributed to the introduction of sewage systems, as a way to combat cholera. And the light-flooded, clinically white tuberculosis sanatoria inspired the wipe-clean aesthetic of modern architecture [47,48]. In a similar way, COVID-19 is expected to affect how we use buildings in the post-pandemic status quo and is likely to affect how we design buildings in the future.

1.2. The impact of the COVID-19 pandemic on working culture and workforce needs

Remote working[1] has proven to be successful during the COVID-19 lockdown, and several factors were found to contribute to its success [49]. According to [50], these factors included a better work–life balance, most notably the reduction in commuting time and cost for employees, having fewer distractions to complete tasks and better collaboration that has been facilitated by the technology. There were initially two extreme ends in the spectrum of debates about the post-COVID-19 workplace speculations:

1. Back to 'normal': once immunity is achieved, the office work will go back to how it used to be.
2. 'Death' of the office: the pandemic induced the end of the office as we know it altogether.

Preliminary research however shows the future of workplace is more likely to be somewhere in between. The post-pandemic work model will comprise a combination of office-based and remote working [49–57]. Leesman [58] found that employees' experience of WFH is very much dependent on their daily activities. For employees with highly collaborative profiles, workplace provided a better experience in 55% of the cases. In contrast, those with highly individual profiles reported a better experience at home in 61% of the cases. Therefore, the choice for businesses is non-binary; a mix of traditional office spaces, home offices and semi-public spaces is most likely the future of work [57].

Workers indicated a greater autonomy and lower work-life conflict when working remotely between 2.4 and 3 days per week [49,51,55]. Anything beyond that could be considered harmful to the relationships with co-workers [49], and could have a perceived cost in long-term productivity, corporate culture, and innovation and creativity [41,53,55]. Several studies highlighted the important role of the office as a place for team building, collaboration, problem-solving and inclusive communication [51,53,54]. Despite the various problems of contemporary offices, research shows that the pandemic is not expected to put an end to the need for office environments [59,60]. People are social beings, excess in isolation and poor interactions with colleagues is likely to cause low performance [61,62]. Furthermore, certain collaborative activities have been proven more effective when the environment allows in-person interactions [63,64]. Finally, the COVID-19 WFH experiment highlighted that remote working is likely to exacerbate economic, gender and other inequalities [65]. Not everyone has the resources or is able to work from home [50]. For all the reasons mentioned above there is optimism that the office will continue to be an important aspect of everyday work life in the future. Therefore, organisations will need to determine *the right balance of remote work to advance their organisational priorities rather than one that sees a move towards an office-free world* [49,p.5].

1.3. The impact of the COVID-19 pandemic on workspace design

Following the increase of remote working, to justify its existence, the office will have to become a destination with a purpose [41]. Certain researchers have used the term social "hub" to define the new role of workspace in the post-pandemic world [52,53,59,60,66]. People argue that the need for personal office space will reduce, since most of individual work can take place at home. Simultaneously, the demand for other kinds of spaces is likely to increase. Preliminary research results show that communal spaces, which promote collaboration, innovation, meaningful interaction among members of the organisation, problem-solving and knowledge sharing, will prevail within an office building in the future [29,51–53,59,60,67]. Instead of ditching their offices all together, companies will have to adjust their real estate portfolio to offer a more "free address" environments [67], more "we" space and less "me" space [64], as a way to support a more mobile workforce. Flexibility of space is at the forefront of future real estate portfolio for most organisations [59,60]. Flexible office arrangements will be key in future real estate strategies [52,53]. In a recent survey conducted by CBRE [66], 82% of building occupiers stated that they desire flexible office space options when they select buildings.

The emerging hybrid working model is also expected to change how much space organisations need, where it will be located and how it will be configured. The future workplace may not be sized to house everyone in case all the employees show up [9]. Instead, the use of intelligent technology could be employed to schedule attendance, to track space utilisation tied to occupancy and to allow transparency for accessing and visualising office usage [9,52,59]. Furthermore, the decades-long trend of densification[2] is now likely to be reversed [52,57]. Social distance requirements and flexible working practices that allow for distancing (i.e. agile working, temporal and spatial flexibility) will likely act as stopper to this trend.

The office of the future will have to become more human-centric than before, synthesising the best of what WFH has to offer and what working from the office should be [51,54,67]. There is a growing need for connectivity, both physically and digitally. To accommodate hybrid working patterns and remote collaboration, private spaces and technologies should be offered (alongside social zones) to support meetings with colleagues who are working remotely [51]. The pandemic has influenced people's expectations around the meaning of workplace. The lessons learned from COVID-19 could allow us to re-evaluate norms and correct past mistakes, as a way to promote a more sustainable, low carbon and healthy office of the future.

2. Methodology

To create offices that will be able to capture people's changing needs, while simultaneously support carbon reduction targets, we need to understand the fundamental working culture shifts that took place over the last months since the beginning of the pandemic. To achieve this, the study presented in this paper adopted a mixed-method approach to the analysis and involved two main phases.

2.1. Phase 1: explorative study on emerging working patterns

Phase one of this research adopted an exploratory stance to research, with the aim to examine a topic which is relatively new, dynamic and still unfolding [68–70]: the future of office work and office space in the post-pandemic era. Since very little research has been done in this field, this preliminary step aimed to provide some initial insights into the nature of the issue [71] and to assist the development of research hypotheses [72] to be tested in the second phase of the analysis (i.e. energy performance evaluation of future offices).

For the data collection, this preliminary exploratory study started with an extensive web and literature search to identify and review any secondary data available. The topic keywords informing the search were "Future of work", "Future office", "Remote working", "Work-from-home" and "Post-pandemic Office". The relevant literature is mainly dominated by industry reports and online newspaper articles, since it is a rather new topic and very few academic articles were identified. The study continued with formal qualitative research through semi-structured online interviews with 12 key professionals from the office building sector and the corporate real estate industry. New empirical

[1] The term "remote working" covers all forms of teleworking. It is used to signify paid work done outside of an office, whether at home, or elsewhere. The term "work-from-home" is used to signify paid work solely done at home.

[2] Densification is the term used to define the trend of business to provide less space per office-using employee.

data were collected on the future of work from exceptional stakeholder groups [72]. The interviewees represented two types of groups: “elites”, in other words senior directors and energy/ sustainability managers, and experts in the topic area, i.e. consultants, researchers and academics in the area of workplace design. The sample of participants was purposive [68], selected to represent people who are behind decision-making in terms of workspace quality and energy performance in office buildings. Data collection seized after 12 interviews, once saturation was achieved and since further new insights were no longer being generated. The aim of the interviews was to provide empirical evidence of participants' perception, experiences and meanings of the studied phenomenon [73,74], covering five main aspects: digitalisation, working patterns, office design, building operation, and organisational outcomes. In that respect and in the nature of social science, the study adopted an inductive approach to qualitative research, aiming to suit the intended objectives [72]. Consequently, its primary contribution was empirical in improving understanding of a new topic and not generating widely generalisable theories.

All interviews were recorded, transcribed and thematically analysed to allow for great theoretical flexibility [75,76]. Given the relatively small size of research sample, the results were analysed manually. Starting the data analysis with some pre-established codes, further newly generated codes were added through the iterative reading of transcripts. A coding framework of 20 top-level codes and 21 sub-codes was developed based on both the initial research questions and the collected data. Following the organisation of initial codes to emerging themes, the interpretation was carried out in order to understand the significance of the patterns and their meaning as well as implications by linking the findings of this research to previous literature and other studies' outcomes [77]. A set of five themes eventually emerged, helping to define a list of possible future scenarios associated to office design and operation. These speculative scenarios were subsequently used to inform the different test cases of the parametric computational analysis used to evaluate the energy footprint of future offices, and which is further described in the next sub-section.

2.2. Phase 2: energy performance evaluation of future offices

The operational energy performance of future offices was evaluated with computational analysis, using quantitative building energy modelling (i.e. dynamic simulation). Dynamic simulation of buildings, also known as Building Performance Simulation (BPS), is generally accepted as a powerful tool for analysing the energy performance in buildings [78–80]. It is often associated with the term *virtual laboratory* used to conduct *virtual experiments* [81]. It is commonly used to assess the performance of hypothetical, alternative design and operation scenarios and to find quantifiable answers to “what-if” design questions [81–83].

2.2.1. Office building model

A representative office building was adopted in this analysis. The office layout used in the building models was based on the example provided by the British Council for Offices (BCO) for a typical office floor plan with a conventional occupancy density of $10m^2$/person, as shown in Fig. 1 [84].

The initial ratio between individual and collaborative spaces was assumed 70%/30% (respectively), based on the recommendations of the BCO [84]. The exploratory survey indicated that one of the key emerging themes in future office design is the use of office space for mainly collaborative activities. This has also been confirmed by other recent studies published in literature [52,60,66]. Therefore, the ratio between individual and collaborative spaces in the post-pandemic long-term adaptation measures (TC3- TC5, as explained in Section 2.2.2) was assumed to be reversed, with roughly around 40% of space dedicated to individual desks and 60% of space dedicated to more collaborative zones. The utilisation factor is defined as the percentage of workstations

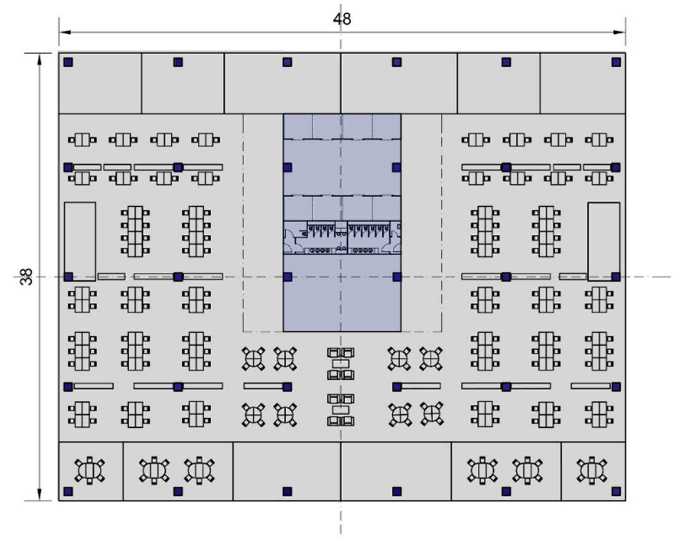

Fig. 1. Typical office floor plan (Adapted from BCO Guide to Specification [84]).

being used at any given time in respect to the notional population of the office [28,85]. According to the BCO guide to specification for office design [84] assuming a utilisation factor of 85% is a reasonable upper limit for the pre-COVID-19 situation (i.e. because it was rare to have an office building being 100% occupied at all times). Following the recent WFH experiment, research has shown that assuming an average 1.5 to 2 days when employees will work from home in the future hybrid working model translates to a utilisation factor of maximum 60% at any given time [52]. All the occupancy profiles with regard to working hours, operation of office equipment and lighting, heating and cooling schedules were adopted according to the National Calculation Methodology[3] (NCM) [86]. Furthermore, the construction method, materials and U-values used in the building fabric were also defined according to the input values described in the NCM [86]. Finally, the building was assumed to be mechanically ventilated, with ventilation rates at 12 l/s/person in the pre-COVID-19 BaseCase, as suggested by the BCO [84], which were later increased according to the latest guidance to 6 ACH in all the post-COVID scenarios (TC2-TC5) [87].

2.2.2. Deterministic building performance simulation

A list of different Test Cases (TC) was developed (as described in Table 1 and illustrated in Fig. 2). The parameters tested in each of the TCs modelled in the deterministic simulation derived from the findings of the exploratory study, in Phase 1 of the analysis. Starting with a BaseCase representing the Pre-COVID-19 situation, TC1 assessed the impact of social distancing and the provision of more space per occupant. TC2 investigated the effect of increased ventilation rates, TC3 looked into the aspect of ABW design with a shift in collaborative vs individual zones split. TC4 investigated the result of reduced office space, due to the adoption of ABW principles (i.e. office is primarily intended for collaborative activities, hence less space is needed overall to accommodate the same number of people). Finally, TC5 analysed the impact of reduced utilisation factor due to the prevalence of hybrid working.

A parametric analysis was conducted using EnergyPlus v.9.5 simulation tools [88]. Parametric analysis is a powerful technique that a modeler can use to evaluate numerous potential designs and to establish

[3] NCM is a procedure for demonstrating compliance with Building Regulations. The NCM provides standard sets of data for different activity areas and includes common databases of construction and service elements [87].

Table 1
The different test cases (TCs) used in the parametric analysis.

TC	Investigated Parameter	NIA (m^2)	Workstations	Utilisation Factor	Occupancy Density	Ventilation Rate	Individual/ Collaborative Split
BC	Pre-COVID performance	8890	575	85%	10(m^2/prs)	12(l/s/prs)	70%/30%
TC1	Physical distancing / lower densities	8890	360	85%	16(m^2/prs)	12(l/s/prs)	70%/30%
TC2	Increased ventilation rates	8890	360	85%	16(m^2/prs)	6ACH (plus two hours in operation prior occupancy)	70%/30%
TC3	More collaborative zones, less individual desks (ABW design)	8890	918	85%	16m^2/prs (individual desks) 10m^2/ prs (collaborative zones)	6ACH	40%/60%
TC4	Reduced NIA according to the needs of the organisation	5570	575	85%	16m^2/prs (individual desks) 10m^2/ prs (collaborative zones)	6ACH	40%/60%
TC5	Impact of hybrid working model	5570	575	60%	16m^2/prs (individual desks) 10m^2/ prs (collaborative zones)	6ACH	40%/60%

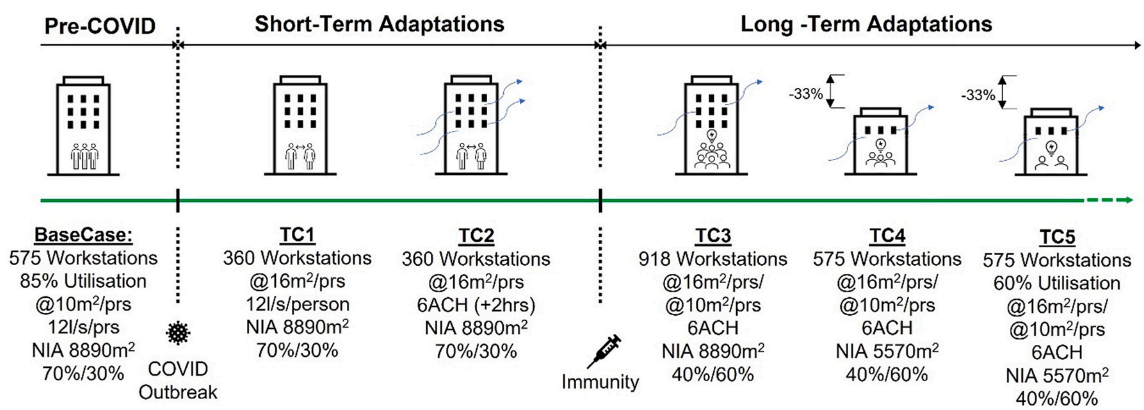

Fig. 2. Test cases used in the parametric analysis. Starting from the pre-COVID-19 situation (BaseCase), the figure illustrates the short-term adaptation measures (TC1-TC2), as well as the long-term design changes resulted from the adoption of activity-based workspace design (TC3- TC5) - For further details can be found in Table 1.

parameter dependencies of the solutions [89,90]. It evaluates the impact of different input parameters on the examined output (in this case the energy consumption of the building being analysed). The first step of the parametric analysis was to assess the energy performance of the building in the pre-COVID-19 situation (i.e. BaseCase). This was performed by looking at the annual energy demand breakdown for several important regulated energy uses: heating, cooling, lighting, fans and pumps, office equipment and computers. This initial step served as a benchmark and a reference point to compare the different future scenarios against. The next step was then to assess the impact of some immediate short-term adaptation measures (TC1 and TC2) on the energy consumption of the office building. Finally, the analysis focused on the long-term adaptations and future changes in office building design and operation, based on the findings of the exploratory study in phase one of the research (TC3 – TC5).

2.2.3. *Probabilistic building performance simulation*

It is generally accepted that we are currently experiencing a rather transient period with regard to the global economic trajectory and the future of work is very unpredictable [57]. Consequently, there is also a high level of uncertainty on some of the assumptions made in the future scenarios of workplace design and office building operation. To account for some of these uncertainties, probabilistic simulation was performed on the future office building model, using Monte Carlo-based global uncertainty and sensitivity analysis (UA/SA) [91,92]. Uncertainty analysis (UA) is conducted to show the variability in the output of a model that can be attributed to variability of the input (uncertain input parameters) [91]. Sensitivity analysis (SA) determines the contribution of individual input variables to the uncertainty in performance predictions.

Monte Carlo Analysis (MCA) requires that the model inputs are described by a probability distribution. All parameters are varied at the same time, hence all possible interactions between the variables are fully accounted for. Latin Hypercube Sampling (LHS) method was employed as a sampling method to generate sampled variables desirable for the UA and SA [91,93,94] using SimLab 2.2.1 [95]. Different techniques are available for the SA [91]. This paper uses the standardised rank regression coefficient (SRCC) to demonstrate the results. The underlying principle is: the higher the coefficient, the more sensitive one variable is.

A total of 300 simulations were performed in JEPlus v.2.1 [96]. The process was undertaken in three main steps:

1. Pre-processing
2. Simulation
3. Post-processing

The tools and methods used for each of these steps are shown in Fig. 3 below.

3. Results

3.1. *Key themes*

The following sub-sections present the results of the exploratory

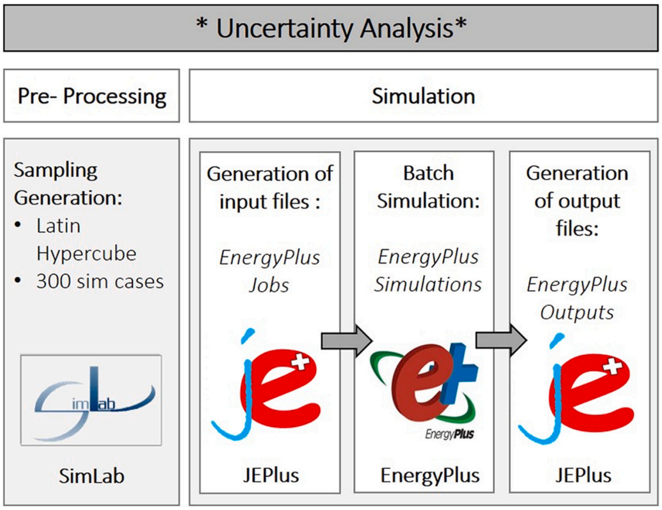

Fig. 3. Three steps within the uncertainty and sensitivity analyses.

study on the future of the "post-COVID-19" offices. To aid the analysis, the participants of the interviews were asked to provide their perspectives on five important issues, as these derived from the literature review:

- The implications of digitisation on emerging working patterns
- The impact of the pandemic on the future of work
- Potential changes on the design of future offices due to changes in working model
- Potential changes on the operation of future offices due to changes in working model
- Challenges and opportunities for organisational outcomes in the post-pandemic era

The analysis focused on office-based work with the aim to define possible future scenarios regarding the post-pandemic workspace design and operation. It is acknowledged, however, that the workplace is not only dedicated to desk-based jobs. There are also cleaners, caterers, security staff and other professions in the broader sense, which are associated with the daily operation of office buildings. However, for the purposes of this study the results were strictly analysed from the scope of white-collar/ office-based workers.

This paper is predominantly intended to explore expected changes in the energy performance of future offices due to flexible occupancy patterns focussing on their operational energy consumption. Therefore, several important elements that are not part of the architecture and are not part of the quantifiable performance of the building were intentionally left outside of the analysis. Aspects such as employees' performance and productivity, creativity, innovation and knowledge-exchange opportunities, although highly affected by the quality of office environment and while often discussed during the interviews, are outside the scope of this study and are not discussed in this paper.

From the results of the qualitative interviews, five prominent themes were identified and are further discussed below.

3.1.1. "De-densification" of contemporary offices is crucial

An important issue that was discussed repeatedly during the interviews was the problem of high densities in contemporary offices. This trend has been evident for several years now [28] and is mainly seen as a result of high rental costs.

> *"… if you look at the office design in the last decade, it's been what I'll call a race to the bottom… how do you squeeze more people into less space by going into open plan, one-size fits all."* (Interviewee 11, Head of occupier business performance at a multinational real estate company)

Increasing office densities have resulted in environments that are not well-accepted by their occupants, having numerous issues that compromised the indoor environmental quality (IEQ), such as problems with acoustic performance, reduced thermal comfort for the users, among others.

> *"I think that contemporary offices have become over-congested, and I think this is one of the things that has driven people to work from home, even before the pandemic started… And there is a degree of inhumanity about it, that people are working in much to close quarters with each other."* (Interviewee 2, Head of environment and sustainability at a big charity organisation)

So, among the various changes in workspace design that are anticipated because of COVID-19, the de-densification of offices is characterised as a crucial one.

3.1.2. The changing role of office

The pandemic has affected the corporate culture around remote working. Increased levels of home-based working are now much more acceptable in comparison to the recent past (before COVID-19). This change in attitudes is also expected to affect the role that the office space will have in the future. Consequently, there is a consensus that office-based work will involve primarily collaborative activities and the office space will be mainly used as an opportunity to socialise and interact with colleagues and clients, whereas focused work is mainly expected to take place at home.

> *"… There is going to be a need, or let's say an appetite from employees to want to go into an environment where they can see each other and engage with each other. Those serendipitous situations, 'water-cooler moments' as they like to say."* (Interviewee 9, Development director at a workplace consultancy company)

The role of the office is changing. However, adopting this binary perspective that 'office is for collaboration, home is for focused work' is potentially an oversimplistic view. In reality, most employees' daily routine involves a combination of individual and collaborative activities. Therefore, most employees will require a mixture of collaborative spaces and spaces dedicated to focused work.

> *"When you think about your typical working day, you don't normally spend 8 hours to having meetings and then spend 8 hours writing up your notes. It is a combination … The office is going to be important still, but it cannot just be for collaboration. It is going to have to be a balance and a mixture of different types of environment, including areas for individual focused work."* (Interviewee 9, Development director at a workplace consultancy company)

Furthermore, there are circumstances in which people are not able to effectively work and concentrate from home. And this is an important consideration and a potential pitfall of office design in the post-pandemic era. Therefore, it is rather important to ensure that a certain percentage of workspace is allocated to individual focused work. However, it is safe to assume that going forward the ratio between collaborative and focused-work zones is expected to change. Allocated individual desks are expected to decrease and shared space is likely to be dominant in the post-pandemic offices.

> *"The office interior will need to shift … to 30% being individual desks … 50% being collaborative spaces and about 20% being support spaces to bring together people for knowledge-sharing, for health and well-being, for community building activities."* (Interviewee 11, Head of occupier business performance at a multinational real estate company)

3.1.3. Workspace design for a greater diversity of spaces

The anticipated changes in the way people work are also expected to affect the needs for office design. And since the office is gradually turning into a merely social hub, mainly intended for collaboration and human interaction, a greater diversity of spaces within the office is going to be needed. ABW environments have seen a rise over the last years. This type of workspace design is thoroughly reviewed in recent literature, primarily in respect to their impact on productivity, employees' satisfaction and Person-Environment fit [38–40,97]. The results of this exploratory survey suggest that the use of ABW environments will increase in the post-pandemic future. This is mainly attributed to the suitability of such environment in supporting a more dynamic and flexible way of working, as the one anticipated in the post-pandemic era. Several participants, when questioned about their "ideal" future office, answered that diversity of spaces is among the most important attributes.

> *"When we measure workplaces, the ones that come out on top are those that have a lot of variety for their stuff, so diversity of spaces is key. And that is not just cookie-cutter like. It is about making sure that they are relevant to the population that is using that space."* (Interviewee 9, Development director at a workplace consultancy company)

3.1.4. A blended/hybrid working model

There is a general consent that flexible and agile working styles were already happening over recent years, a finding also evident in previous studies published before COVID-19 [2,4,98]. The BCO [28,p.4] defined agile working *"as a range of workstyles that are technology-enabled, not dependent on a single place of work, characterised by a high level of choice and mobility and usually involving desk-sharing"*. Digitalisation has been commonly discussed as a significant enabler to flexible working patterns, which has also been identified as a significant factor affecting the design of office building over the last years.

> *"And office design … has definitely changed over the years, for example, with increasing aspects of activity-based working whereby you don't allocate desks but give people choice of different settings and they would go in and they would definitely need laptops or digital devices to kind of choose various work points throughout the day, taking their laptop with them"*. (Interviewee 6, Senior academic at a higher education institution)

It is widely accepted that COVID-19 acted as a catalyst to the adoption of home-based and remote working, and it has drastically affected corporate culture and attitudes around agile working. Even those organisations that were more sceptical about it, for security or other management-related issues, were forced to accept the imposed situation of having their workforce work remotely during the lockdown. In line with other studies conducted on employees' satisfaction around home-working during COVID-19 [50,52,54,55,66], the interviews indicated a positive feeling towards and a likely increase in the levels of flexible working:

> *"…90% of people felt trusted by their managers to work remotely. And … baby boomers, who tend to be managers, actually had the best WFH experience during the pandemic. … The ability to trust people to do work remotely means that organizations are much more prepared to embrace flexible working patterns."* (Interviewee 11, Head of occupier business performance at a multinational real estate company)

However, the study confirmed that the office environment will continue to be an important asset for organisations for reasons related to social interaction, collaboration and team building. Therefore, a blended/hybrid approach between remote and office-based working is expected to prevail in the post-pandemic corporate world.

> *"… when you look at the surveys … people are going to want to come in the office maybe 2-3 days a week. That's going to be the norm."* (Interviewee 7, Workplace strategist and change manager at a workplace consultancy company)

This anticipated hybrid approach between remote and office-based working is also expected to affect the utilisation factors in offices, in other words, the percentage of workstations being used at any given time in respect to the notional population of the office [28]. The utilisation factors in offices are expected to decrease. Some organisations see that as an opportunity to reduce their real estate footprint. Taking advantage of this new approach to working model can effectively reduce the organisations' need for office space. And a potential real estate portfolio downsize could have significant economic and environmental benefits (i.e., reduced use of resources). However, it is important to ensure that any office space reduction does not compromise the true spirit of agile working. There seems to be a common misinterpretation that rotating people in the office, where certain members of workforce coming in the office certain days, while others coming on other days, is considered flexible working. But in fact, this is not flexible, it is a kind of planned use of the space.

> *"… There should be a flexible approach when people come in and go. The whole idea around agile working is that people would come in the office when they need to; work from home when they want to do focused work, come in the office when they want to interact."* (Interviewee 7, Workplace strategist and change manager at a workplace consultancy company)

3.1.5. Dynamic and flexible office operation

The prevailing hybrid model of work implies that the occupancy of future offices will become much more dynamic in the post-pandemic era. As a consequence, flexibility in the design of the space is important. It is imperative to ensure that our buildings will be able to adjust to future changes imposed by numerous global issues, including safety, climate change resilience, digital transformation, among others. In addition, flexibility in the use of building services[4] was also discussed as a key consideration for office building construction going forward. Several participants discussed the importance of associating buildings' operation to occupancy patterns.

> *"You need flexibility, flexibility in services, HVAC, lighting; either zone-controlled or small areas controlled… Some form of control that is occupancy-based rather than heat/cool the whole building whether it's one, two or ten people in it."* (Interviewee 4, Energy manager at a higher education institution)

Table 2 summarises the key findings of the exploratory study and explains how the key themes relate to the different factors and test cases investigated in the computational analysis. Furthermore, a short definition is given for each of the different investigated factors to clarify how they are used in the context of this paper.

3.2. Parametric analysis on future office scenarios

The findings of the exploratory study were issued to inform the different Test Cases (TCs) used in the parametric analysis. The results of the parametric analysis are illustrated in Fig. 4. The graph shows the annual energy consumption breakdown according to the different energy uses for each of the analysed test cases. Looking at the pre-COVID situation (i.e. BC in Fig. 4) we can see that for the specific building, the total annual energy consumption of the building was estimated to be

[4] The term building services is used to define the systems installed in the building for lighting, space conditioning (HVAC), escalators and lifts, and domestic hot water (DHW).

Table 2
Summary of key themes, explanation of how they relate to different factors and test cases investigated in computational analysis and definition of key factors investigated in the analysis.

Key Themes	Factor Investigated in Computational Analysis	Test Case Scenario
3.1.1 "De-densification" of contemporary offices is crucial *The occupancy densities in office building need to be reduced and more generous space has to be provided to the occupants.*	Occupancy Densities: *The amount of space allocated per working station*	TC1
3.1.2 The changing role of office Office *The role of the office is changing. Office-based work will involve primarily collaborative activities and the office space will be mainly used as an opportunity to socialise and interact with colleagues and clients. The split between individual/ collaborative zones is expected to change, with the latter occupying most of office space.*	Activity-Based Workspace design: *Working environments that involve a variety of indoor workspaces purposively designed to accommodate different tasks.* Individual/ Collaborative zones split: *The percentage of space dedicated to individual, focused* work versus *the percentage of space dedicate to collaborative work.*	TC3
3.1.3 Workspace design for a greater diversity of spaces *The office is gradually turning into a merely social hub, mainly intended for collaboration and human interaction. Therefore, a greater diversity of spaces within the office is going to be needed. The use of ABW environments will increase in the post-pandemic future offices.*		
3.1.4 A blended/ hybrid working model *The emerging hybrid approach between remote and office-based working is expected to affect the utilisation factors in offices. The percentage of workstations being used at any given time is expected to decrease.*	Utilisation Factor: *The number of workstations being used at a time divided by the maximum number of workstation available in the office.*	TC5
3.1.5 Dynamic and flexible office operation *Hybrid working will result in more dynamic office occupancy. Flexibility in the use of space and the operation of building services is a key consideration for future office buildings.*	Flexible occupancy: *Variable utilisation factors and dynamic occupancy densities.* Flexibility in building services: *Occupancy-based building services operation.*	Probabilistic Analysis

around 1000MWh, with heating and equipment energy use dominating the energy demand, followed closely by lighting and cooling. When physical distancing (desk spacing out) was introduced in the space as an immediate response to COVID-19 (i.e. TC1 in Fig. 4), there was a negligible decrease in energy use, and the demand breakdown was identical to the pre-COVID situation. In TC2, when the ventilation rates were increased to 6ACH and the ventilation schedule was prolonged to start at least 2 h prior to occupancy (according to the latest safety guidance - [99]), the total energy consumption has more than doubled (above 2000MWh), with the annual heating demand becoming more than 3 times higher in comparison to the previous two TCs. The annual cooling demand was, as expected, decreased and the energy attributed to fans and pumps of the ventilation system was significantly increased due to the enhanced operation of the system.

When looking at the long-term adaptation measures, and more specifically the introduction of ABW design (i.e. more collaborative zones and less area dedicated to individual desks, TC3), we can see that the annual heating demand was significantly decreased in comparison to TC2. This is mainly attributed to the change in ventilation schedule, which after immunity has been achieved is expected to go back to the pre-COVID regime (system in operation only when spaces are occupied). The ventilation rates however remained high and equal to 6ACH, assuming that the provision of fresh air will continue to be an important consideration even after this specific virus is no longer a threat. TC4 showcases the impact of reducing the Net Internal Area (NIA) to reflect on the needs of the specific organisation (more collaborative zones in ABW design allows for more people to be hosted in a smaller building, in comparison to having mainly individual desk areas). As illustrated in the graph, the reduction of the NIA by 33% was able to host the same number of employees while simultaneously decreasing the total annual energy consumption to slightly above the pre-COVID-19 situation (i.e. slightly above 1000MWh per annum). TC5 illustrates the expected impact of hybrid working and reduced utilisation factors (i.e. around 60% of notional population in the space on a daily basis). In this TC the heating demand was still higher in comparison to the pre-COVID-19 situation (BC), because the provision of fresh air was still high. However, the total energy consumption of the building was below the pre-COVID-19 levels (i.e. 874MWh), while a better IEQ was provided for the occupants (better occupancy densities, more diverse spaces, better indoor air quality (IAQ)) (Table 3).

3.3. Uncertainty and sensitivity analysis on energy consumption of future offices

Assuming that the space utilisation factor is going to be 60% each and every day of the week is a gross simplification. Moreover, no one really knows what will happen with the ventilation rates in the post-pandemic office. Will the high provision of fresh air continue to be high, or are we going back to the situation that existed pre-COVID-19? These two aspects represent two highly uncertain input variables for the simulation predictions. Furthermore, since the occupancy of social and collaborative areas is effectively very dynamic (there are no structured ways of sitting) it is important to investigate the occupancy densities in such zones using a probabilistic range rather than a deterministic value. Finally, since the results of the deterministic simulation (parametric analysis) indicated that the heating demand is the most important parameter in the annual energy consumption of the future office, the analysis investigates the impact of relaxing heating and cooling setpoints in the secondary (supportive) zones of the building.

For all the reasons stated above, the computational analysis in this paper included the use of probabilistic simulation (i.e uncertainty analysis - UA) to assess the variability in the simulation predictions resulted from unknown input variables in the simulation models. Moreover, sensitivity analysis (SA) was performed to evaluate which of the uncertain input variables have the highest impact on the investigated output. All the parameters included in the probabilistic simulation are summarised in Table 4 below, as well as their distribution range.

The results of the UA show that, despite the many unknowns, the total annual energy consumption of the building in the post-COVID-19 situation (i.e. TC5 in parametric analysis) is always calculated to be below the pre-COVID-19 standards, despite the provision of increased fresh air for the occupants. The estimated future energy consumption ranges between 543MWh and 950MWh (Fig. 5). These findings indicate that if the future office is indeed transformed to a social hub providing more collaborative areas and less space for individual focused work, the hybrid model of work continues to exist and the use of building services is flexibly tied to occupancy patterns, then the energy consumption of the building is expected to decrease significantly in comparison to current situation (i.e. around 2200MWh) and it is expected to fall below the

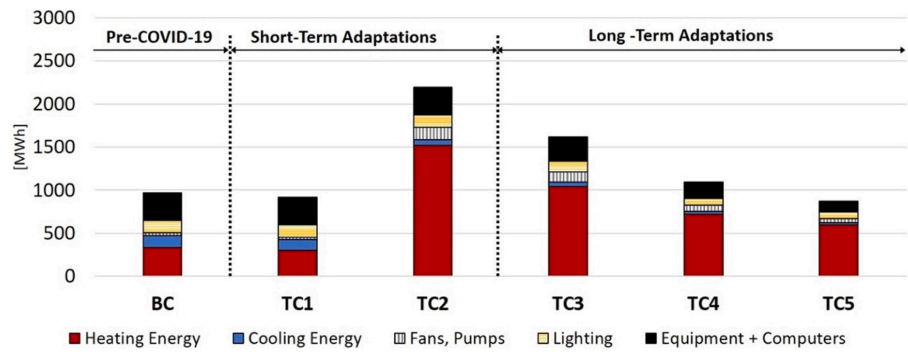

Fig. 4. Annual energy consumption of the building according to the different test cases. The bars illustrate the energy demand breakdown according to the energy uses: heating energy, cooling energy, fans and pumps of ventilation system, lighting and electrical equipment & computers.

Table 3
Annual energy demand of each test case according to the different energy uses, as well as total annual energy consumption per test case.

Actual Energy Demand	BC	TC1	TC2	TC3	TC4	TC5
Heating Energy	336	305	1523	1041	720	596
Cooling Energy	136	124	61	56	36	24
Fans, Pumps	31	24	145	114	70	50
Lighting	146	146	146	125	77	77
Equipment + Computers	320	320	320	285	194	126
Total Energy Consumption (MWh)	969	919	2195	1621	1097	874

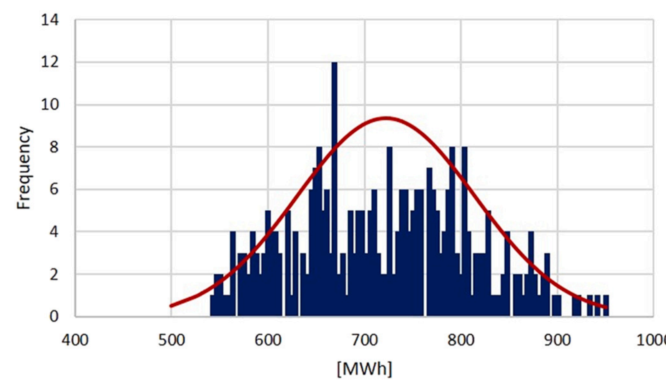

Fig. 6. Frequency distribution of annual energy consumption when considering uncertainty in all parameters investigated.

Table 4
Uncertain parameters investigated in the UA and SA, as well as their distribution ranges.

Ventilation Rates	U[3ach, 6ach]
Utilisation Factor	U[40% - 85%]
Occupancy Density Social Area	U [8m^2/prs – 12m^2/prs]
Heating Setpoint (in secondary zones)	U [18 °C – 20 °C]
Cooling Setpoint (in secondary zones)	U [25 °C – 27 °C]

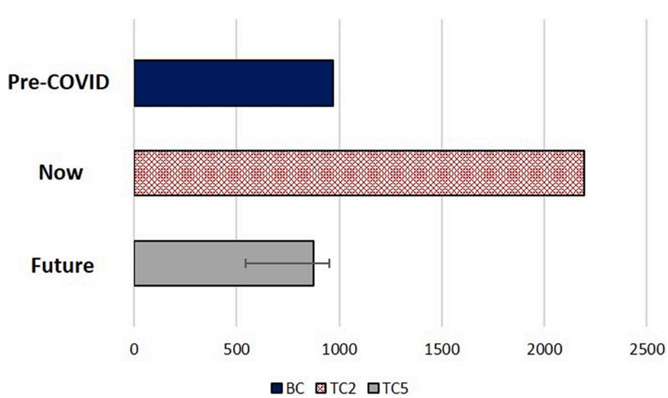

Fig. 5. Total annual energy consumption: comparison of building's energy demand in the pre-COVID situation, the current situation informed by latest safety guidelines and possible future performance of the "social-hub" office, accounting for uncertainty in future scenario predictions (error bar in the graph).

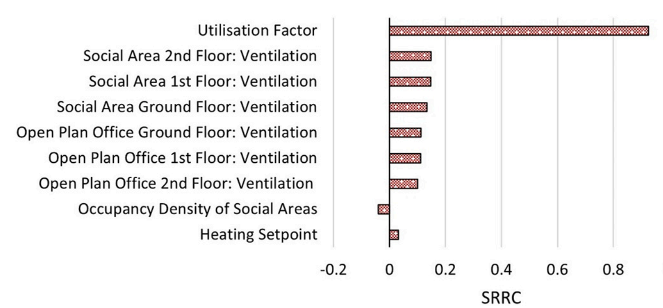

Fig. 7. Sensitivity plot showing the 9 most sensitive parameters based on annual energy consumption when considering uncertainty in all parameters.

levels that existed before the pandemic. Fig. 6 illustrates the frequency distribution of the annual energy consumption for the future office scenario In most cases the histogram shows energy demand fluctuations between 650MWh and 800MWh per year with a clear peak at 670MWh.

Fig. 7 shows the sensitivity ranking of the different uncertain parameters based on the SRCC. The higher the SRCC the higher the impact of this variable on the investigated simulation output (i.e. in this case annual energy consumption). A positive sign in the SRCC implies that when the value of the variable increases, so does the energy consumption of the building (positive effect). In contrast, a negative sign in the SRCC indicates a negative effect of the variable to the simulation output. The plot shows that the most significant parameter affecting the annual energy consumption of the office building is the utilisation factor, in other words how many people of the notional population of the building are indeed in the space. The higher the utilisation factor the more the energy consumption. This is somehow expected, because more people will require more fresh air (hence more heating demand), more energy is used in lighting, equipment and so on and so forth. This is of course based on the assumption that the building services (i.e. lighting, ventilation, etc.) are operated in accordance with occupancy levels.

The second most important parameter affecting the variability of the simulation output is the ventilation rate of the social areas on each floor. Furthermore, the ventilation rate of the focused-work zones is also considered an important parameter affecting the energy demand of the building. Increased ventilation rates result in increased energy consumption. The occupancy density of the social areas seems to have a negative (but negligible) effect on the energy consumption. In other words, when the occupancy densities increase, the energy consumption of the building decreases. Finally, the heating setpoint of the secondary zones also has a negligible effect on the energy demand (i.e. when the heating setpoints are higher, then the energy demand increases – as expected).

4. Discussion

Office buildings are considered one of the five largest sectors in the UK building stock in terms of energy consumption [8]. The requirements of the current workforce for office space have been changing massively since COVID-19 started, due to the increase of flexible and agile working. Therefore, a significant opportunity has been presented to take advantage of current transitions in working culture to redefine our needs for office environments, and to simultaneously incorporate energy reduction targets and climate change agenda in future office design and operation.

The aim of this paper was therefore to explore the impact of flexible working patterns on the operational energy consumption of office buildings in the post-pandemic era. Flexible working can be divided into three areas – flexible space, flexible location, and flexible time. Flexible location implies people's ability to choose where they work. And since WFH has recently become much more acceptable, the occupancy profiles in the workspace are also expected to become much more dynamic, with people coming and going, resulting in decreased utilisation factors in the office during a typical working day. In the future, after the pandemic has ended, people are expecting and hoping to be able to work more often from home, where some focused-work activities are better supported. This finding is discussed in published literature [52,53,56] and is also evident in the findings of our survey. Consequently, the office environment is expected to turn into a place mainly dedicated to social interaction. People are more likely to go to the office, when they wish to collaborate, interact, and socialise with colleagues and clients. Expectedly, some people will still prefer to do focused work in their office as well. Therefore, the future workspace is expected to include some zones allocated to desk-based, individual activities.

A more dynamic occupancy is found to be better supported by flexible office environments. Flexible office space is much more than merely an open-plan layout. A flexible office provides a greater diversity of spaces, where people are able to move freely during their working day, choosing the right setting to complete their daily activities. As a result, there are ongoing discussions in current literature that ABW design is expected to prevail in the post-pandemic offices [51,58]. This finding was also confirmed by the exploratory study conducted as part of this research. The distribution of workspace in more collaborative zones and less space dedicated to focused work will also affect the occupancy densities at the same time. The trend of intense office densification, which was evident over the last years [28], is expected to stop. Preliminary findings on the needs of current workforce from the post-COVID-19 offices show that people will desire to have additional personal space in the office [49,52,57]. Furthermore, increased physical distancing is most likely to continue to be a requirement even after immunity to COVID-19 will be achieved.

Time flexibility is also an important consideration in the future offices. The assumptions, commonly used in the past, of a 9 to 5 working day, whereby most people would sit on their desk doing their job, currently appears obsolete. Working hours in a typical working day are becoming more variable. According to the different types of working flexibility as described by the UK Government, flexitime is defined as "*the ability of employees to choose when to start and end work (within agreed limits) but works certain 'core hours'*" [100]. This effectively translates to extended occupancy hours for office buildings. This practice might come in conflict with the traditional use of energy management systems that require pre-programming of daily temperature setpoints (allowing for night setbacks) [19]. In other words, if the space is occupied outside of typical working hours, using a setback temperature would compromise the thermal comfort of the occupants.

An important lesson learned from the pandemic is that the future is highly unpredictable. As a consequence, future resilience and planning for uncertainty are now at the forefront of future real estate portfolio for most organisations [59,60,66]. Flexibility in the use of space, but also in the building services emerged as a key point of discussion throughout the qualitative interviews conducted in this research, a finding which was also highlighted by the energy simulation analysis presented in this paper.

Deterministic simulation was used to evaluate the estimated energy consumption for a list of different future office scenarios. The results pointed out that although currently the energy consumption of offices is somewhat increased in comparison to pre-COVID-19 situation, due to the higher ventilation rates, the adoption of a more collaborative workspace design, following the principles of ABW, can effectively reduce the energy demand of the building. This finding is also confirmed by previous research [101]. The transformation of the office into a social 'hub', as commonly mentioned in literature [52,53,60], can also reduce the needs of organisations for workspace. A reduction in the real estate footprint is possible since less office space will be needed because some of the individual activities may now take place at home. Our energy simulations showed that decreased utilisation factors (due to hybrid working) can further reduce the energy consumption of ABW offices even below the pre-COVID-19 standards.

Another significant finding of our computational analysis is the importance of incorporating a level of flexibility in the operation of building services. More specifically, if the use of building systems is tied to occupancy, then even further energy savings are possible. The results of the UA showed that, if the space is conditioned only when occupied, based on occupancy levels the energy consumption of the future office can be almost half of what it used to be in the pre-COVID-19 office. The results of the SA confirmed that the most significant parameter affecting the energy demand of future offices is the utilisation factor, or in other words the occupancy levels on a typical working day. If the utilisation of the space is high (and the use of building systems is adjusted to occupancy levels), then more energy will be required to operate the building.

Reducing energy use in the office building sector makes sense from a business perspective because it saves money, it enhances corporate reputation [102–104] and reduces the impact on climate change. Companies in the UK (and globally) are gradually becoming more energy conscious [103,105] and the analysis presented in this paper supports this effort by assessing some key energy saving considerations for workspace design and office operation going forward. The results of both the deterministic and probabilistic simulation demonstrated that the office of the future that adopts the principles of ABW design and is operated following the model of hybrid work will require less energy that the pre-COVID-19 equivalent, while simultaneously providing a better IEQ with a higher provision of fresh air for safety reasons and more diversity of spaces, thus making the work environment more attractive to the users with improved and more humane occupancy densities. Buildings for office space are a significant expense for businesses, yet, if used efficiently, also a resource that can be optimised to deliver real benefits in employee satisfaction, resulting in increased performance and well-being. Energy efficient solutions in offices, however, are sometimes perceived as a potential threat to perceived comfort, well-being, and performance of office users [106]. Productivity is a difficult concept to measure empirically, especially with regard to workers' output. To overcome this issue, researchers often measure workers' *perception* of productivity, and how it relates to their working environment. According to [106], staff productivity and output can be improved by providing a more comfortable working environment. Therefore, improving energy efficiency not only can save money for the business, but it can also improve working conditions which can potentially increase staff productivity.

5. Research limitations

There are several constraints and limitations in the study presented in this paper. One of the most important is that the whole analysis was performed for the context of a typical UK office building. Both phases of the study explored the impacts of COVID-19 on the UK office sector by interviewing participants that are all based in the UK and by analysing a typical office building according to the recommendations of the BCO. This poses a question with regard to the external validity of the research findings; consequently, it should not be assumed that the findings of the paper are easily generalisable to different contexts elsewhere (nor was it our intention to generalise the results). Although current literature suggests that a similar situation is evident in other countries of the world [54,55], it is not possible to confirm this from the results of this analysis.

The energy consumption quantification was performed for a single theoretical building, representing a typical office in the UK according to the recommendation of the BCO. This inevitably relies on some assumptions on building construction, occupancy profiles and systems operation. Typical schedules and benchmarks values published in current literature, guidance and standards (such as [86,87,99]) were used to represent an average use of the space. This is a simplification that was deemed to be acceptable considering that the purpose of the study was to compare the relative performance of the building before and after the COVID-19 outbreak. However, if the aim was to attempt an estimation of the actual future energy consumption of office buildings in the post-pandemic era, then the analysis would have to focus on real building case studies and the analysed sample would have to include a variety of different examples to cover the whole range of office buildings design in the UK (i.e. cellular, open-plan and landscape offices). Furthermore, the computational analysis relied on several assumptions with regard to the occupancy densities, utilisation factors and ventilation rates, as these are published in latest guidance (i.e. BCO guide to specification [84]). These are all highly uncertain input values and to account for the uncertainty in the simulation results, probabilistic analysis and sensitivity test were performed. As an initial estimate a standardised assumption of a $\pm$ 20% uniform distribution was used to explore the input ranges of the uncertain parameters (with respect to their normative or assumed base value). The rationale for this standardised approach, in the absence of more certain information, was to avoid introducing bias to the SA results due to assigning variable ranges of uncertainty. However, it should be acknowledged that representing the actual range of uncertainty more realistically could potentially reveal further influential parameters that in a fixed uncertainty range would be disregarded as unimportant. Finally, another limitation of this paper is that the analysis was only conducted for mechanically ventilated office buildings, whereas naturally ventilated cases and buildings that rely on hybrid ventilation (a combination between natural and mechanical ventilation) were excluded and could form the basis for further research.

6. Conclusions

This study is the first explorative analysis on the operational energy consumption of future offices in the post-pandemic era, as an effort to promote energy efficiency and the climate change agenda in the commercial and real estate sector. To be able to provide a working environment that satisfies the needs of the current workforce, it is important first to comprehend what those needs are. Facing the impacts of the pandemic, the white-collar workers globally were forced to re-consider and re-define various norms and habits related to office work that were established for many decades. We are currently experiencing a very transient period in which the meaning of the office work is changing rapidly as does the role of workspace. As Janda [107] comments, it is not the buildings that use energy, but the occupants within the buildings. For that reason, it is now rather important to synthesise building technology and energy efficiency research with social science, as an effort to understand the interconnection between humans and buildings. Occupancy and representation of people's behaviour in an office is important and has a direct effect on the building's energy performance [22]. Human behaviour is stochastic, so it is difficult to define the number of people occupying a specific space, as well as the duration of the occupancy [108]. In the past, the occupancy profiles in office buildings were considered relatively easy to characterise - at least easier in comparison to other building types. The relationship between the number of employees and the required office space grew arithmetically in parallel to each other. Moreover, activity patterns in offices were considered relatively steady and mainly related to typical working hours [22]. Nowadays, however, a more dynamic model of office work is prevailing, and this is also expected to affect the occupancy and operation of office buildings. Consequently, this paper explored the impact of flexible working patterns on the operational energy consumption of office buildings in the post-pandemic era by providing new insights on the emerging working culture and the role of workspace in the future.

The paper involved an exploratory study in the form of qualitative interviews, seeking to shed light into the future of office work and office space. Key professionals from the office building sector were asked to provide their perspectives and views on the future of offices, once the pandemic is over. Subsequently, the paper deployed computational analysis with the aim to quantify the potential energy demand for a list of likely future office scenarios.

The findings of the study indicate that the future office will be mainly needed for solidarity, for community building, for knowledge exchange, but also for social interaction and to create a feeling that employees are part of something bigger. The operation of office buildings is changing too. A new blended/hybrid way of work is expected to dominate in the future, with a typical working week divided between office-based and remote work. The analysis highlighted that by embracing such transitions in office work, the energy demand in the office building sector is expected to fall below the pre-COVID-19 levels. This could be achieved while simultaneously providing a better working environment for the occupants, with increased ventilation rates, better occupancy densities and more diverse spaces, able to accommodate the changing needs of current and future workforce.

Additionally, the results of this paper highlighted the significance of flexible office building use. When flexibility is incorporated in the use of workspace and most importantly in the operation of building services, significant energy savings can be achieved (close to 50% in comparison to pre-COVID-19 situation, based on the findings of this research). This is a potentially significant finding, pointing towards future directions for research in the field of intelligent controls and smart HVAC system operation. Combining booking technology with smart buildings services control could support hybrid working by synchronising the use of space by employees, while simultaneously saving carbon and money from wasted energy and promoting organisations' energy efficiency targets.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors gratefully acknowledge Loughborough University and the Engineering and Physical Sciences Research Council (EPSRC) for the provision of a grant (number EP N5095161) to undertake this research. Furthermore, they would like to thank Prof Malcolm Cook and Mr. Chris Carter for their help and advice.

References

[1] Ö. Duran, Evaluation of Retrofitting Strategies for Post-war Office Buildings, Loughborough University, 2018. https://hdl.handle.net/2134/32268.
[2] Condeco, The Modern Workplace: People, Places & Technology, London, 2019.
[3] Oktra, The Annual Workplace Report, London, 2018.
[4] Gensler, U.S. Workplace Survey, New York, 2019.
[5] C. Nixey, The Death of the Office. https://www.economist.com/1843/2020/04/29/death-of-the-office, 2020. (Accessed 26 May 2021).
[6] S. Bajno, L. Yap, C. Murphy, V. Chan, Coronavirus Forces World's Largest Work-From-Home Experiment. https://www.bloomberg.com/news/articles/2020-02-02/coronavirus-forces-world-s-largest-work-from-home-experiment, 2020. (Accessed 8 June 2021).
[7] A. Allsuch Boardman, Covid-19 Has Forced a Radical Shift in Working Habits. https://www.economist.com/briefing/2020/09/12/covid-19-has-forced-a-radical-shift-in-working-habits, 2020. (Accessed 8 June 2021).
[8] BEIS, Building Energy Efficiency Survey, London, 2016.
[9] N. Usher, The Future Workplace and the Triple Bottom Line: The Planet. https://www.linkedin.com/pulse/future-workplace-triple-bottom-line-planet-neil-usher/, 2020. (Accessed 26 May 2021).
[10] J. Wade, J. Pett, L. Ramsay, Energy Efficiency in Offices: Assessing the Situation, London, 2003.
[11] BRECSU, Energy Consumption Guide 19: Energy Use in Offices, Watford, 2000.
[12] Z. Ding, H. Zhu, Y. Wang, X. Ge, Study and analysis of office building energy consumption performance in severe cold and cold region, China, Adv. Mech. Eng. 9 (2017) 1–21, https://doi.org/10.1177/1687814017734110.
[13] A.C. Menezes, A. Cripps, R.A. Buswell, J. Wright, D. Bouchlaghem, Estimating the energy consumption and power demand of small power equipment in office buildings, Energy Build. 75 (2014) 199–209, https://doi.org/10.1016/j.enbuild.2014.02.011.
[14] Z. Wang, Y. Ding, An occupant-based energy consumption prediction model for office equipment, Energy Build. 109 (2015) 12–22, https://doi.org/10.1016/j.enbuild.2015.10.002.
[15] The Carbon Trust, Office Based Companies: Maximising Energy Savings in an Office Environment, London. https://www.carbontrust.com/media/13151/ctv007_office_based_companies.pdf, 2018.
[16] O.T. Masoso, L.J. Grobler, The dark side of occupants' behaviour on building energy use, Energy Build. 42 (2010) 173–177, https://doi.org/10.1016/j.enbuild.2009.08.009.
[17] J. Von Grabe, The systematic identification and organization of the context of energy-relevant human interaction with buildings - a pilot study in Germany, Energy Res. Soc. Sci. 12 (2016) 75–95, https://doi.org/10.1016/j.erss.2015.12.001.
[18] S.C. Staddon, C. Cycil, M. Goulden, C. Leygue, A. Spence, Intervening to change behaviour and save energy in the workplace: a systematic review of available evidence, Energy Res. Soc. Sci. 17 (2016) 30–51, https://doi.org/10.1016/j.erss.2016.03.027.
[19] I.N. Pettersen, E. Verhulst, R. Valle Kinloch, A. Junghans, T. Berker, Ambitions at work: professional practices and the energy performance of non-residential buildings in Norway, Energy Res. Soc. Sci. 32 (2017) 112–120, https://doi.org/10.1016/j.erss.2017.02.013.
[20] D. Li, X. Xu, C. Fei Chen, C. Menassa, Understanding energy-saving behaviors in the American workplace: a unified theory of motivation, opportunity, and ability, Energy Res. Soc. Sci. 51 (2019) 198–209, https://doi.org/10.1016/j.erss.2019.01.020.
[21] C. Fei Chen, T. Hong, G.Z. de Rubens, S. Yilmaz, K. Bandurski, Z.D. Bélafi, M. De Simone, M.V. Bavaresco, Y. Wang, P. Ling Liu, V.M. Barthelmes, J. Adams, S. D'Oca, Ł. Przybylski, Culture, conformity, and carbon? A multi-country analysis of heating and cooling practices in office buildings, Energy Res. Soc. Sci. 61 (2020), 101344, https://doi.org/10.1016/j.erss.2019.101344.
[22] T. Harputlugil, P. de Wilde, The interaction between humans and buildings for energy efficiency: a critical review, Energy Res. Soc. Sci. 71 (2021), 101828, https://doi.org/10.1016/j.erss.2020.101828.
[23] M.V. Bavaresco, E. Ghisi, S. D'Oca, A.L. Pisello, Triggering occupant behaviour for energy sustainability: exploring subjective and comfort-related drivers in Brazilian offices, Energy Res. Soc. Sci. 74 (2021), 101959, https://doi.org/10.1016/j.erss.2021.101959.
[24] D. Tverskoi, X. Xu, H. Nelson, C. Menassa, S. Gavrilets, C. Fei Chen, Energy saving at work: understanding the roles of normative values and perceived benefits and costs in single-person and shared offices in the United States, Energy Res. Soc. Sci. 79 (2021), 102173, https://doi.org/10.1016/j.erss.2021.102173.
[25] S. D'Oca, C.F. Chen, T. Hong, Z. Belafi, Synthesizing building physics with social psychology: an interdisciplinary framework for context and occupant behavior in office buildings, Energy Res. Soc. Sci. 34 (2017) 240–251, https://doi.org/10.1016/j.erss.2017.08.002.
[26] J. Bonan, C. Cattaneo, G. d'Adda, M. Tavoni, The interaction of descriptive and injunctive social norms in promoting energy conservation, Nat. Energy 5 (2020) 900–909, https://doi.org/10.1038/s41560-020-00719-z.
[27] X. Xu, C.F. Chen, D. Li, C. Menassa, Energy saving at work: exploring the role of social norms, perceived control and ascribed responsibility in different office layouts, Front. Built Environ. 6 (2020) 1–12, https://doi.org/10.3389/fbuil.2020.00016.
[28] BCO, Office Occupancy: Density and Utilisation, London. http://www.bco.org.uk/Research/Publications/Office_Occupancy_Density_and_Utilisation.aspx, 2018.
[29] Cushman & Wakefield, How a global pandemic changed the world, Edge Mag. 4 (2020).
[30] IEA, Working from home can save energy and reduce emissions. But how much?. https://www.iea.org/commentaries/working-from-home-can-save-energy-and-reduce-emissions-but-how-much, 2020 (accessed May 26, 2021).
[31] N. Gillen, Future Office. Next-Generation of Workplace Design, RIBA Publishing, London, 2019.
[32] F. Duffy, The Changing Workplace, Architecture Design and Technology Press, London, 1991.
[33] A. Delgado, The Enormous File: A Social History of the Office, John Murray, London, 1979.
[34] T. Ebbert, Refurbishment Strategies for the Technical Improvement of Office Facades, Technical University of Delft, 2010.
[35] P. Russell, S. Moffatt, IEA Annex 31 Energy-Related Environmental Impact of Buildings: Assessing Buildings for Adaptability, 2001.
[36] S. Chaillou, Metabolism(S) Space Flexibility in the 21st Century. https://medium.com/built-horizons/metabolism-s-spatial-flexibility-in-the-21st-century-d7cef8aaaf84, 2018. (Accessed 19 September 2021).
[37] K. Sailer, Covid Will Force us to Reimagine the Office, Let's get it right this time, https://www.theguardian.com/commentisfree/2020/aug/04/covid-reimagine-office-workplace-cubicles-hotdesking?CMP=Share_AndroidApp_Share_in_a_post, 2020. (Accessed 26 May 2021).
[38] M. Babapour, M.A. Karlsson, A.L. Osvalder, Appropriation of an activity-based flexible office in daily work, Nord. J. Work. Life Stud. 8 (2018) 71–94, https://doi.org/10.18291/njwls.v8iS3.105277.
[39] J.G. Hoendervanger, A.F. Ernst, C.J. Albers, M.P. Mobach, N.W. Van Yperen, Individual differences in satisfaction with activity-based work environments, PLoS One 13 (2018) 1–15, https://doi.org/10.1371/journal.pone.0193878.
[40] M. Babapour Chafi, L. Rolfö, Policies in activity-based flexible offices -'I am sloppy with clean-desking. We don't really know the rules, Ergonomics 62 (2019) 1–20, https://doi.org/10.1080/00140139.2018.1516805.
[41] WSP, Thoughts on the Post-pandemic Office, London, 2020.
[42] J.H. Pejtersen, H. Feveile, K.B. Christensen, H. Burr, Sickness absence associated with shared and open-plan offices - a national cross sectional questionnaire survey, Scand. J. Work Environ. Health 37 (2011) 375–382, https://doi.org/10.5271/sjweh.3167.
[43] G.A. Laurence, Y. Fried, L.H. Slowik, "My space": a moderated mediation model of the effect of architectural and experienced privacy and workspace personalization on emotional exhaustion at work, J. Environ. Psychol. 36 (2013) 144–152, https://doi.org/10.1016/j.jenvp.2013.07.011.
[44] A. Seddigh, E. Berntson, C. Bodin Danielson, H. Westerlund, Concentration requirements modify the effect of office type on indicators of health and performance, J. Environ. Psychol. 38 (2014) 167–174, https://doi.org/10.1016/j.jenvp.2014.01.009.
[45] M. Kwon, H. Remøy, M. van den Bogaard, Influential design factors on occupant satisfaction with indoor environment in workplaces, Build. Environ. 157 (2019) 356–365, https://doi.org/10.1016/j.buildenv.2019.05.002.
[46] WSP, The Future of the Workplace, London, 2020.
[47] M. Campbell, What tuberculosis did for modernism: the influence of a curative environment on modernist design and architecture, Int. J. Hist. Med. Relat. Stud. 49 (2005) 463–488, https://doi.org/10.1017/s0025727300009169.
[48] K. Chayka, How the Coronavirus Will Reshape Architecture. https://www.newyorker.com/culture/dept-of-design/how-the-coronavirus-will-reshape-architecture, 2020. (Accessed 26 May 2021).
[49] D. Katsikakis, D.C. Smith, M. Rodriquez, C. Leinberger, Purpose of Place: History and Future of the Office, London, 2020.
[50] CIPD, Embedding New Ways of Working. www.cipd.co.uk, 2020.
[51] JLL, Reimagining Human Experience: How to Embrace the New Work-life Priorities and Expectations of a Liquid Workforce, London. https://www.us.jll.com/content/dam/jll-com/documents/pdf/research/jll-reimagining-human-experience-11-2020.pdf, 2020.
[52] D.C. Smith, D. Katsikakis, R. Rockey, C. Leinberger, M. Rodriquez, D. Bitner, Workplace Ecosystems of the Future, London. https://www.cushmanwakefield.com/en/insights/covid-19/the-future-of-workplace, 2020.
[53] CBRE Research, Global occupier sentiment survey, in: The Future of the Office Building, London, 2020, 2020, https://doi.org/10.1108/02632779810693557.
[54] Gensler Research Institute, The Hybrid Future of Work. U.S. Workplace Survey, Summer / Fall 2020., USA, 2020.
[55] GWL Labs, State of Remote Work: COVID Edition, USA, 2020.
[56] BCO, Most British Workers Reluctant to Work Mainly From Home, New Polling Shows. https://www.bco.org.uk/News/News45664.aspx, 2020. (Accessed 26 May 2021).
[57] R. Rockey, K. Thorpe, R. MIller, U. Mark, A. Phipps, K. Bowman, J. Shepherd, C. Chen, E. Zhai, D. Brown, W.K. Lai, Global Office Impact Study & Recovery Timing, London, 2020.
[58] Leesman, The Workplace of the Future, London, 2020.
[59] AECOM, Post Pandemic We Will Still Need the Physical Office, London. infrastructure.aecom.com, 2020.
[60] ARUP, Future of Offices: In a Post-pandemic World, London. www.arup.com/covid-19, 2020.
[61] C. Spinuzzi, Working alone together: Coworking as emergent collaborative activity, J. Bus. Tech. Commun. 26 (2012) 399–441, https://doi.org/10.1177/1050651912444070.
[62] N. Oseland, Loneliness Has Always Been a Workplace Issue - Workplace Insight. https://workplaceinsight.net/why-loneliness-is-a-workplace-issue/, 2020. (Accessed 26 May 2021).

[63] C. Tagliaro, Will Working from Home Become the New Normal?. https://www.buildingsandcities.org/insights/commentaries/working-from-home.html, 2020. (Accessed 26 May 2021).
[64] J. Partridge, Covid-19 Has Changed Working Patterns for Good, UK Survey Finds. https://amp-theguardian-com.cdn.ampproject.org/c/s/amp.theguardian.com/business/2020/oct/05/covid-19-has-changed-working-patterns-for-good-uk-survey-finds, 2020. (Accessed 26 May 2021).
[65] F. Gillett, Coronavirus: What's the Future for the Office?. https://www.bbc.co.uk/news/uk-52720007, 2020. (Accessed 26 May 2021).
[66] CBRE Research, The Future of the Office: Survey Highlights, London, 2020, https://doi.org/10.1177/0013916582145006.
[67] CBRE, The Role of Great Offices in the Future of Work, London, 2020.
[68] A. Bryman, Social Research Methods, 5th ed., Oxford University Press, Oxford, 2016.
[69] E. Babbie, The Practice of Social Research, 11th ed., Thompson - Wadsworth, Belmont CA, 2007.
[70] M. Casula, N. Rangarajan, P. Shields, The potential of working hypotheses for deductive exploratory research, Qual. Quant. (2020), https://doi.org/10.1007/s11135-020-01072-9.
[71] C. Marlow, Research Methods for Generalist Social Work, Thomson Brooks/Cole, New York, 2005.
[72] B.K. Sovacool, J. Axsen, S. Sorrell, Promoting novelty, rigor, and style in energy social science: towards codes of practice for appropriate methods and research design, Energy Res. Soc. Sci. 45 (2018) 12–42, https://doi.org/10.1016/j.erss.2018.07.007.
[73] U. Schultze, M. Avital, Designing interviews to generate rich data for information systems research, Inf. Organ. 21 (2011) 1–16.
[74] S. Kvale, The qualitative research interview, J. Phenomenol. Psychol. 14 (1983) 171–196.
[75] V. Braun, V. Clarke, Using thematic analysis in psychology, Qual. Res. Psychol. 3 (2006) 77–101, https://doi.org/10.1191/1478088706qp063oa.
[76] D. Howitt, D. Cramer, Introduction to Research Methods, Prentice Hall, London, 2011.
[77] M.Q. Patton, Qualitative Evaluation and Research Methods, 2nd ed., SAGE, 1990.
[78] P.J. Waltz, Computerized Building Energy Simulation Handbook, The Fairmont Press, Lilburn, GA, 2000.
[79] J.A. Clarke, Energy Simulation in Building Design, 2r.e. ed, Oxford, Butterworth-Heinemann, London, 2001.
[80] M. Davies, Building Heat Transfer, Wiley and Sons, Ltd, Sussex, 2004.
[81] R.C.G.M. Loonen, S. Singaravel, M. Trčka, D. Cóstola, J.L.M. Hensen, Simulation-based support for product development of innovative building envelope components, Autom. Constr. 45 (2014) 86–95, https://doi.org/10.1016/j.autcon.2014.05.008.
[82] S. Attia, J.L.M. Hensen, L. Beltrán, A. De Herde, Selection criteria for building performance simulation tools: contrasting architects' and engineers' needs, J. Build. Perform. Simul. 5 (2012) 155–169, https://doi.org/10.1080/19401493.2010.549573.
[83] J.A. Clarke, J.L.M. Hensen, Integrated building performance simulation: Progress, prospects and requirements, Build. Environ. 91 (2015) 294–306, https://doi.org/10.1016/j.buildenv.2015.04.002.
[84] BCO, Guide to Specification, British Council for Offices, London, 2019.
[85] BCO, Occupier Density Study, London, 2013.
[86] DCLG, National Calculation Methodology (NCM) Modelling Guide, London, 2008.
[87] SAGE Environmental and Modelling group, Role of ventilation in controlling SARS-CoV-2 transmission, London, 2020.
[88] EnergyPlus, EnergyPlus, (n.d.). https://energyplus.net/ (accessed May 28, 2018).
[89] H. Samuelson, S. Claussnitzer, A. Goyal, Y. Chen, A. Romo-Castillo, Parametric energy simulation in early design: high-rise residential buildings in urban contexts, Build. Environ. 101 (2016) 19–31, https://doi.org/10.1016/j.buildenv.2016.02.018.
[90] Y. Zhang, I. Korolija, Performing complex parametric simulations with jEPlus, in: SET2010 - 9th Int. Conf. Sustain. Energy Technol., 2010.
[91] C.J. Hopfe, Uncertainty and Sensitivity Analysis in Building Performance Simulation for Decision Support and Design Optimization, 2009, https://doi.org/10.1016/j.enbuild.2015.09.010.
[92] I. MacDonald, Quantifying the Effects of Uncertainty in Building Simulation, University of Strathclyde, 2002.
[93] J.C. Helton, F.J. Davis, Latin hypercube sampling and the propagation of uncertainty in analyses of complex systems, Reliab. Eng. Syst. Saf. 81 (2003) 23–69, https://doi.org/10.1016/S0951-8320(03)00058-9.
[94] A. Saltelli, S. Tarantola, F. Campolongo, M. Ratto, Sensitivity Analysis in Practice: A Guide to Assessing Scientific Models, John Wiley, Chichester, 2004.
[95] SimLab, SimLab 2.2, Reference Manual, (n.d.). https://ec.europa.eu/jrc/en/samo/simlab (accessed March 12, 2018).
[96] JEPlus, jEPlus User's Manual, Version 2.1, (n.d.). http://www.jeplus.org/wiki/doku.php?id=docs:manual_2_1 (accessed May 27, 2021).
[97] J.G. Hoendervanger, N.W. Van Yperen, M.P. Mobach, C.J. Albers, Perceived fit and user behavior in activity-based work environments, Environ. Behav. (2021), https://doi.org/10.1177/0013916521995480.
[98] BEIS, Good Work: The Taylor Review of Modern Working Practices, London, 2017.
[99] CIBSE, CIBSE COVID-19 Ventilation Guidance, London, 2020.
[100] UK Government, Flexible Working, (n.d.). https://www.gov.uk/flexible-working/types-of-flexible-working (accessed September 19, 2021).
[101] J. Holmin, E. Levison, S. Oehme, The Utilization of Office Spaces and its Impact on Energy Use Energy Use, 2015.
[102] M. Nurunnabi, J. Esquer, N. Munguia, D. Zepeda, R. Perez, L. Velazquez, Reaching the sustainable development goals 2030: energy efficiency as an approach to corporate social responsibility (CSR), GeoJournal 85 (2020) 363–374, https://doi.org/10.1007/s10708-018-09965-x.
[103] G. Pellegrini-Masini, C. Leishman, The role of corporate reputation and employees' values in the uptake of energy efficiency in office buildings, Energy Policy 39 (2011) 5409–5419, https://doi.org/10.1016/j.enpol.2011.05.023.
[104] A.C. Chao, L. Hong, Corporate social responsibility strategy, environment and energy policy, Struct. Chang. Econ. Dyn. 51 (2019) 311–317, https://doi.org/10.1016/j.strueco.2018.11.010.
[105] R. Galvin, N. Terry, Selling energy savings in the United Kingdom: a case study of top-down pro-environmental behaviour change in commercial office buildings, Energy Res. Soc. Sci. 11 (2016) 155–163, https://doi.org/10.1016/j.erss.2015.10.001.
[106] M.W. Kozusznik, L.P. Maricutoiu, J.M. Peiró, D.M. Vîrgă, A. Soriano, C. Mateo-Cecilia, Decoupling office energy efficiency from employees' well-being and performance: a systematic review, Front. Psychol. 10 (2019), https://doi.org/10.3389/fpsyg.2019.00293.
[107] K.B. Janda, Building communities and social potential: between and beyond organizations and individuals in commercial properties, Energy Policy 67 (2014) 48–55, https://doi.org/10.1016/j.enpol.2013.08.058.
[108] I. Gaetani, P.J. Hoes, J.L.M. Hensen, Occupant behavior in building energy simulation: towards a fit-for-purpose modeling strategy, Energy Build. 121 (2015) 188–204, https://doi.org/10.1016/j.enbuild.2016.03.038.