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Impact of building design and occupancy on office comfort and energy performance in different climates

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ABSTRACT

The building sector has a significant share in a county's total greenhouse gas emissions, and as a reaction to the Kyoto commitment most countries are constantly adjusting building energy requirements in order to reduce greenhouse gas emissions and mitigate the climate change. While it is easier to set standards for the building fabric and for technical systems, the impact of occupants on comfort and energy performance in buildings has proven to be important, but is a lot harder to account for. This paper therefore aims to investigate the magnitude of influence of occupants in relation to climate and architectural design on thermal comfort and CO_2 emissions in offices in different climate zones of the world. The aim is to identify typical patterns and key parameters for optimisation.

For this purpose, a parametric study for a typical cellular office room has been conducted using the simulation software EnergyPlus. Two different occupant scenarios are each compared with three different architectural design variations and modelled in the context of three different locations for the IPCC climate change scenario A2 for 2030. The evaluation of the results is focused on two different modes of operation. For natural ventilation adaptive thermal comfort according to ASHRAE Standard 55 has been evaluated, and for mixed mode operation final energy consumption and resulting CO_2 emissions. The results indicate a first approach to estimate comfort levels based on climatic data, architectural design priorities and occupancy. Additionally, warmer climates seem to have larger optimisation potential for comfort and energy performance in offices compared to colder climates.

1. Introduction

In the context of the climate change, buildings have to provide satisfying comfort levels for occupants with minimum energy consumption in order to reduce resulting greenhouse gas emissions. This is a particular challenge in office buildings where significant internal heat gains are caused by occupancy, while at the same time the building is exposed to solar heat gains from the sun.

With the climate change decreasing cold stress and increasing heat stress can be expected which will increase the cooling energy demand especially in warm climates to maintain comfort under summer conditions [1]. As indicated by Wan et al. [2] for the Chinese context, CO_2 emissions are likely to increase with the climate change, and significant mitigation potential is related to energy efficient lighting, higher cooling set points and a cleaner fuel mix for electricity generation. This suggests that in order to mitigate the climate change a combination of different strategies needs to be considered which balances the specific climate, the building design and occupancy.

Based on the climate change scenario A2 of the Intergovernmental Panel on Climate Change [3] for the year 2030, this paper aims to compare the impact of building design and occupancy on comfort and energy performance in offices in order to derive optimisation strategies. It is based on a parametric study using the simulation software EnergyPlus [4] for a typical cellular office room to investigate the balance of architectural design and occupancy in three different climates. Simulations are run over a whole year, however the evaluation of the results is focused on summer conditions by considering a particularly hot year with similar characteristics to a year in the past decade with major heat waves. The aim is to investigate whether patterns of comfort and energy performance can be identified, that could be helpful for design considerations in early design stages.

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The study is conducted to compare three different climate zones of the world, the moderate climate of Hamburg, Germany, the Mediterranean climate of Athens, Greece and the hot and dry climate of Alice Springs in Australia. These locations allow for a comparison of the share of heating, cooling and lighting on the total final energy consumption in different climates.

In order to evaluate the impact of building design different parametric prototypes have been developed for this study. For comparability these prototypes had to be similar for all locations, but also reflect the variability of building design that can occur within one context. This has been achieved by focussing on the design priorities on the real estate market. Although the architecture of a building is a response to a multitude of influences, ranging from climate, urban and social and cultural context, occupancy parameters, comfort expectations, economic situation of the client, etc., mechanisms of the real estate market are similar in most countries and design priorities can be identified. In this study these are “prestige” reflecting a more luxurious office configuration, “low-cost”, reflecting lowest initial costs, and “green” reflecting a more sustainable configuration. These configurations have been developed in a previous publication and more details on the development of these variations can be found in Roetzel et al. [5,6].

As with building design, the behaviour of occupants in buildings is extremely various and context dependent [7,5]. The magnitude of impact and influencing parameters has been discussed more in depth in a previous literature review [5], however the main conclusion is that average standard values that are typically assumed in norms and regulations do not reflect the influence of occupants on comfort and energy performance to a satisfying level. In order to address this issue different suggestions have been made. One of those is to model occupant behaviour precisely based on observations in field studies as proposed by Wilke et al. [8] for residential buildings. As investigated by Widén et al. [9] for domestic context, if sufficiently detailed time-use data are available, occupancy patterns with an unlimited degree of detail can be generated and modelled. However they also raise the question which degree of detail would be necessary for different applications. Another difficulty with occupant behaviour modelling based on field data is that results valid for one context are not necessarily as valid in another context, as indicated by Schweiker et al. [10] comparing occupant interactions with windows in Switzerland and Japan.

Another approach to occupant modelling is the definition of different occupant types, e.g. Parys et al. [11] suggested an approach to consider the variability in behaviour amongst individuals by defining representative active and passive users. Such an approach comes with higher levels of uncertainty for the results, however the applicability of the model might be increased since it is less dependent on individual building context.

This paper does not aim to model occupant behaviour precisely, but the approach is also based on the definition of different occupant types. The inclusion of specific contextual data seemed contradictory to the nature of the parametric study the investigation is based on. And also the focus of this work was to develop a simplified methodology that can be used in early design stages of an architectural project. This is the building stage where the optimisation potential is largest and where even a rough estimate of occupant’s influence on comfort and energy performance can make a difference. This influence of occupants has been considered in this study by using extreme cases such as an ideal and a worst case scenario. Rather than precise predictions, the aim is to indicate the magnitude of influence that occupants can have on comfort and energy performance in buildings, and to derive recommendations for optimisation in early design stages.

This paper is the continuation of two previous publications. The first sets up the comparison of occupant behaviour, building design and climate [5]. It provides a more detailed literature review on occupant behaviour, more details on the development of the simulation models, and a more detailed description of input parameters for EnergyPlus. The second paper [6] as well as this third paper are updates of the initial simulation model, changes and additions have been made to suit the different focus of the studies. In this present paper, only the changes made to previous modelling assumptions have been described, for further details the reader is referred to the previous publications.

2. Development of the simulation models

2.1. Selection of weather data

In order to compare the impact of building design and occupants, three locations in different climate zones of the world have been chosen. They were selected to represent a moderate, a Mediterranean and a hot climate, and all three locations are in climate zones without extreme humidity, which makes comfort evaluation based on temperatures only more reliable. On the updated world Koeppen-Geiger climate classification map [12] Hamburg, Germany is classified as ‘temperate, warm summer, without dry season’ (Cfb), Athens in Greece as ‘temperate, with hot dry summer’ (Csa), and Alice Springs in Australia as ‘arid, hot desert climate’ (BWh).

In order to reflect these climate characteristics in building simulation, the selection of the weather data set is very important. And while national bureaus of meteorology offer a range of climate data observations and forecasts, these are very rarely available in a file format that can be used for building simulation. Additionally, there is no standardised input format, but different software requires different input file types and data content.

For use with the software EnergyPlus the weather file needs to be in “.epw” format, and a common source such weather files for many locations in the world is available from the EnergyPlus website [13]. These files are ready for use in simulation but they are based on data from the past. Additionally real time measurements from recent years are available for download [14], however they can have gaps of recording or the amount of recorded parameters can be limited. As such, they cannot be directly used as input for simulation, however in most cases they provide enough data to identify e.g. major temperature characteristics in a certain year.

For this study, the real time weather data from the EnergyPlus website have been used to get an overview of the main temperature characteristics for the hottest year in the past decade for the three locations Hamburg, Germany, Athens, Greece and Alice Springs, Australia. The hottest year has been defined as the year that has been associated with major heat waves, which had impact on human health as well as on the environment (bushfires), and is likely to be used as a reference year for comfort predictions due to expectations of increasing heat stress in summer in a future warmer climate [1]. For the location of Hamburg this is the year 2003, in Athens it was the year 2007 and in Alice Springs the year 2009, and all three countries apply different criteria to identify extreme heat. In Germany there is no official definition of a heat wave but the German Meteorological Service [15] issues a warning for the day when the perceived temperatures (related to temperature, humidity, wind speed and radiation) exceeds a threshold between 32 and 38 °C. In Athens, the Greek meteorological service defines a heat wave as a series of at least three consecutive days with a maximum daily temperature >37 °C [16]. Australia has no common definition of a heat wave, and different state emergency services issue heat warnings based on different thresholds. The Northern Territory does not have a specific threshold for such warnings, but as an approximation the threshold for South Australia can be used, where warnings are issued when an ‘average daily temperature’ ADT (maximum daytime temperature + minimum daytime temperatures/2) of 32 °C or above is predicted for three or more consecutive days [17].

Table 1 summarises the temperature characteristics for the three locations of Hamburg, Athens and Alice Springs based on the number of days with average daily temperature ADT above 32 °C, maximum daily temperature above 30, 35 and 40 °C, minimum daily temperature below 10 and 0 °C. The first column shows values for the EnergyPlus standard weather set. The second column shows values from EnergyPlus real time measurements for the hottest year at the location during the past decade, and it can be observed that the standard weather data sets largely underestimate the temperatures compared to the real time data for the hot year. This makes the standard data set less useful for comfort and energy performance predictions in comparison with recent extreme years or for the future life cycle of a building, i.e. the next approximately 15 years. This study is therefore based on weather data generated with the software Meteonorm [18], which has the option to generate data sets for future climate change scenarios according to the Intergovernmental Panel on Climate Change IPCC [3]. For the investigated locations of this study data sets based on temperature extremes and the IPCC scenario A2 for 2030 (which approximately reflects the timeframe for the life cycle of a new building today) have shown characteristics that are roughly comparable to those for the respective extreme year. The related characteristics of the weather data sets used for this study are shown in the third columns of Table 1.

2.2. Development of building design configurations

In order to account for the impact of different building design on comfort and energy performance in offices, different configurations had to be considered in this study. All configurations are variations of a typical cellular office room with the dimensions 5.4 × 3.5 × 2.7 m. These dimensions are identical with the reference office for simulation of lighting and energy as developed in IEA task 27 and 31 [19,20]. The dimensions also correlate with ergonomic guidelines in Germany [21] and an Australian Ventilation Standard [22] to provide 8–10/10 m^2 of office space per person. The investigated office is assumed to be occupied by two persons. In order to limit the amount of data, this study is limited to one orientation, with the room facing South in the Northern Hemisphere and North in the Southern hemisphere. During periods of natural ventilation the room is ventilated by a centrally located top hung window, which is assumed to be manually controlled by occupants.

Based on the assumption that the main stakeholders in a building process influencing the design are the client and the architect, these configurations have been developed from an architectural point of view and with driving forces of the real estate market in mind. For all locations the ‘prestige’ configuration has properties that are equivalent to what would be considered an up-market/quality commercial building in Hamburg, Athens or Alice Springs, with the main design drivers being representativeness and flexibility. The ‘low cost’ configuration is assumed to be driven by the intention to cause lowest initial cost, as is often the case for commercial buildings built for rent or sale on the real estate market. Representativeness, flexibility, comfort and energy performance are more likely to be compromised in this configuration. The ‘green’ configuration has properties that are focused on the use of thermal mass, daylight as well as effective solar protection. In this configuration flexibility of internal organisation is compromised for the sake of comfort and reduced energy consumption. Further details on the design development of these configurations are available in Roetzel et al. [5,6]. The key characteristics and façade properties for each location are summarised in Tables 2–4.

Opaque elements in the low cost as well as the green design configurations are modelled as solid wall constructions with u-values that meet the requirements of the national building codes in Greece, Australia and Germany [23–25]. The wall constructions for the different climates are as follows (from outside to inside): For Alice Springs: Plaster (1.5 cm), concrete blocks (19 cm), air gap (2 cm), reflective insulation, gypsum plasterboard (1.3 cm). Since the modelling of reflective insulation is not possible in EnergyPlus, it has been modelled indirectly using the same construction without the reflective insulation and air gap, but with the thickness of the concrete blocks adjusted so that the u-value is equivalent. For Athens: Plaster (1.5 cm), brick (9 cm), insulation (5 cm), brick (9 cm), plaster (1.5 cm). For Hamburg: Plaster (1.5 cm), insulation (12 cm), lima sand brick (17.5 cm), plaster (1.5 cm). For each climate two different glazing systems have been compared, a basic glazing system which fulfils standard requirements and an advanced

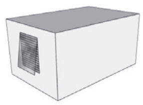
Table 2
Properties of the ‘prestige’ configuration for Athens, Alice Springs and Hamburg.

Prestige design	Athens	Alice Springs	Hamburg
			
Facade	$U = 0.5$ W/m^2 K	$U = 0.34$ W/m^2 K	0.26 W/m^2 K
Internal walls	Gypsum walls		
Ceiling	Suspended acoustic ceiling		
Floor construction	False floor construction		
Window area	100%		
Glazing	Low-e ($u = 1.6$ W/m^2 K)	Double ($u = 3.1$ W/m^2 K)	Triple 0.513 W/m^2 K
Shading	Internal venetian blind		
Overhang	No		
Lighting system	13.1 W/m^2		

Table 1
Basic temperature characteristics for different weather data sets in Hamburg, Germany, Athens, Greece and Alice Springs, Australia.

	EnergyPlus standard weather data set			EnergyPlus real time weather data for 2003			Meteonorm extreme year, IPCC scenario A2 for 2030		
	HAM	ATH	ALICE	HAM	ATH	ALICE	HAM	ATH	ALICE
ADT >32 °C days total	0	2	16	0	16	22	0	11	24
Days with max day temp >30 °C	3	64	176	10	101	156	13	96	216
Days with max day temp >35 °C	0	9	82	0	52	84	1	31	107
Days with max day temp >40 °C	0	0	16	0	8	10	0	3	23
Nights with min night temp <10 °C	262	120	113	265	n/a (incomplete data)	173	229	111	74
Nights with min night temp <0 °C	71	0	14	108	n/a (incomplete data)	83	88	11	2

Table 3
Properties of the ‘low cost’ configuration for Athens, Alice Springs and Hamburg.

Low cost design	Athens	Alice	Hamburg
			
Facade	$U = 0.5$ W/m^2 K	$U = 0.34$ W/m^2 K	0.26 W/m^2 K
Internal walls	Gypsum walls		
Ceiling	Suspended acoustic ceiling		
Floor construction	Solid floor (screed)		
Window area	20%		
Glazing	Standard ($u = 2.7$ W/m^2 K)	Single ($u = 5.7$ W/m^2 K)	Low-e 1.25 W/m^2 K
Shading	Internal venetian blind		
Overhang	No		
Lighting system	21.3 W/m^2		

system with better thermal properties. The overhang in the green building configuration is an opaque horizontal element to obstruct direct sunlight.

2.3. Building occupants

Occupants interact with a building and thus directly as well as indirectly affect the building's energy performance as well as thermal and visual comfort. However the actual interaction of occupants with their building is strongly depending on the context. Among other factors, the use of office equipment depends on the tasks performed, the use of blinds is influenced by daylighting, views, glare as well as privacy requirements, the use of lights is influenced by the task, the lighting concept, the luminaires and the number of people in the room, the use of air conditioning also depends on the control options, and the use of night ventilation is affected by security issues. Thus the specific modelling of occupant behaviour only seems a viable option in the optimisation process of a specific real building where all these contextual influences can be researched at a detailed level. For a parametric study however, which aims to produce results that are to some degree context independent and applicable to more than just one building, a different approach seemed necessary. The approach used in this study is therefore based on two extreme case scenarios for occupant behaviour – an ideal and a worst case scenario. Within the range of possible occupant behaviour in a building, these two scenarios reflect the boundaries of this range from a comfort and

Table 4
Properties of the ‘green’ configuration for Athens, Alice Springs and Hamburg.

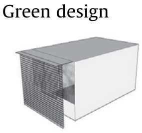
Green design	Athens	Alice	Hamburg
			
Façade	$U = 0.5$ W/m^2 K	$U = 0.34$ W/m^2 K	0.26 W/m^2 K
Internal walls	Brick walls		
Ceiling	Uncovered concrete slab		
Floor construction	Screed floor construction		
Window area	70%		
Glazing	Low-e ($u = 1.6$ W/m^2 K)	Double ($u = 3.1$ W/m^2 K)	Triple 0.513 W/m^2 K
Shading	External venetian blind		
Overhang	Yes		
Lighting system	13.1 W/m^2		

Table 5
Power consumption of office equipment.

Updated values for office equipment according to EU-Energystar [18]			
Office equipment for an architectural office	On mode (W/person)	Standby (W/person)	Off (W/person)
Workstation	190	7.4	1.5
2x value 22″ LCD	42	0.8	0.6
Phone with answering machine	2	2	2
Colour laser multi-function device 6–12 ppm	3	1	1
Total with desktop	237	11.2	5.1
Total with large notebook instead of workstation	72.5	5.5	4.5
Large notebook	25.5	1.7	0.9

energy performance perspective. This means that the scenarios are based on and limited to parameters that are directly or indirectly related to thermal comfort, visual comfort and/or energy consumption and can be modelled in the simulation software EnergyPlus.

For both scenarios the occupancy profile equals 8 h of full time work as defined for a ‘busy office’ in the EU-Energystar database [26]. These working hours however, are distributed among occupied hours from 8 am to 8 pm, to account for flexitime, lunchbreaks, and the presence of cleaning staff after working hours. Additional details can be found in Roetzel et al. [5]. Data for office equipment and user profiles are taken from the EU-energy-star website [26]. Lighting control for the ideal scenario is based on a set point of 500lux on the work plane according to EN 12464-1:2011 [27] and considering the whole working plane as task area. Venetian blinds are assumed to be manually controlled for glare protection (discomfort glare index >22) and/or overheating (room air temperature >26 °C and at the same time solar radiation on the facade ≥200 W/m^2 [28], and slat angles differ for glare protection (ideal scenario) or privacy (worst case scenario). Natural ventilation is based on the EnergyPlus Airflow Network model and controlled by the EnergyPlus Energy Management System. The top hung window has been modelled, according to Coley [29], and the impact of shading devices on the effectiveness of natural ventilation has been accounted for according to Tsangrassoulis [30].

In order to evaluate adaptive thermal comfort according to ASHRAE Standard 55 [31] as well the energy performance with cooling, simulations have been run twice. As ‘free-floating’ without heating and cooling for thermal comfort evaluation, and then again including heating and cooling set points to evaluate the energy performance of each configuration.

More details concerning the development of the concept as well as additional occupant modelling details can be found in Roetzel et al. [5,6]. Compared to previous work, for this study the ideal and worst case occupant scenarios have been slightly modified. The modifications are:

- Update of the power consumption of office equipment based on an updated database of the source [26], new values are given in Table 5.
- Updated concept for the use of air-conditioning. For the worst case scenario a fixed cooling set point of 23 °C is assumed in all climates, which is the average value in the typical range of cooling set points for the three locations between 22 and 24 °C. For the ideal scenario and assuming mixed mode operation the cooling set points are adjusted on a monthly basis for each climate separately following the upper limits for 80% satisfaction of the ASHRAE Standard 55 adaptive thermal comfort model (Table 7). This assumption is based on indications from

Table 6
Summary of parameters for ideal and worst case occupant scenarios.

Ideal and worst case occupant scenarios			
Influenced on	Parameter	Ideal scenario	Worst case scenario
Company level	Office equipment	Notebooks, possibility to disconnect office equipment from power supply outside office hours	Desktop computers, no possibility to disconnect office equipment from power supply outside office hours
Company level	Night ventilation	Night ventilation	No night ventilation
Individual level	Use of blinds	Blinds opened and closed according to heat and glare (active user)	Blinds closed all day (passive user)
Individual level	Use of lights	Light on/off according to daylight (active user)	Light on during working hours (passive user)
Company level	Use of air conditioning (if applicable)	Set points according to upper limits of ASHRAE Standard 55 adaptive comfort model 80% satisfaction	Setpoint 23 °C

literature that occupant's comfort preferences in mixed mode buildings are more closely related to those in naturally ventilated rather than air conditioned building [32,33]. While the acceptability of such adaptive cooling set points would require further testing in a field study, this approach takes advantage of potential energy savings compared to fixed cooling set points. Although a simplification which also does not account for other influences such as air distribution systems and humidification, it seemed reasonable for the purpose of this study.

- Adjustments to the window control strategy for natural ventilation for the location of Alice Springs to account for differences in the Southern hemisphere.

A summary of the parameters assumed for the ideal and worst case scenario in this study is given in Table 6.

2.4. Heating, cooling and lighting

The building context assumed in this study is a medium sized office building, and the main usage for energy in this study is related to heating, cooling, lighting and office equipment. In Germany and to some extent in Greece medium sized office buildings are likely to have different systems for heating and cooling, e.g. heating based on natural gas and a separate cooling system e.g. absorption chiller. In Australia however it is most common to provide both, heating and cooling by the same source, commonly multi split air conditioners. Also different types of systems are available in different countries and the efficiency ratings are based on different parameters. Since the efficiency of different heating and cooling systems is not the focus of this study, assumptions have been made that aim for comparability of the results across the climate zones. These are:

A multi split air conditioner for cooling as well as heating has been assumed for all three climates, in all configurations that are conditioned. This is standard in Australia and to some extent in Greece, and it is not uncommon in Germany, too. However in this context one difficulty was, that European and Australian air conditioners are based on different efficiency evaluation systems, the Minimum Energy Efficiency Standards (MEPS) in Australia [34] and the Seasonal Coefficient of Performance/Seasonal Energy efficiency Ratio SCOP/SEER in Europe [35]. Since these two evaluation systems are not directly comparable, just one system has been selected for all three climates, which is a class A multi split air conditioner with an SCOP of 3.7 and a SEER of 5.35 [36]. Within the European standards this is a state of the art system, but not the best available technology and thus a common and not the most expensive system on the market. Since this study focuses on the evaluation of summer conditions, only cooling set points have been varied, the heating set point is 19° during occupied hours for all configurations in all three climates.

No changes have been made to the lighting performance assumption from the previous study, since the values for a standard and the advanced lighting configuration, still reflect the current state of the art performance range. The standard lighting concept is based on surface mounted luminaires with specular louvres and an installed lighting power of 21.3 W/m^2. And the advanced lighting system is based on pendant luminaires with micro-prismatic light redirection and an installed lighting power of 13.1 W/m^2.

2.5. CO_2 emission factors

The results for greenhouse gas emissions in this study are based on the final energy consumption multiplied with the location specific CO_2 conversion factors. Since heating, cooling, lighting and office equipment are all powered by electricity, the same factor is applied for all these services. The CO_2 emission factors for Australia's Northern Territory are 0.68 kg CO_2-e/kWh [37], for Hamburg 0.56 kg CO_2-e/kWh [38], and for Greece 0.989 kg CO_2-e/kWh [23]. In this context it is important to consider that the emission factors within Australia vary significantly between the states (from 0.32 in Tasmania to 1.23 in Victoria), and therefore results are valid for the Northern Territory only and not transferrable to other states. National or regional emission factors are generally based on the primary energy sources used for electricity production and can thus be subject to change. The value for Germany has dropped within the last years as a result of an increased use of renewable energy and an increased use of gas and oil rather than coal. The higher value for Greece can be explained by the predominant use of lignite in the energy production. The lower value for the Northern Territory is also based on the predominantly gas and diesel driven

Table 7
Cooling set points equal the upper comfort limits according to ASHRAE Standard 55 for the IPCC A2 scenario (2030) for each weather data set.

Cooling set points for mixed mode operation [°C]	Cooling set points for each climate equal the ASHRAE Standard 55 adaptive thermal comfort upper limits for 80% satisfaction, based on the IPCC A2 climate change scenario for the year 2030		
	Athens	Hamburg	Alice Springs
Jan	24.0	21.0	30.0
Feb	24.0	22.0	30.0
Mar	25.0	22.0	29.0
April	27.0	25.0	29.0
May	28.0	26.0	27.0
June	30.0	27.0	27.0
July	31.0	28.0	26.0
Aug	31.0	28.0	28.0
Sept	29.0	27.0	28.0
Oct	27.0	24.0	29.0
Nov	26.0	23.0	30.0
Dec	24.0	21.0	30.0

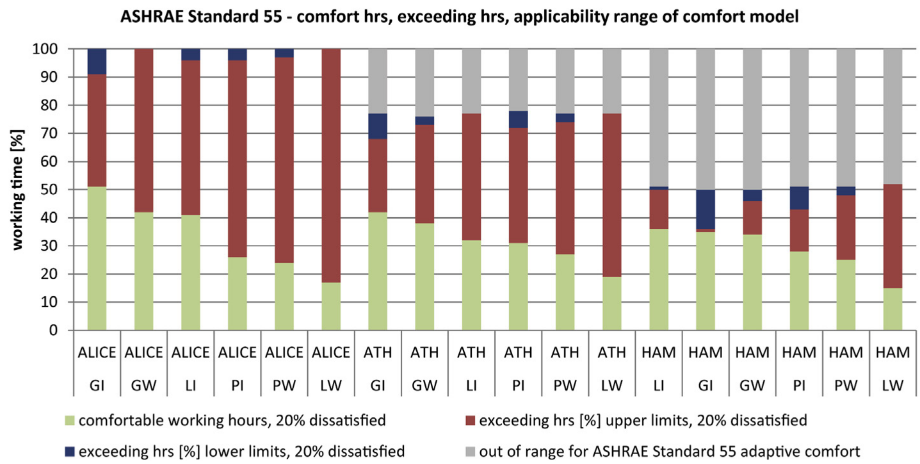


Fig. 1. AHSRAE Standard 55, comfort hrs., exceeding hrs., applicability range of comfort model for Athens (ATH), Alice Springs (ALICE) and Hamburg (HAM) for the configurations green (G), prestige (P), and low-cost (L) in combination with ideal (I) or worst case (W) occupant scenario. The dotted lines indicate the average percentage of comfortable working time per climate.

energy production, and the absence of coal as a primary energy source.

3. Discussion of simulation results

3.1. Thermal comfort according to ASHRAE Standard 55 (naturally ventilated)

Fig. 1 illustrates the shares of comfortable working time, exceeding hours and model applicability among the total working hours per year based building simulation results. The building design and occupant configurations for each climate are ordered according to percentage of comfortable working time from left (highest value) to right (lowest value).

In the following paragraphs the simulation results illustrated in Fig. 1 are compared with results from an analysis of the weather data files which have been used as simulation input, and common patterns and similarities are discussed. The different climate characteristics for the three locations are illustrated in Fig. 2, where outside air temperatures are plotted against the mean monthly outdoor air temperature calculated based on ASHRAE Standard 55.

3.1.1. Applicability of the model

Adaptive thermal comfort can only be evaluated according to ASHRAE Standard 55 if the mean monthly outdoor temperatures at the location is within the applicability range of 10–33.5 °C of the model. The percentage of working time when this criterion is met varies from one location to another. Fig. 1 illustrates, that the percentage of working time where the model is not applicable is relatively consistent for all configurations in the same climate. According to the simulation results, in Alice Springs the adaptive thermal comfort model can be applied for 100% of the working time, in Athens this percentage is about 80%, and in Hamburg this model can only be applied for about 50% of the working time. As can be expected these results are consistent with the results from the climate analysis, because the applicability of the model is based on outdoor temperatures only.

It can be concluded that the ASHRAE Standard 55 adaptive comfort model has a larger applicability range, and therefore potentially a larger optimisation potential, in hot climates than in cold climates. The applicability range can be identified without any simulations by plotting the hourly outside air temperatures for a location against the mean monthly outdoor air temperature according to ASHRAE Standard 55. These results might be affected in the context of the future development of the ASHRAE Standard 55 adaptive thermal comfort model [39].

3.1.2. Comfortable working time

When using natural ventilation, the temperature of the fresh air entering a room will affect the room temperature inside. If the indoor temperature is within the comfort range, then ventilation with outdoor air that is also in the comfort range will maintain the existing comfort levels. If the outdoor temperature is above or below the comfort range, then it will reduce existing comfort levels. On this basis, aim of this study was to identify in how far the percentage of working time when outside air temperatures are within the ASHRAE Standard 55 comfort range can be a first approximation to the comfort levels that can be achieved inside a naturally ventilated office. Table 8 illustrates the results, comparing simulations for indoor temperatures with the analysis of outside air

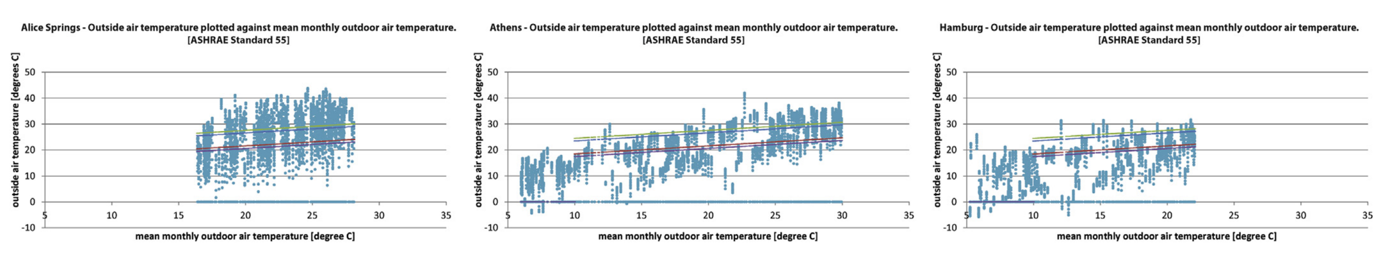


Fig. 2. Outside air temperatures plotted against the mean monthly outdoor air temperature calculated based on ASHRAE Standard 55 for Alice Springs (left), Athens (middle) and Hamburg (right).

Table 8
Percentage of comfortable working time according to ASHRAE Standard 55 for simulated indoor operative temperatures compared with the evaluation of outside air temperatures.

Thermal comfort evaluation based on natural ventilation		Alice Springs	Athens	Hamburg
Percentage of working time with comfortable temperatures according to ASHRAE Standard 55, 20% dissatisfied	Indoor operative temperature based on simulation results, average value for different building design and occupant configurations	34%	32%	29%
	Outdoor air temperatures based on weather files	30%	31%	27%

temperatures. Interestingly, the variation of comfort percentages across the different climates is very small, each in the ballpark of 30%. And this is the case for both, the simulated average indoor temperatures as well as for the outside temperatures. Further validation would be needed, however this leads to the conclusion that the analysis of outdoor air temperatures according to ASHRAE Standard 55 might be a useful comfort indicator for early design stages.

Beyond the consistency of the average comfort percentages, the simulation results also indicate significant comfort variability when evaluating the different building design and occupant configurations individually. Table 9 illustrates the comfort variability compared to the average values for each location, based on building design and occupant behaviour. It becomes obvious that, although the average comfort percentages are a useful first indicator, none of the investigated configurations is actually reflected in the average values. However certain patterns can be observed:

For the green building design, comfort percentages are about 6–13% above the average values for each location. The warmer the climate the higher this percentage (lowest in Hamburg and highest in Alice Springs). The variability due to occupants ranges from ±1 to $\pm5\%$ and also increases the hotter the climate. This indicates that in warm climates it is important to improve both, building design as well as occupancy in order to maximise comfort percentages.

For the low cost building design, comfort percentages are below the average values for each location (minus 3–6%). This design has the largest variability due to occupants ($\pm$6–12%). Since this variability is also larger than the impact of the low cost building design, this variation can achieve comfort percentages above average and similar to the green configuration when related to the ideal occupant scenario, and lowest overall percentages, well below average when related to the worst case occupant scenario. In combination with the low cost variation, occupants have significant responsibility for thermal comfort.

For the prestige building design comfort percentages are 2–9% below the average values for each location. The variability due to occupant scenarios is rather low in all climates with $\pm1\%$ in Alice Springs and $\pm2\%$ in Athens and Hamburg, which means that in all combinations comfort percentages are below the average. Unlike the green configuration where comfort percentages increase the warmer the climate, for the prestige configuration comfort percentages decrease in warmer climates, and are especially low in Alice Springs. This could be explained by the lacking thermal mass in the design in combination with the high façade u-value, which does not buffer the large average diurnal range of 7.8° (compared to 3.5 in Athens and 3.3 in Hamburg) in this climate very well.

3.1.3. Effectiveness of night ventilation

As indicated above the low cost variation, is the most sensitive towards occupant behaviour. While the ideal occupant scenario assumes that night ventilation is possible during summer months, the worst case scenario assumes that windows are closed during the night and night ventilation is not possible. This indicates that the lower the heat transmission through the façade (e.g. low cost configuration), the more the configuration relies on night ventilation via operable windows in order to provide thermal comfort. Night ventilation however is most effective when the outside temperature is below the room/comfort temperature for at least 6 h during the night [40], which is the case in all three climates for most days of each month. The results show that based on ASHRAE Standard 55 adaptive thermal comfort temperatures for 80% satisfaction, night ventilation is effective in each month of the year in all three climates. In climates where the possibility for night ventilation is lower, the impact of occupants on comfort and resulting energy performance is likely to be lower than indicated in this study.

3.2. Daylight autonomy and view

In this study daylight autonomy and view are only evaluated for the ideal occupant scenarios, where active operation of blinds is assumed, whereas for the worst case occupant scenario, blinds are assumed to be constantly closed and the daylight autonomy zero.

Table 10 shows the daylight autonomy for the different building design configurations and climates together with the percentage of working time when shading is activated. Daylight autonomy is measured in the middle of the work plane which is located in the window facing half of the room. Some basic patterns can be observed:

Although daylight autonomy generally increases with window size till a certain size where saturation has been reached, highest percentages occur for the green configuration with 70% window area as opposed to the prestige configuration with 100% window area. Whereas in Athens and Hamburg external illuminance is significantly lower during winter compared to summer, the external illuminance in Alice Springs is more consistent over the year. This is the reason for the higher daylight autonomy even for the low cost configuration in Alice Springs. Additionally Hamburg on latitude of 53° has significantly shorter daylight periods compared to Athens (38°) and Alice Springs (24°). This indicates a significant potential for daylighting in climates with high external illuminance and lower latitudes such as Alice Springs and Athens, especially if solar protection, window area and glazing type are carefully balanced (e.g. green configuration).

As can be expected, daylight autonomy for all configurations is significantly higher, the higher the average global horizontal illuminance, with highest values in Alice Springs and lowest in Hamburg. This is despite the fact that the percentage of working time with activated shading significantly increases with higher outdoor illuminances, too. This means that the higher the outdoor illuminance, the more likely it is that daylight autonomy can be achieved even with activated shading (slat angle of venetian blind = 45°).

The percentage of working time with activated shading ranges from around 50% in Hamburg to around 75% in Alice Springs. While the deviations due to different building design are small, this means that the shading system will be perceived as part of the building's aesthetic appearance for up to 3/4 of the working time. This emphasises the importance of the design integration of shading systems into the building's architectural concept.

Table 9
ASHRAE Standard 55 adaptive thermal comfort percentages for different climates, building design variations and occupant scenarios.

Thermal comfort evaluation based on natural ventilation	Alice Springs	Athens	Hamburg
Average percentage of working time with comfortable temperatures according to ASHRAE Standard 55, 20% dissatisfied	34%	32%	29%
Variability to average percentage above for the **green building** (and influence of ideal vs. worst case occupant scenario)	+13% (±5)	+9% (±2)	+6% (±1)
Variability to average percentage above for the **low cost building** (and influence of ideal vs. worst case occupant scenario)	−5% (±12)	−6% (±6)	−3% (±11)
Variability to average percentage above for the **prestige building** (and influence of ideal vs. worst case occupant scenario)	−9% (±1)	−3% (±2)	−2% (±2)

3.3. Final energy consumption (mixed mode)

Fig. 3 illustrates the final energy consumption for the different design and occupant configurations in the three climates. It is obvious that for all climates the final energy consumption for configurations based on the worst case occupant scenario is on average 2.5 times higher than the consumption based on the ideal scenario. This factor is slightly lower (around 2) for the colder climate of Hamburg as well as for all low cost design variations. And it is slightly higher (3–3.5) for the prestige and green variations in the warmer climates of Alice Springs and Athens. This makes the occupant scenarios the strongest influence on final energy consumption, about 80% higher than the impact of building design.

The influence of different building design is not as strong but nevertheless significant. Based on the green configuration with lowest values, the final energy consumption for the prestige design is by factor 1.2 higher and for the low cost design by factor 1.6 higher. Like with occupant scenarios, the influence of building design is stronger in Athens and Alice Springs than in Hamburg. In these climates the solar radiation has a stronger influence on energy and light transmission into a building, which – unlike outdoor temperature – can be controlled by architectural design/shading.

The variability of the final energy consumption for the same design and occupancy configuration in different climates is around factor 1.2 on average. This value is slightly higher for configurations based on the ideal occupant scenario (1.3) and slightly lower (1.1) for the worst case occupant scenario. It is interesting to observe

Table 10
Daylight autonomy and percentage of working time with activated shading for different building design configurations in Alice Springs, Athens and Hamburg.

		Alice Springs	Athens	Hamburg
Daylight autonomy [%]	Green ideal 70% window area	72	58	41
	Lowcost ideal 20% window area	25	12	11
	Prestige ideal 100% window area	67	56	39
Average percentage of working time with activated shading for all three design variations [%]		74	66	50

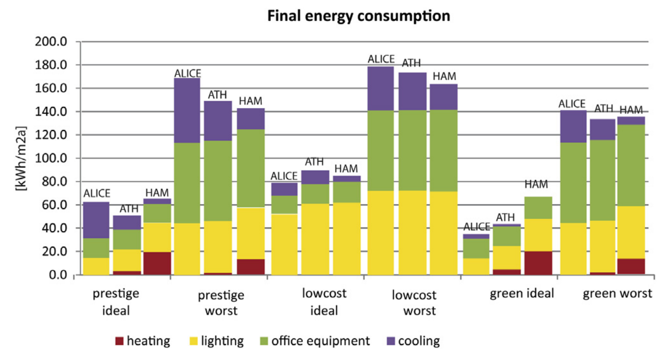


Fig. 3. Final energy consumption of the investigated configurations.

that most of the configurations in Athens tend to have lower final energy consumption than in Alice Springs, and the highest final energy consumption for each configuration occurs in the coldest climate, Hamburg, due to increased use of heating and lighting. This is also influenced by the fact that the multi split air conditioners assumed in this study are more efficient in cooling than in heating mode and thus penalise cold climates.

The lowest (35 kWh/m^2 a) as well as the highest final energy consumption (180 kWh/m^2 a) occur in Alice Springs, which therefore has the largest range (145 kWh/m^2 a) of variability depending on occupants and design. The second largest range of variability occurs in Athens (125 kWh/m^2 a) with a minimum of 45 kWh/m^2 a and a maximum of 170 kWh/m^2 a. The smallest range (100 kWh/m^2 a) occurs in the coldest climate with a minimum of 65 and a maximum of 165 kWh/m^2 a.

This indicates that the colder the climate the larger the minimum final energy consumption for ideal configurations, which is caused by increased need for heating as well as for artificial lighting due to lower outdoor illuminances. Additionally differences in latitude and related daylight periods cause higher lighting energy consumption in Hamburg, compared to Athens and Alice Springs. The hotter the climate, the larger the maximum final energy consumption for worst case configurations, which is caused by increased need for cooling due to high internal as well as external heat loads.

It is interesting to observe that in all climates and for almost all configurations, lighting and office equipment are the largest influences on final energy consumption. Shares for lighting can be slightly higher where window areas are small and/or in climates such as Hamburg with lower external illuminance. The only case where cooling is the predominant influence, is the prestige ideal configuration in Alice Springs. The highest (low cost and prestige worst configurations) as well as the lowest (green and prestige ideal) overall final energy consumption can be observed for the two warm climates Alice Springs and Athens. In all climates, the low cost variation generally tends to lead to higher energy consumption and the green configuration to lower energy consumption. The prestige configuration however has the strongest sensitivity towards occupant behaviour. In combination with the worst case scenario it causes high energy consumption, whereas with an ideal occupant scenario the resulting final energy consumption is relatively low.

3.4. CO_2 emissions (conditioned)

All investigated services (heating, cooling, lighting and office equipment) in this study are run based on electricity. As described in Section 2.4, the same systems are assumed in all countries, since it was not the focus of this study to compare the efficiency of

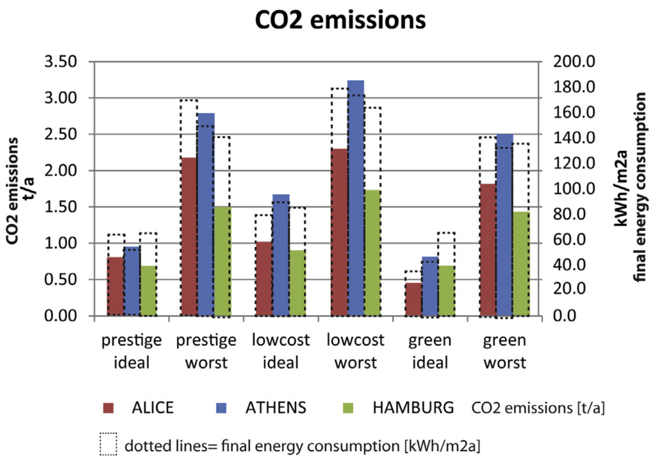


Fig. 4. CO_2 emissions for the investigated configurations and comparison with final energy consumption.

different heating and cooling systems. The evaluation of greenhouse gas emissions in comparison to the final energy consumption expresses therefore the significance of a country's efficiency in electricity production in relation to building design, occupant behaviour and climate. In terms of greenhouse gas emissions, in this study only CO_2 emissions are considered.

Of the three compared countries, Germany currently has the highest efficiency in electricity generation (CO_2 Emission factor 0.56 kg CO_2-e/kWh), followed by the Northern Territory of Australia (CO_2 Emission factor 0.68 kg CO_2-e/kWh) and Greece with a CO_2 emission factor of 0.98 kg CO_2-e/kWh. In this context it has to be noted that energy conversion factors change over time and are also context sensitive. In spatially smaller countries such as Greece and Germany, emission factors are provided for the whole country. In a large country as Australia however, CO_2 emission factors vary by up to factor 4 among different states depending on available fuel sources in different regions.

As for the final energy, CO_2 emissions are at least twice as high for the worst case compared to the ideal scenarios for all three climates (Fig. 4). Highest total CO_2 emissions occur for the three worst case scenarios in Athens, followed by the three worst case scenarios in Alice Springs (in all cases in the order low cost, prestige, green), and the three worst case scenarios in Hamburg with the one exception where the low cost ideal scenario in Athens causes higher CO_2 emissions than the prestige and green worst case scenarios in Hamburg. Lowest total CO_2 emissions occur for the green ideal scenarios in the three climates. The prestige ideal scenario has second lowest CO_2 emissions in all climates.

This order clearly reflects the impact of the emission factors. It indicates that for the worst case scenarios which are the configurations with the highest final energy consumption, the national efficiency in electricity production has more influence than the building design, but less than occupant behaviour. However this is not the case for the configurations with the lowest CO_2 emissions, where the influence of building design and occupants is more significant than the emission factor.

It can be concluded that the predominant influence of occupants on final energy consumption is also reflected in the related CO_2 emissions. The impact of the CO_2 emission factors at the different locations is important in this context, however less so than occupant scenarios and building design. CO_2 emission factors tend to be more influential for configurations with high absolute final energy consumption such as the worst case scenarios.

Interestingly the lowest final energy consumption as well as the lowest CO_2 emissions are related to the green ideal configuration in Alice Springs. This configuration takes best advantage of the climatic conditions, so that heating as well as cooling energy consumption are minimised. Although being a hot climate, the daily air temperature amplitude (average day temperature − average night temperature) is significantly higher than in Athens or in Hamburg, which makes night ventilation more efficient. And although winter nights in Alice Springs can be cold, winter daytime temperatures are significantly warmer so that by using passive solar heating, comfort levels can be maintained during office hours with a minimum requirement for heating. The high illuminance levels across the year are another benefit in this climate reducing the need for artificial lighting.

4. Conclusions

This paper investigates comfort and energy performance in offices based on a typical cellular office room in three different climates − the hot and dry climate of Alice Springs, Australia, the Mediterranean climate of Athens, Greece, and the temperate climate of Hamburg, Germany. Aim of this study was to investigate whether patterns related to climate, building design or occupancy can be detected, and how these can be used for predictions and prioritisation in early design stages. The following main observations could be made:

1. Building occupants are the predominant influence on office final energy consumption in all investigated climates. For all investigated configurations the worst case occupant scenario causes approximately 2.5 times the final energy consumption of the ideal scenario. These patterns are generally reflected in the resulting CO_2 emissions, too, however difference between the investigated countries occur due to different efficiencies in electricity generation (different CO_2 emission factors). In order for the ideal scenario to be applied, occupants should a) use low energy consuming office equipment, i.e. prefer notebooks over desktop computers, b) actively operate blinds in order to allow for daylighting while preventing heat and glare, c) actively operate artificial lighting depending on daylight availability, d) actively operate windows during the day and for night ventilation, and e) use adaptive cooling set points as suggested in Table 7.
2. This study is based on an ideal and worst case scenario approach for modelling occupancy in offices. This approach demonstrates the large magnitude of influence that occupants have on comfort and energy performance in offices in various climates. This magnitude of influence is especially important to be aware of in early design stages of architectural projects, where basic performance criteria of a building are defined and the optimisation potential is larger than in later project stages. Due to the use of extreme cases this approach does aim to accurately predict or model occupancy in a particular building. It also does not intend to define a 'typical' or average occupancy pattern. Due to the strong influence of building context on occupant behaviour [5], any more specific occupant behavioural pattern would make indirect assumptions on the context of the project and thus limits the applicability of the approach. The ideal and worst case scenario approach to occupant modelling is suggested for early design stages where detailed occupancy data are not yet available. The criteria mentioned above which define the ideal scenario can be used as design guidelines for building controls and recommendations to occupants in early design stages.
3. This study suggests a first approach for a methodology to estimate maximum and minimum achievable adaptive thermal comfort percentages for office buildings in early design stages: As a first step, outside air temperatures at the investigated locations have been plotted against the mean monthly outdoor air

temperatures similar to the method of the ASHRAE Standard 55 adaptive thermal comfort model. The results show that for all three investigated locations outside air temperatures are within the adaptive comfort limits for approximately 30% of the working time ('outside air comfort' ~ 30%). For all locations this value correlates with the average comfort percentages of indoor operative temperatures for different design and occupancy configurations. This means that as a first approach, the percentage of working time when outside air temperatures are within the comfort limits can be used as an estimate for average expected indoor comfort percentages at all investigated locations. Based on this value, maximum and minimum achievable comfort percentages can be roughly estimated for each climate. As derived from the analysis of thermal comfort for naturally ventilated operation above (Section 3.1), maximum and minimum predicted comfort percentages can be calculated for each location by adding or subtracting a value to the previously calculated 'outside air comfort'. First approximations for this value are +20/−10% for Alice Springs, +10/−10% for Athens and +5/−15% for Hamburg. Since building design is the predominant influence on adaptive thermal comfort in offices in all investigated climates, in order for the maximum values to be achieved, the following strategies incorporated into the green variation should be applied: a) An efficient external sun protection system has to be in place that allows for daylighting even in activated mode, b) window to wall ratios should be 70% or larger and located above the work plane if possible, c) thermal mass should be exposed to the room air in floor, walls, and ceiling. Although the impact of building design is predominant, the maximum comfort values can only be achieved if occupants a) actively operate windows during the day and for night ventilation, b) actively operate blinds in order to allow for daylighting while preventing heat and glare, c) actively operate artificial lighting depending on daylight availability, d) operate office equipment with a low power consumption.

This methodology requires further testing and validation, and is only valid in climates where the outside temperature is below the room/comfort temperature for at least 6 h during the night in order for night ventilation to be effective. It indicates an easy strategy to estimate adaptive thermal comfort potentials and limitations in early design stages, when more sophisticated evaluation strategies such as building simulation are not feasible.

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