An international review of occupant-related aspects of building energy codes and standards

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Abstract

In light of recent research, it is evident that occupants are playing an increasingly important role in building energy performance. Despite the important role of building energy codes and standards in design, the occupant-related aspects are typically simple and have not kept up with the leading research. This paper reviews 23 regions' building energy codes and standards by first comparing their quantitative aspects and then analyzing their mandated rules and approaches. While the present paper focuses on offices, general recommendations are applicable to other building types as well. The review revealed a wide range of occupant-related values, approaches, and attitudes. For example, code-specified occupant density varies by nearly a factor of three between different codes.

This underlines the need for development of advancement in occupant behavior modeling approaches for future occupant-centric building performance codes and standards. Moreover, occupants are often referred to only implicitly; underlying expectations about energy-saving occupant behavior from building occupants varies greatly; and, only a few codes address occupant feedback and system usability. Based on the findings of the review, a set of initial recommendations for future building energy codes is proposed.

1 Introduction and literature review

It is becoming widely accepted that building performance is increasingly sensitive to occupant behavior as the efficiency of building materials and systems improves and plug loads become an increasing part of energy end uses [1-3]. In commercial/institutional and residential buildings alike, occupants have been shown to affect the energy use in architecturally-identical offices and homes by a factor of three or more [4-6]. These differences largely result from use of operable windows, plug-in equipment, lighting, shading devices, thermostats, and occupant presence itself. Accordingly, the topic of occupant behavior in buildings has received a surge of research interest [7, 8], with several international projects coordinating the effort (IEA EBC Annex 66 and 79) [9, 10]. Yet, since much of the research is rather fundamental and academic in nature, significant knowledge transfer efforts are needed to have an impact on the architecture, engineering, and construction industry.

One of the most impactful ways to improve the energy performance of buildings is through advancement of building codes [11]. Building energy codes can be used to enforce a minimum set of building energy efficiency requirements, such as envelope, HVAC, DHW, and lighting. Numerous studies have shown that building energy codes can achieve on the order of 5 to 20% energy savings for the building stock [11-13].

Before proceeding, it is important to define building energy codes and standards separately (though they are largely treated the same in the context of this paper). Building energy codes are legal requirements mandated by government as the minimum acceptable performance level, whereas standards are recommendations that are not legally-binding [14]. Some standards (e.g. ASHRAE Standard 90.1) have been widely adopted in part or entirety by energy codes, as will become evident in this paper. Herein, codes and standards are used synonymously unless a specific country is discussed. A third category of document, rating standards (e.g. LEED, BREEAM), are used primarily for marketing purposes (e.g., to command higher rent), though some regions adopt these as requirements that are additional to the building code.

There are two main paths in most building codes: prescriptive- and performance-based. Many codes and standards (e.g., ASHRAE Standard 90.1 [15]) allow users to choose one compliance path to follow. The prescriptive path is a list of rigid requirements that is relatively straightforward to follow and enforce, but it lacks flexibility. For instance, it may not give credit for new technologies or novel design and operating strategies. The performance-based path on the other hand does not necessarily enforce individual requirements (e.g., R-value or HVAC equipment efficiency), but rather places the responsibility on the building owner to demonstrate that the overall energy performance will be better than an equivalent building (referred to as notional or reference building) with the minimum requirements of the prescriptive path. This improvement is normally verified through a detailed building energy model and annual simulations for the proposed and code-minimum equivalent (reference) building models. The flexibility of the performance path, combined with advances in building performance simulation (BPS), have increased its popularity. For instance, it enables buildings to have architecturally desirable features (e.g., very large windows with a window-to-wall area ratio approaching 60 to 70%) that may not be allowed by the prescriptive path. There is a general international transition towards performance-based codes [11]. A third path is available in many codes; the trade-off path is a model-less way to deviate somewhat from the prescriptive requirements through equivalent measures. As stated by Canada's National Energy Code of Canada for Buildings (NECB) [16], "The trade-off options present an easy way to make small adjustments to the characteristics of the building without having to follow the whole-building performance route."

The benefits of building energy codes are undeniable and widespread (lower environmental impact, lower energy bills, occupant health and comfort, energy resilience, safety, building longevity, etc.). However, building energy codes must ultimately be enforced by officials to fully realize these benefits [13, 17]. Non-compliance may be a result of designer negligence or be intentional, knowing that officials are unlikely to enforce requirements [18]. Methods of enforcement, stringency, and consequences of violations vary widely between jurisdictions [11, 19]. The current paper does not cover enforcement in depth, but it is ultimately a consideration for codifying requirements. Accordingly, balancing stringency and level of detail with ease of use by designer and code officials alike is critical. Performance-based energy codes are particularly challenging to enforce because of the number of inputs in building performance simulation (BPS) tools. For example, the National Energy Code of Canada for Buildings [16] states the following question as a consideration for amendments in its preamble: "Will enforcement agencies be able to enforce the requirement?" Consideration of enforcement is particularly important regarding the way occupants are treated in building energy codes, relative to the state-of-the-art in occupant modeling research. For instance, what is the responsibility of a building designer if an occupant behaves unexpectedly?

As noted by Evans, Roshchanka and Graham [11], few studies have comprehensively reviewed building codes at the international level. Even fewer have examined specific aspects of buildings codes, with few exceptions such as Pérez-Lombard, Ortiz, Coronel and Maestre [20], which is focused on HVAC-related requirements in building codes. And notably, none of the reviews have focused on occupant-related aspects, perhaps due to the relatively recent interest in the topic.

In contrast to wall assemblies, lighting technology, and HVAC systems, which can be specified in a quantitative way and later enforced by code officials – often using tangible evidence (e.g., drawings, specifications and product labels), occupant-related aspects of the building codes are significantly more complex. Future occupants and space uses are often unknown during the building design and permitting process. Thus, it is typically not appropriate or possible to specify occupant behavior the same way as other building requirements are specified. Nevertheless, occupants play an ever-growing role in building performance. Thus, they can no longer be neglected or otherwise treated simplistically by building codes.

To date the occupant-related aspects of building codes are quite simplistic and treated more as a boundary condition (much like weather) rather than as active agents in buildings [21, 22]. However, in contrast to weather, building design can influence how buildings behave [23]. The most common way to specify occupants in the performance-based path of building codes is through hourly schedules. O'Brien, Gaetani, Gilani, Carlucci, Hoes and Hensen [24] found that many modelers use code-based occupant-related schedules for lack of better information at the time of design, even if the code allows flexibility. Through a workshop of building energy modelers, Abuimara, O'Brien, Gunay, Abdelalim, Ouf and Gilani [25] reported that modelers tend to use defaults/code assumptions about occupants to avoid liability, even if they know these values are unrealistic.

Modelers seem to have doubts over the current approach to require occupants to be modeled identically in the reference and proposed building models. However, few papers have looked at building codes with focus on occupants. O'Brien and Gunay [26] showed that the current occupancy schedules for offices in North American codes – which are near-full capacity during weekdays – may cause design teams to overlook the benefit of occupancy-adaptive building controls (namely, demand-controlled ventilation and occupancy-controlled lighting with small lighting control zones). Gilani, O'Brien, Gunay and Carrizo [27] showed that optimal window area is significantly affected by the assumptions made about occupants, thus demonstrating the importance of modelling appropriate and realistic occupant behavior. Sun and Hong [28] conducted a simulation case study to demonstrate assumptions of occupant activities and behaviors have strong influences on the energy savings potential of energy conservation measures. Besides, an overestimated level of occupancy may also lead to an overestimation of occupant actions, since occupants are necessarily required for adaptive actions to be made. Three methodologies are proposed in Mora, Carpino and De Simone [29] to represent the occupants' activities in residential buildings located in Southern Italy: using surveys and interviews, applying the National Standards, and elaborating statistical data. The analysis showed that different approaches to modeling occupancy can lead to considerable variations in building performance. In particular, the data provided by the Standards produces a significant underestimation of heating energy consumption if compared to the current-use scenario. Furthermore, Carpino, Mora, Arcuri and De Simone [30] investigated the influence of housing occupancy patterns on the definition of net-zero energy buildings. The analysis was conducted considering a case study building designed according to the Italian Standards. Successively, different building usage scenarios were analyzed and the results indicate that "nearly" zero energy building is dependent on occupant related factors.

The objective of this paper is to first present a comprehensive international review of the occupant-related aspects and considerations of building energy codes, and then to make initial recommendations to code committees and other policymakers around the world. While occupants are quite central in comfort-related building standards (e.g., ASHRAE Std. 55, EN 16798-1:2019, ISO 7730), this paper is restricted to energy codes and standards. Moreover, the focus is on office buildings, though the general conclusions can be extrapolated to other types of buildings.

First this paper provides a methodology, which summarizes the reviewed codes as well as the two-phase framework for analyzing the codes. Next, the results are presented whereby quantitative and qualitative aspects of the codes are compared and analyzed. The discussion section is forward looking and focuses on innovative code requirements found through the review and potential methods to enhance current codes.

2 Methodology

The review process was initiated by contacting participants of IEA EBC Annex 79 to request their assistance in providing information about their national building codes. Annex 79, "Occupant-centric building design and operation", is an international collaboration project (2018-2023) under the International Energy Agency's Energy in Buildings and Communities Programme. Among participants' contacts in other countries, 22 participating countries provided information on 23 regions' (mostly whole countries except United Arab Emirates (UAE)) building energy codes and/or standards. The countries/regions and corresponding documents are listed in Table 1. The countries that participated are shown in Figure 1. While there is a mix of codes, standards, and rating systems in the review (refer to definitions in the previous section), the documents are directly or indirectly legally binding. For example, the national rating schemes of Singapore and the UAE require a certain number of points (somewhat like a trade-off path of building codes).

Data were collected using a template on an online spreadsheet tool such that all participants could enter data and see all results. The participants were required to translate the collected data into English; this is justified on the basis that they generally perform research in English and have advanced technical knowledge of buildings and energy codes. The data collection was formalized into two phases described next, after which the data was analyzed both through a quantitative and qualitative lens.

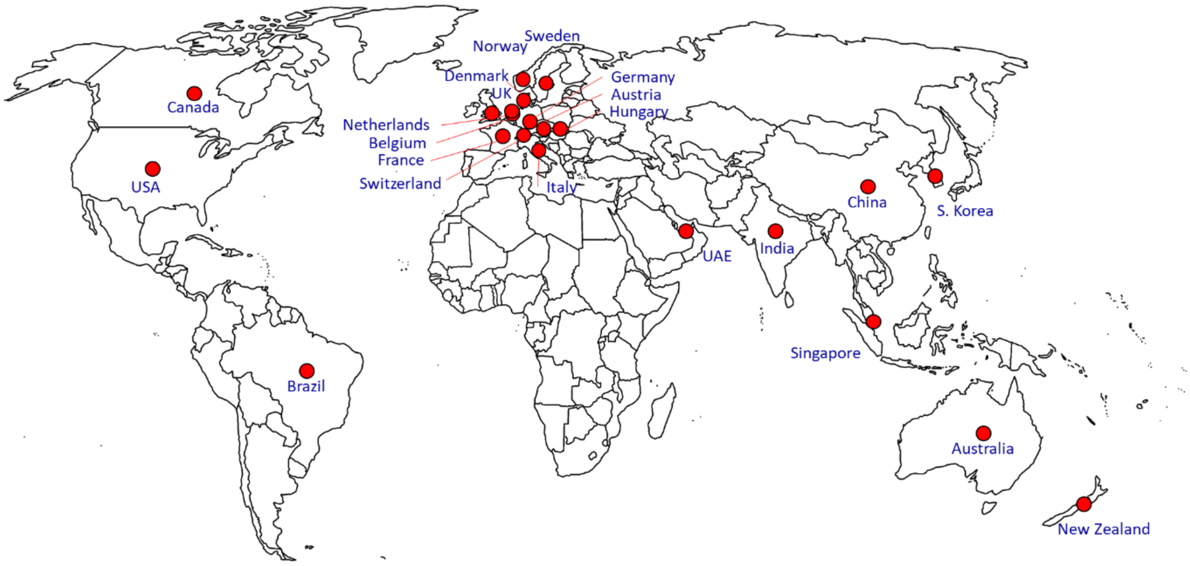

Figure 1: Map of countries included in the building energy code review

Table 1: The participating countries/regions and the corresponding building code or standard and corresponding documents that were reviewed in this paper

Country	**Reviewed code/standard name in local language**	**Reviewed code/standard name translated into English**	**Document type (code, standard, or rating system)**[1]	**Purpose of document**	**Reference**
Australia (AUS)	National Construction Code (NCC) 2016 Volume One	same	Code	Legally required for permit	[31]
	AS/NZS 1680.2.2:2008: Interior and workplace lighting - Specific applications - Office and screen-based tasks	same	Standard	Legally required for permit	[32]
	AS1668.2 2012 The use of ventilation and air-conditioning in buildings, Part 2:	same	Standard	Legally required for permit	[33]

[1] Contributors were asked to categorize their reviewed document(s); however, the context for how the document is used/enforced should also be considered (column to right)

	Mechanical ventilation in buildings				
Austria (AUT)	ÖNORM B 8110-6-1 - Wärmeschutz im Hochbau - Teil 6-1: Grundlagen und Nachweisverfahren - Heizwärmebedarf und Kühlbedarf	ÖNORM B 8110-6-1 - Thermal insulation in building construction - Part 6-1: Principles and verification methods - Heating demand and cooling demand	Standard	Legally required design guideline	[34]
	ÖNORM B 8110-5 - Wärmeschutz im Hochbau - Teil 5: Klimamodell und Nutzungsprofile	ÖNORM B 8110-5 - Thermal insulation in building construction - Part 5: Model of climate and user profiles	Standard	Legally required design guideline	[35]
	ÖNORM H 5059-1 - Gesamtenergieeffizienz von Gebäuden - Teil 1: Beleuchtungsenergiebedarf	ÖNORM H 5059-1 - Energy performance of building - Part 1: Energy use of lighting	Standard	Legally required design guideline	[36]
Belgium (BEL)	Energiebesluit	Energy Decree	Code	Legally required for permit	[37]
Brazil (BRA)	Requisitos Técnicos da Qualidade para o Nível de Eficiência Energética de Edifícios Comerciais, de Serviços e Públicos (RTQ-C) will change to - Instrução normativa Inmetro- Método para	Technical Requirements for the determination of the level of energy efficiency of	Rating system	Required for rating, but not legally required	[38]

	a avaliação da eficiência energética com base em energia primária de edificações comerciais, de serviços e públicas (INI-C) in 2020	commercial, services and public buildings (RTQ-C) will change to - Normative Instruction Inmetro - Method for energy efficiency determination based on primary energy for commercial, services and public buildings (INI-C) in 2020			
Canada (CAN)	National Energy Code of Canada for Buildings	same	Code	Legally required for construction/permit	[16]
China (CHN)	公共建筑节能设计标准（GB50189-2015）	Design standard for energy efficiency of public buildings (GB50189-2015)	Standard	Legally required for construction/permit	[39]
Denmark (DNK)	Bygningsreglementet 2018.dk BR18 4/7 2019	Building regulations 2018.dk BR18 4/7 2019	Code	Legally required for construction/permit	[40]
England (ENG)	National Calculation Methodology (NCM) Modelling Guide in support of the 2013 Edition of the Building Regulations Approved	same	Guideline in support of Building Regulati		[41]

	Document L2A (Conservation of fuel and power in new buildings other than dwellings)		on Approved Document		
France (FRA)	Réglementation thermique 2012	2012 Building Regulation	Code	Legally required for construction/permit	[42]
	Méthode de calcul de la réglementation thermique 2012	Calculation Methodology in support of the 2012 Building Regulation	Code	Legally required for construction/permit	[43]
Germany (DEU)	Verordnung über energiesparenden Wärmschutz und energiesparende Anlagentechnik bei Gebäuden (Energieeinsparverordnung - EnEV)	Ordinance on energy saving insulation and energy saving technical services in buildings (Energy saving ordinance)	Code	Legally required for construction/permit	[44]
	DIN V 18599-10 Energetische Bewertung von Gebäuden - Berechnung des Nutz-, End- und Primärenergiebedarfs für Heizung, Kühlung, Lüftung,Trinkwarmwasser und Beleuchtung - Teil 10: Nutzungsrandbedingungen, Klimadaten	DIN V 18599-10 Energy efficiency of buildings - Calculation of net, final, and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting - Part 10: Boundary	Standard	Legally required for construction/permit	[45]

		conditions of use, climatic data			
Hungary (HUN)	7/2006. (V. 24.) TNM rendelet az épületek energetikai jellemzőinek meghatározásáról	Ministerial Decree No. 7/2006. (V. 24.) TNM on the establishment of energy characteristics of buildings	Code	Legally required for construction/permit	[46]
India (IND)	Energy Conservation Building Code 2017	same	Code	Legally required for construction/permit in select states	[47]
	National Building Code of India 2016 Volume 2	same	Code	Legally required for high-rise buildings	[48]
Italy (ITA)	UNI/TS 11300-1 Prestazioni energetiche degli edifici, Parte 1: Determinazione del fabbisogno di energia termica dell'edificio per la climatizzazione estiva ed invernale	UNI/TS 11300-1 Energy performance of buildings, Part 1: Evaluation of energy need for space heating and cooling	Standard	Legally required for construction/permit	[49]
Netherlands (NDL)	Energieprestatie van gebouwen - Bepalingsmethode	Energy performance of buildings - methodology	Standard	Legally required for construction/permit	[50]
New Zealand (NZL)	New Zealand Building Code Clause H1 Energy Efficiency	same	Code	Legally required for construction/permit	[51]

Norway (NOR)	SN/TS 3031:2016 Bygningers energiytelse Beregning av energibehov og energiforsyning	SN/TS 3031:2016 Energy performance of buildings Calculation of energy needs and energy supply	Standard	Legally required for construction/permit	[52]
Singapore (SGP)	Green Mark for Non-residential Buildings	same	Rating system	Point-based; but legally required	[53]
	Code for Environmental Sustainability for Buildings	same	Code	Legally required for construction/permit	[54]
South Korea (KOR)	건축물의 에너지절약설계기준	Building Design Criteria for Energy Saving (BDCES)	Code	Legally required for construction/permit	[55]
Sweden (SWE)	BFS 2017:6 - BEN 2 Boverkets föreskrifter om ändring av verkets föreskrifter och allmänna råd (2016:12) om fastställande av byggnadens energianvändning vid normalt brukande och ett normalår	BFS 2017:6 - BEN 2 The Swedish National Board of Housing, Building and Planning's regulations on amendments to the regulations and general advice (2016:12) on the determination of the building's energy use during normal use	Code	Legally required for construction/permit	[56]

		and a normal year			
	Sveby brukarindata kontor	Sveby standard for the energy use in buildings - occupant input data for offices	Voluntary guideline	Design guideline, but not legally required	[57]
Switzerland (CHE)	SIA 2024:2015 Raumnutzungsdaten fuer die Energie- und Gebaeudetechnik	SIA 2024:2015 Space usage data for energy and building installations	Standard	Legally required for construction/permit	[58]
	SIA 380:2015 Grundlagen für energetische Berechnungen von Gebäuden	SIA 380:2015 Basics for energetic calculations of buildings	Code	Legally required for construction/permit	[59]
	SIA 380/1:2016 - Heizwaermebedarf	SIA 380/1:2016 Requirements for heating	Code	Legally required for construction/permit	[60]
	SIA 385/2:2015 Anlagen für Trinkwarmwasser in Gebäuden - Warmwasserbedarf, Gesamtanforderungen und Auslegung	SIA 385/2:2015 Installations for domestic hot water in buildings - Hot water demand, overall requirements and design	Code	Legally required for construction/permit	[61]
United Arab Emirates/Abu Dhabi (UAE-1)	Pearl Building Rating System: Design & Construction	same	Rating system	Point-based; but legally required	[62]

United Arab Emirates/Dubai (UAE-2)	Al Sa'fat Dubai Green Building Evaluation System	same	Rating system	Point-based; but legally required	[63]
United States of America (USA)	Standard 90.1: Energy Standard for Buildings Except Low-Rise Residential Buildings	same	Standard	Standard that can be locally adopted as legally-binding code	[64]

2.1 Data collection

Phase 1 involved collecting quantitative data focused on schedules and densities for occupancy, lighting, equipment, and other internal heat gains. Further information was collected on workplane illuminance requirements, ventilation requirements, heating and cooling setpoints and nighttime setbacks, operable windows, and window shades. Together these represent the common specifications in model/performance-oriented paths of the reviewed building codes.

Phase 2 focused on both prescriptive and modelling requirements of building codes that were provided in the form of sentences. First, contributors were asked specific questions about requirements for automation and occupant sensing. These results were analyzed in light of the Phase 1 results to help explain trends and anomalies. Next, contributors were asked to both extensively search for keywords (e.g., occupant, user, occupancy) and read their respective code to identify implicit references to occupants (e.g., how window shades should be assumed to be used and requirements for manual modes of building systems). Contributors were required to provide at least five instances of occupant-related code requirements (many provided 10 or more to yield a total of 167 items); thus, collected data is not exhaustive but provides a wide spectrum of the sorts of occupant-related code requirements and the nature of their specification.

2.2 Purpose of the codes

All the studied codes are indented to be used for energy performance compliance or rating. Most of the codes' performance target is based on secondary or primary energy use. However, the codes of Italy and Austria are based on heating and cooling energy demand. England's code uses a defined target emission rate and the French code exploits a maximum operative temperature target for a summer day in addition to the energy targets. The UAE documents introduce both energy and water performance targets. The Swedish code requires that measured energy performance be verified against predicted performance 24 months into operations.

2.3 Data analysis

Phase 1 is focused on a direct comparison of occupant-related design values and schedules. It compares the codes in terms of the magnitude of the values and the granularity of assumptions and modeling methods.

Because the open-endedness of Phase 2 is not as comprehensive but rather based on examples, the analysis is primarily qualitative. When analyzing the data, the following questions were considered:

- What building systems are required to be controlled based on occupant presence?
- What aspects of buildings are considered in the context of occupants (e.g., lights)?
- What terms do building codes use to refer to occupants?
- How simple or complex are occupants treated?

- What do building codes assume about occupant behavior and its ability to reduce energy use or improve comfort?

3 Results and analysis

3.1 Phase 1: Results of quantitative code requirement analysis

This section summarizes and compares the quantitative occupant-related assumptions and recommendations obtained from the 23 regions' building energy codes. While some of the reviewed values (e.g., lighting power density) are used for both prescriptive and performance paths of the code, schedules and densities are generally specified because they are intended to be used in the simulation-based performance path. Note that regions missing from the tables in this section indicates that their code does not specify these values.

As part of the data collection process, the contributors of this paper provided or paraphrased the code text specifying the intended application of the densities and schedules. In general, there are a few common threads and some disagreements about the details. Of the reviewed codes, it is widely understood and often explicitly stated that the values are not intended/expected to hold true in the occupied building, but serve as a standard upon which to make fair comparisons. However, flexibility to adjust the schedules varies greatly be country, as discussed in more detail in Section 3.2.4.

3.1.1 Occupancy density and use of lights, equipment, and hot water

Assumptions concerning people density, lights and equipment power, and hot water use are the key elements that implicitly represent occupant energy-related behavior in the studied codes. In most of the codes these time-varying parameters are defined with a maximum design value (addressed in the present section) and an associated schedule (see Section 3.1.2).

The results, above all, reveal that the design values for the aforementioned aspects of occupant behavior, which are given in Table 2, differ considerably across the codes. Figure 2 and Figure 3 demonstrate that occupancy and lighting power density vary by nearly a factor of three between countries. The variation is more significant for equipment use. This wide range can be seen in Figure 4, as Singapore's code considers 16 W/m^2 for equipment power density, while Austrian code defines an equipment load of not more than 2.6 W/m^2.

Once all data were plotted, the contributors were asked to try to justify the specified occupant density of their reviewed code(s) – particularly if their region's value is particularly high or low compared to the others. The main insight from this retrospective analysis are that two of the highest values –from Australia and Singapore– originate from egress requirements. These are likely to be conservative (i.e., high) given the relative importance of safety and egress. This finding, albeit anecdotal, indicates a need for further research for whether it is appropriate to use the same occupancy density values for heat gains, ventilation requirements, egress, and other application areas.

Besides the variations in terms of the magnitude of these parameters, the studied codes also reveal different approaches to establish the assumptions with regard to lighting power. While the majority of codes have tried to provide a "reasonable" single value for the lighting power density in office buildings, the Swedish code explicitly provides two different values for "efficient" and "very efficient" lighting. It also provides different equipment power density values at different occupancy levels. The codes used in England and Germany deploy simplified calculation procedures to derive the lighting power density based on zone geometry and luminaire efficacy. Hungary's code also explicitly considers a reduction factor of 0.7 in case daylight or occupancy sensors are installed.

ASHRAE Standard 90.1 also reflects the requirement for occupancy sensors by a modification in lighting profiles such that the hourly fraction of lighting density reaches 0.65 at maximum. In this regard, there seems to be a need for further explicit considerations of manual and automated control modes and emerging lighting technologies.

As for hot water use, the codes use several different units, which limits the possibility of a straightforward comparison. More precisely, occupant use of hot water has been estimated in terms of the volume of water or heating energy and has been normalized by floor area or number of occupants. It is worth mentioning that, as opposed to occupant use of lights and equipment that is commonly represented with a power value and an accompanying hourly schedule, hot water use is mainly given as an aggregated value of energy or volume over a day or a year.

Table 2: Occupant-related assumptions concerning presence, use of lights, equipment and hot water in office buildings found in the national/regional building energy codes. The units are as specified in the headers unless stated otherwise.

Country	People density or heat gain [person/m^2]	Lighting power density [W/m^2]	Equipment power density [W/m^2]	Hot water consumption [l/(d.m^2)]
AUS	0.10	9.0, 7.0[2]	15.0	4.0 l/(d.person)
AUT	1.7, 3.3 W/m^2	25.76 kWh/(m^2.a)	1.3, 2.6[3]	9.0 Wh/(m^2.d)
BEL	0.07	6.0	3.0	5.0 MJ/(m^2.a)
BRA	0.10	14.1	9.7	-
CAN	0.04	8.5	7.5	90 W/person
CHE	0.07	15.9	7.0	3.0 l/(d.person)
CHN	0.10	9.0	15.0	5-10 l/(shift.person)
DEU	0.07	n/a[4]	7.1	0.70
DNK	0.044[5]	11.0	6.0	0.27
ENG	0.11	n/a[6]	11.8	0.20
FRA	0.10	-	16.0	0.18
HUN	n/a[7]	11.0 kWh/(m^2.a)[8]	n/a	9.0 kWh/(m^2.a)
IND	0.05	10.0	-	-
ITA	1, 0.4, 0.18, 0.07, 0.05[9]	-	15.0	0.2
KOR	0.05	15.8[10]	12.9[10]	0.237[10]
NLD	0.06	-	4.0	65 l/(m^2.d)
NOR	50 Wh/(m^2.d)	9.6	13.1	19.22 Wh/(m^2.d)
NZL	0.07	12.0	8.1	-
SGP	0.1, 0.06[11]	12.0	16.0, 22.0[12]	-
SWE	0.05	7.6, 3.2[13]	9.0, 6.3[14]	2/η kWh/(m^2.a)[15]

[2] Respectively for spaces that require more and less than 200 lux.
[3] Note that the power density values for Austria are considered for 24 hours (not related to occupancy profiles). They are based on the consumption of the energy certificate calculations. Besides, the two values given for people and equipment power density are for heating and cooling modes respectively.
[4] Lighting power is calculated based on office geometry and other parameters according to a simplified calculation routine referred to as efficiency procedure.
[5] Derived based on stated values of 4 W/m² for internal heat gain by occupants and 90 W/person for metabolic rate.
[6] Power density is calculated based on lighting with efficacy of 60 luminaire lumens per circuit-watt and a regression-based function for zone geometry.
[7] Internal heat gains from people, lighting and equipment are not specified, only a single value of 7 W/m^2 is given for all internal heat gains.
[8] It can be multiplied by 0.7 in case daylight, occupancy or movement sensors are installed.
[9] The code offers five classes of occupant density for non-residential buildings.
[10] Based on a research effort on reference building energy models for South Korea (Kim et al. 2017).
[11] 0.1 for admin/general office room, 0.06 for director/manager room.
[12] 22 W/m2 for computer-intensive areas
[13] 7.6 for efficient lighting, 3.2 for very efficient lighting.
[14] The given value is based on estimated average power of medium level. 9.0 and 6.3 is for 100% and 70% occupancy respectively.
[15] η is the annual efficiency of hot water production.

UAE-1	0.05	8.7	8.1	-
UAE-2	0.05	10.0	-	-
USA	0.054	11.06	8.1	4.16 l/(d.person)

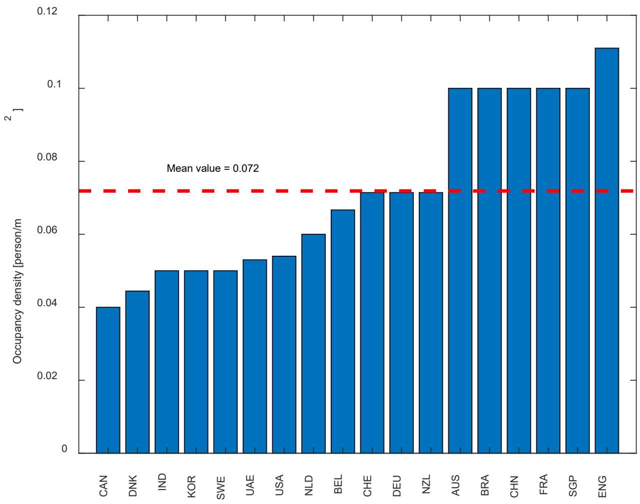

Figure 2: The values of occupancy density for offices given in national building energy codes

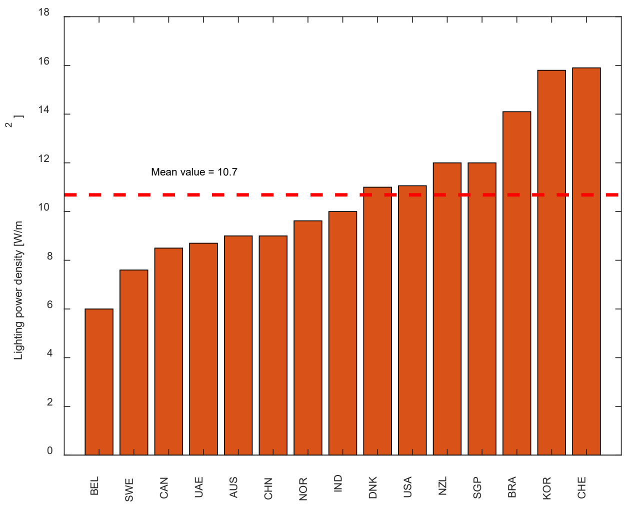

Figure 3: The values of lighting power density for offices given in national building energy codes

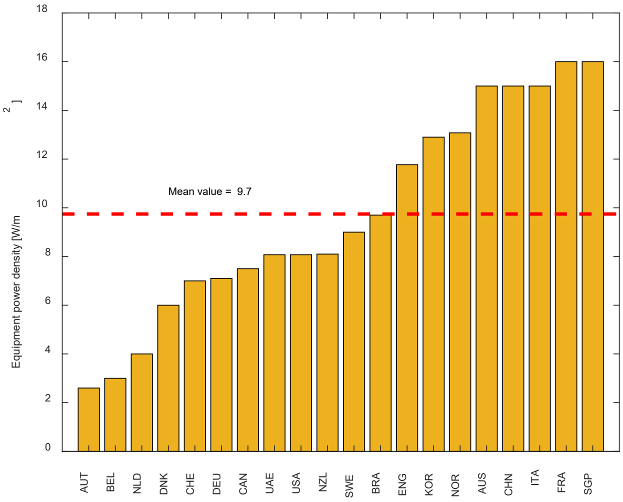

Figure 4: The values of equipment power density for offices given in national building energy codes

3.1.2 Hourly schedules for occupancy and use of lights and equipment

Among the 23 regions' reviewed codes, 11 (i.e., Australia, Brazil, Canada, China, England, France, India, Norway, New Zealand, Singapore, Sweden, and USA) are based on dynamic performance simulation – or at least have the option to use it for compliance. These codes require –and in most cases provide– hourly schedules for occupancy, use of lights and equipment (and in some cases for service hot water). Switzerland and Norway also provide such hourly profiles, even though they use monthly heat balance calculations. The other codes, which are based on a monthly calculation frequency (e.g., Germany and Denmark), only consider a Boolean pattern for nominal working hours and otherwise. Figure 5 to Figure 7 illustrate the weekday schedules for occupancy density, lighting and equipment obtained from those codes, which either offer a dynamic simulation path or explicitly consider hourly patterns on working days. Tables A.1, A.2 and A.3 provide the hourly values of these schedules.

The collected hourly profiles suggest that the cross-country variety in schedules is not as considerable as design values. Nonetheless, there are still a number of notable differences between the codes in terms of the hourly profiles associated with occupants, which are likely to result from different working cultures in the countries. For example, as illustrated in Figure 7, one can see the variety in view of the equipment base load outside nominal working hours. As it can be seen in Table A.3, this can vary from zero in case of Brazil to 40 percent of design value in case of USA. Notably, the transition to and from nominal working hours is also different among the codes. While in the majority of simulation-based codes, it takes one to two hour to reach maximum occupancy in the morning, the codes of Brazil, New Zealand and Singapore jump from fully vacant to fully occupied, which has implications for heating and cooling demand estimations. Similarly, while in a number of codes there is a clear separation between the nominal working time and following hours, in other codes the occupancy and associated load lasts until late evening. In a rather odd case, England's equipment schedule used in this study (referred to as Office_OpenOff_Equip_Wkdy in NCM database) suggests 100 percent equipment load from 17:00 to 19:00, while according to the corresponding occupancy profile (referred to as Office_OpenOff_Occ_Wkdy in NCM database) people density is assumed to be 50 and 25 percent in this period.

Another noteworthy difference is the way in which the codes treat lunch break. A number of countries' codes (such as Australia, Brazil, New Zealand and Singapore) do not suggest any reduction in terms of occupancy density and associated light and plug loads for this period of the day. However, USA and India codes, for example, suggest a reduction of 45 percent of maximum occupancy density during lunch break. India code maintains this reduction for the lighting load as well. The contributor of the French code noted that a formal lunch time (out of the office) is a widespread practice in France, though notably eight of the 11 schedules suggest that this practice is prevalent.

Aside from the abovementioned differences, it is important to note that all the occupancy profiles reach 90 to 100 percent of the maximum occupancy density. While previous studies [65, 66] underlined this as an overestimation of actual occupant patterns, the codes unanimously adopt this conservative (perhaps system-sizing oriented) approach.

Despite the diversity of schedule shapes, the daily sums (which can be interpreted as the daily number of people-hours, equipment-hours, and light-hours) are relatively consistent across the reviewed codes. The means and standard deviations for occupancy, lighting, and equipment are 9.0 ± 1.1 hours, 10.6 ± 0.8 hours, and 10.4 ± 1.9 hours, respectively. It might be expected that the daily hours and corresponding densities would be negatively correlated to yield consistent values for occupant-hours/m^2 and Wh/m^2 for lighting and equipment. However, this was not found to be the case (the R^2 values for these correlations are near-zero). Thus, the schedules and densities would appear to be derived separately without a daily target in mind.

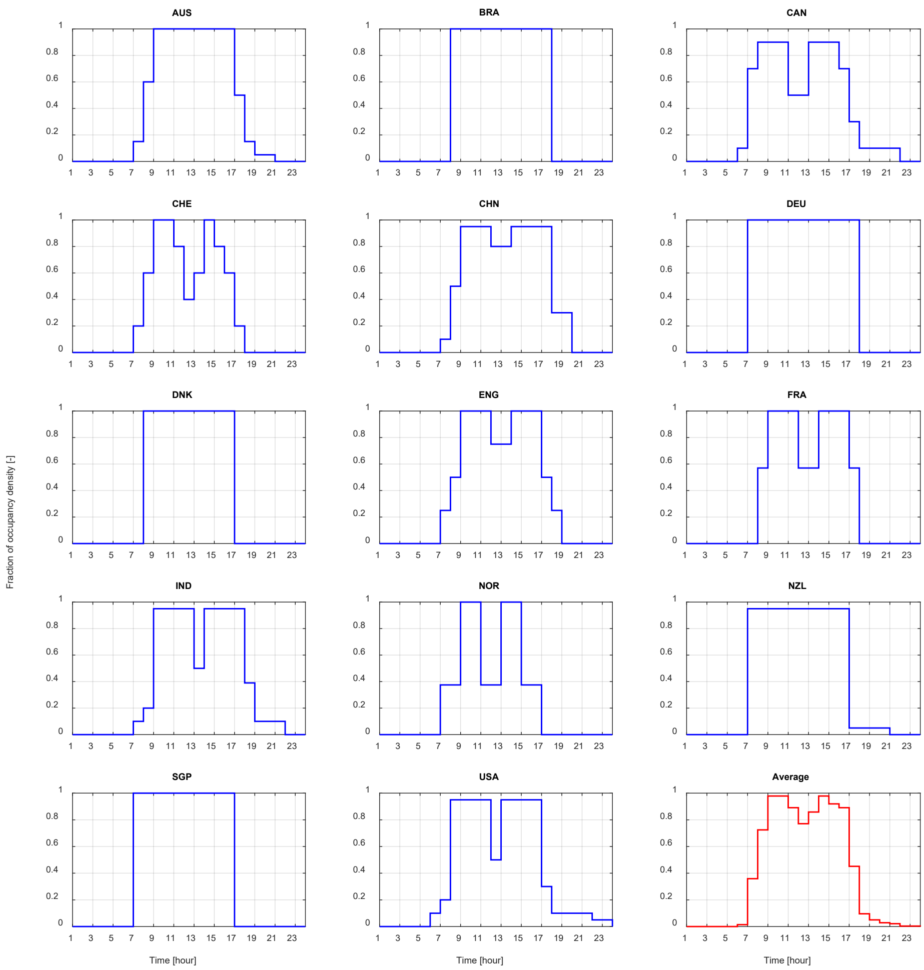

Figure 5: The schedules of weekday occupancy for offices given in national building energy codes and the average schedule

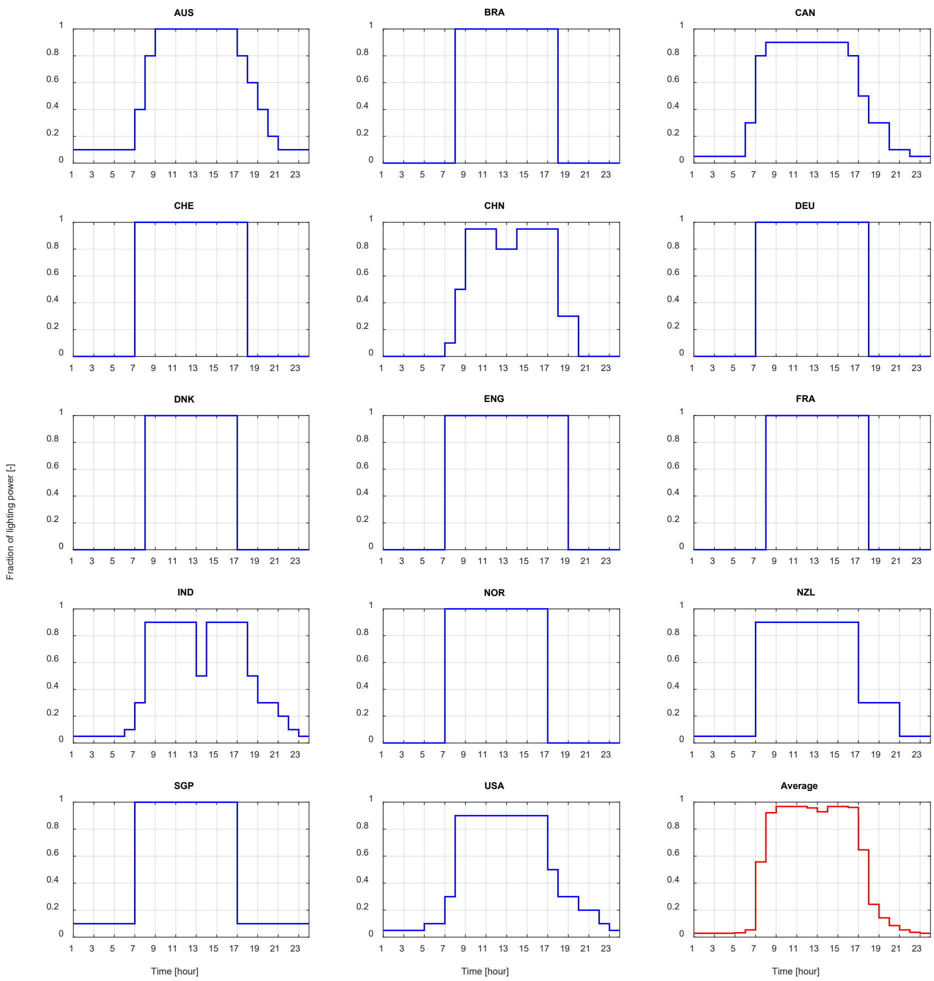

Figure 6: The schedules of weekday lighting power for offices given in national building energy codes and the average schedule

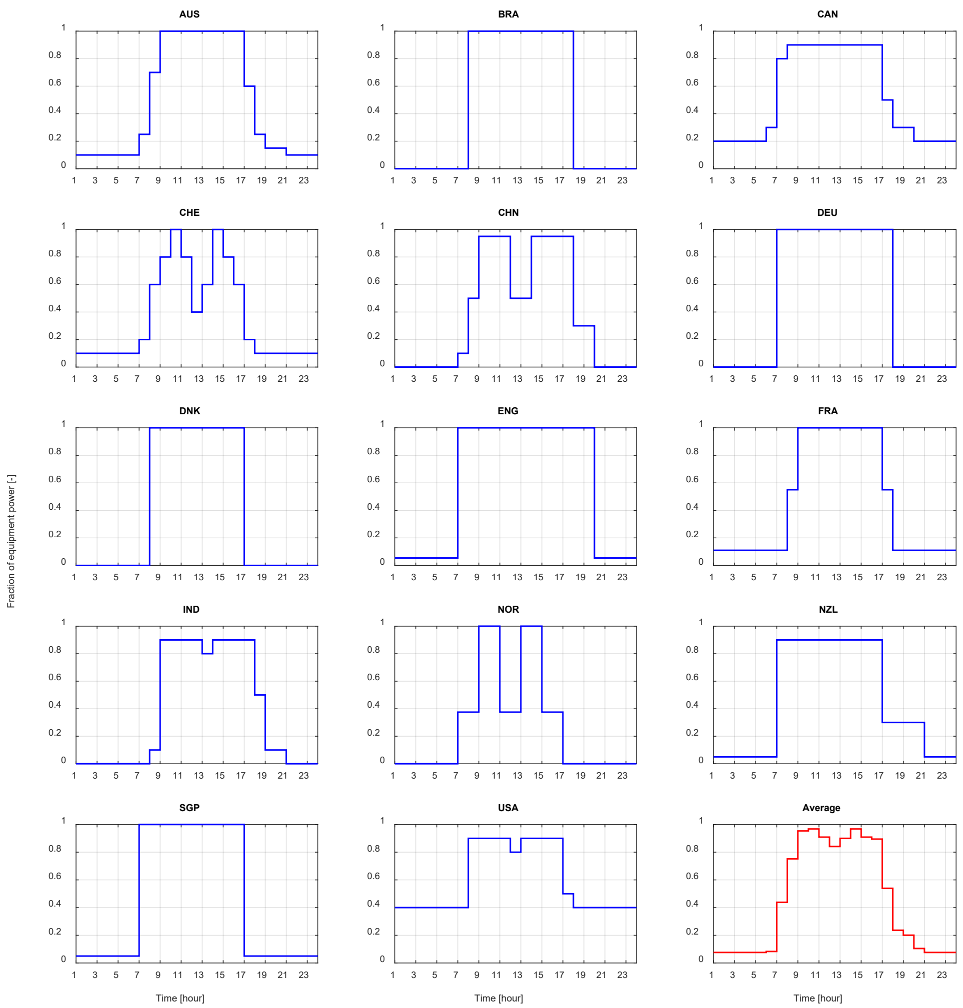

Figure 7: The schedules of weekday equipment power for offices given in national building energy codes and the average schedule

3.1.3 Lighting level, ventilation rate, setpoint and setback temperatures

While the studied building energy codes, above all, treat occupants as sources of internal heat gain for the heat balance calculations, to some degree they consider the occupant needs in terms of indoor environmental conditions. The main examples are recommendations with regard to ventilation rate and the workplane illuminance along with the heating and cooling setpoint and setback temperatures, which implicitly consider occupant thermal preferences (see Table 3). This, however, does not constitute a consideration of the interactions between occupant and control system as a result of different environmental conditions.

The 22 countries considered in the study mainly recommend a desk illuminance of 300 to 500 lux. In the French building code, the lighting power is not a conventional input value but it is decided by the modeler and needs to meet the minimum requirements set in the French Labour Code [67], which prescribes 120 lux as the minimum desk level illuminance. Such a value, given the current screen-based nature of office activities, can potentially reduce electrical energy use without compromising occupant visual comfort. Among the codes that recommend a ventilation rate per person, this varies from 6 l/(s.person) in Belgium to 11 l/(s.person) in Italy.

While none of the codes explicitly considers occupants interactions with thermostats, cooling setpoint temperature varies from 23°C in Sweden to 28°C in South Korea and heating setpoint ranges from 18°C in Australia (as the allowed minimum) and India to 22°C in Austria, Canada and England. Many codes do not consider a setback temperature (no value in the corresponding columns in Table 3), while others represent an automated adjustment of the setpoint for some degrees or do not assume any heating or cooling outside working hours (specified as *off* in the corresponding columns in Table 3).

A number of countries have further considerations for setpoint and setback temperatures. For example, Belgium code considers a temperature setback only in low inertia buildings. The French code offers two heating setback temperatures, namely 16°C for off-periods shorter than 48 hours and 7°C for off-periods longer than 48 hours. Singapore code also considers two cooling setpoints, 23°C for zones with solar gain and 25°C otherwise.

Table 3: Occupant-related recommendations and assumptions concerning lighting level, ventilation rate, heating and cooling setpoint and setback temperatures. The units are as specified in the headers unless stated otherwise.

Country	Recommended desk illuminance [lux]	Recommended ventilation rate [l/(s.person)]	Cooling setpoint [°C]	Heating setpoint [°C]	Cooling setback [°C][16]	Heating setback [°C]
AUS	320	10	26.0[17]	18.0	off	off
AUT	380	1.05 1/h	26.0	22.0	off	off
BEL	500	6	25.0	21.0	28[18]	15[18]
BRA	500	7.5	24.0	-	off	-
CAN	400	8.5	24.0	22.0	off	18.0
CHE	500	10	26.0	21.0	off	off
CHN	300	8.33	26.0	20.0	off	off
DEU	500	1.8 l/(s.m^2)	24.0	21.0	off	17.0
DNK	300	7	25.0	20.0	off	-
ENG	400	10	24.0	22.0	off	12.0
FRA	120[19]	7[20]	26.0	19.0	30	16, 7[21]
HUN	-	7	26.0	20.0	-	-
IND	300-500	8.5	26.0	18.0	-	12
ITA	300	11	26.0	20.0	-	-
KOR	-	8.05	28.0	20.0	-	-
NLD	-	1.3 l/(s.m^2)	24.0	20.0	off	18.0
NOR	-	1.94 l/(s.m^2)	24.0	21.0	-	19.0
NZL	400	10	24.0	20.0	-	-
SGP	500	0.6 l/(s.m^2)[22]	23.90, 25.0[23]	-	off	-
SWE	300-600	1.3 l/(s.m^2)	23.0[24]	21.0	-	-
UAE-1	250	8.5	23.9	-	26.7	-
UAE-2	400	8.5	24.0	-	-	-
USA	300-500	8.5	23.9	21.1	26.7	15.6

[16] Off indicates that the mechanical cooling system is turned off and the setpoint is effectively ignored.
[17] The temperature must be between the heating and cooling setpoint for 98% of operation time.
[18] The given value is for low inertia buildings. For high inertia buildings no heating or cooling setback temperature is assumed.
[19] This is the minimum desk illuminance prescribed by the French Labour Code.
[20] This is the minimum ventilation rate prescribed by the French Labour Code.
[21] 16 for off periods less than 48 hours, 7 for off periods more than 48 hours.
[22] Maximum of 0.6 l/(s.m^2) and 5.5 l/(s.person).
[23] 23 for zones with solar gain, 25 for other zones.
[24] 23 and 21 are the minimum setpoints

3.2 Phase 2: Results of qualitative code requirements

This section compares and contrasts the countries' codes regarding how occupant-related requirements are specified and the underlying philosophies. The results are presented according to the questions in the methodology section. For readability, the country is named rather than the specific building code name as per Table 1. For the first question below, contributors were asked to choose from a list of options (or specify) their code requirements for occupancy, plug-in equipment, HVAC, and operable window control. For the open-ended question that asked contributors to provide any occupant-related specifications, 167 examples were provided. Because these examples are non-exhaustive, quantitative analysis could not be performed.

3.2.1 What building systems are required to be controlled based on occupant presence?

The closed-ended survey for Phase 2 yielded the results that are summarized in Table 4. Note that the current focus is on categorizing the codes requirements into broad categories, while the following sections analyze the details in greater depth. The results do not appear to strongly correlate to the values from Phase 1. For example, the countries with the highest allowable lighting power density (e.g., Brazil, South Korea, and Switzerland are all above 14 W/m^2) do not typically have more stringent lighting control requirements than the others. The situation is similar for demand-controlled ventilation, where the codes requiring the highest ventilation rates are not necessarily more likely to require demand-controlled ventilation (DCV). Correlations aside, Table 4 shows significant room for improvement with regards to mandating occupancy-based controls to help reduce energy wastage when occupants are not present. While contributors were asked about occupancy-based receptacle control (e.g., smart plugs), only the American codes was reported to require this (further details in Section 4.1).

Table 4: Summary of code requirements for the occupancy-related automation of lighting, plug-in equipment, HVAC, and operable windows

Country	Occupancy-based lighting controls requirement	Occupancy-based HVAC controls	Operable window automation or sensing
AUS	Vacancy-off /daylight-controlled	Vacancy-off	Allowed; not controlled
AUT	Vacancy-off/daylight-controlled	DCV is credited	For mechanical ventilation,
BEL	Vacancy-off /daylight-controlled	DCV is credited	None
BRA	Vacancy-off /daylight-controlled lighting is credited, but not required	DCV is credited	None
CAN	Vacancy-off /daylight-controlled	DCV is credited	None
CHE	Vacancy-off /daylight-controlled	None	None
CHN	Vacancy-off /daylight-controlled	None	None
DEU	Daylight-controlled in the reference building	DCV in reference building	None
DNK	Daylight-controlled	None	None
ENG	Vacancy-off /daylight-controlled lighting is credited, but not required	DCV is credited	None
FRA	Vacancy-off /daylight-controlled	HVAC must be equipped with occupancy sensors or window sensors as a control input	
HUN	None	None	None
IND	Vacancy-off /daylight-controlled	DCV required for large densely-occupied spaces	None
ITA	Vacancy-off /daylight-controlled	DCV is credited	None
KOR	Vacancy-off /daylight-controlled	DCV is credited	None
NLD	Vacancy-off /daylight-controlled	DCV is credited	None
NOR	None	DCV is credited	None
NZL	Manual, automated, or both	DCV is credited	None
SGP	Vacancy-off /daylight-controlled	DCV is credited	None
SWE	Vacancy-off /daylight-controlled	DCV is credited	None

UAE-1	Vacancy-off	DCV is credited	None
UAE-2	Vacancy-off	DCV required for large densely-occupied spaces	None
USA	Vacancy-off /daylight-controlled	DCV is credited	None

3.2.2 What aspects of buildings are considered in the context of occupants?

The vast majority of the collected occupant-related code requirements involve HVAC equipment, lights, and window blinds/shades. Other occasional mentions include escalators and moving sidewalks, water use, and plug/receptacles loads. Very few requirements address details of manual systems, such as usability, nature of interface, and required feedback to occupants (e.g. energy dashboard).

3.2.3 What terms do building codes use to refer to, or imply, occupants?

Overall, there is minimal explicit mention of occupants in the building codes reviewed. Numerous contributors stated that they struggled to find just five mentions of occupants in their respective building energy code. Most of the occupant-related requirements relate to whether the building is occupied or not, occupancy sensors, and the degree to which building systems (HVAC and lighting, primarily) should be manual or automated. For example, many countries' codes specify that certain HVAC equipment (e.g., air conditioners) or lighting must be capable of being manually turned off or adjusted. The lack of explicit mention of occupants is likely rooted in the fact that building codes specify design and technology requirements rather than occupant requirements.

3.2.4 How simple or complex are occupants treated?

In contrast to recent international collaborative efforts [e.g., 9], all reviewed building energy codes treat occupants in very simplistic ways – though to varying degrees. The predominant methods are listed below, followed by examples and discussion.

Assume the system (e.g., window shade) is not used at all. This method is particularly common for window blinds/shades; according to some building codes (e.g., Canada, India, New Zealand), blinds shall not be modeled (i.e., they are modeled as fully open). This may either because shade use is considered too uncertain or reliant on occupants or because shade system selection is not considered part of the code – both of which are unfortunate considering their impact on energy and comfort. It may also be aimed at providing a conservative assumption for cooling-dominated climates. Models to predict shade use are relatively mature and shade fabric selection is important for solar gains control and visual comfort [68, 69].

Assume the system is partially used. Recognizing that the above assumption is unrealistic as per numerous field studies [70, 71], several codes use a more typical and moderate approach. In the French code, shades and windows can be either automated or manually controlled. When they are automated, during occupied hours, occupants can override the automatic operation of shades and windows. Hence, it is assumed that a given percentage of windows and shades are always manually operated. In the code it is written that this percentage depends on behavioral and building contextual factors (such as accessibility of the windows). Hungary requires that the mean properties for shades open and closed be used to model windows. The USA does the same for manually-controlled dynamic glazing (e.g., electrochromic windows). In Austria, the code allows users to decide whether occupants predictively or reactively adjust shades to address thermal discomfort. In the former case, the shade is assumed to be 50% closed, whereas the latter is 25% closed.

Furthermore, instead of assuming the shades open or closed, the Swedish codes introduce the factor of the shade to be 0.71 for the manually controlled condition related to the user behavior.

Provide fixed credit depending on the level of manual or automation of systems (e.g. lighting). Numerous codes (e.g. Australia, Norway, Singapore, USA, Canada) give credit through prescriptive and/or performance paths to motion sensors that control lighting. Such credit is normally assigned as a decrement to the full lighting energy or power density. Belgium gives credit to annual lighting energy if a control system is present; however, it gives four times as much credit for automatic control (40%) versus manual switching (10%). Australia allows a 30% reduction in modeled lighting power density if a motion detector is linked to a zone of three to six luminaires and 45% reduction if it is one or two luminaires. Norway gives 20% credit if lighting is automatically controlled by daylight or occupancy. Singapore defines a power saving factor of 15% for lighting system with occupant sensing control.

Schedules and densities for the performance path. As evident from Phase 1, schedules and densities are a common approach to specify occupancy and behavior for performance paths of codes. However, the flexibility of modifying schedules varies widely. For example, for Canada, India, and the US, the schedules can be modified if better information is available, but all values must be equal for the reference and design buildings. In fact, NECB states the default schedules should only be used if "more accurate information is not available". In contrast, New Zealand's code requires that default values be used unless a different schedule can be justified as being likely for the building's life. NECB also states "the reference building's operating schedules shall be modeled as being identical to those determined for the proposed building". For the American and Canadian codes, the schedules of the proposed building can only differ from the reference building schedules if used to model efficiency measures (e.g., automated lighting controls)

Rule-based operation of equipment. Relatively few codes have this more advanced form of occupant modeling, where occupant behavior depends on indoor or outdoor conditions. For the French code, occupants are assumed to keep the windows open even if the outdoor air temperature is higher than the indoor air temperature. Interestingly (and quite realistically [72]), window opening is assumed to be affected by noise, depending on the nature of, distance to, and obstruction of the noise source. In the American code's building envelope trade-off option, shades are assumed to be closed when the transmitted luminous intensity is exceeds 2000 cd/m^2 or the direct solar transmitted energy exceeds 95 W/m^2; they then remain closed for the rest of the day (which incidentally corresponds to the Lightswitch-2002 model [69]). In contrast, for the French code, manual shade positions are assumed to vary linearly with the incident light and depending on the type of shade (shutter, roller blind, venetian blind), on the season (winter, mid-season and summer), on the indoor air temperature in the previous time step and on the wind speed (for the case of venetian blinds). France also assumes lights are controlled linearly with daylight levels. The English code requires the reference building to have natural ventilation modeled such as to yield up to five air changes per hour if the indoor temperature exceeds the heating setpoint by 1°C. This requirement is intended to produce a neutral effect that is neither overly adverse nor beneficial.

3.2.5 What do building codes assume about occupant behavior and its ability to reduce energy use or improve comfort?

The degree to which the reviewed codes imply an expectation that occupants will behave to save energy varies greatly between countries. Some countries credit occupants for behaving in ways that improve comfort or energy performance, while others assume occupants cannot be relied upon. To some extent, this range is appropriate considering the severity of the climates they cover.

Several codes provide explicit statements on their philosophy regarding occupants. For example, the National Energy Code of Canada for Buildings (NECB) takes a strict stance that occupants cannot be relied upon to improve energy performance: “provided it…is not dependent on occupant behavior”. In a less direct way, the American code gives a similar message: “In no case shall schedules differ where the controls are manual (e.g., manual operation of light switches or manual operation of windows).” The North American approach has a tendency to reward greater levels of automation rather than providing features such as manual operable windows and blinds that are understood to improve perceived control and comfort [e.g., 73]. The German code states that boundary conditions related to occupants and the associated operations are aimed at neutral evaluation for the sole purpose of determining energy demand. The Swedish code states that energy calculation should be carried out based on the actual conditions and be verified with the measurement during user stage. Similarly, the Indian code acknowledges that actual energy use depends on occupant behavior and other factors that cannot be controlled for during design. France’s code states that the provided schedules are as close as possible to average conditions, but that they cannot be expected to predict energy consumption during the operating phase of the building.

The English code also indirectly provides some hints at the underlying philosophy: “A centralised switch would be more reliable than depending on each individual occupant to, for example, switch off their computer.” In a more specific example, for the performance path, the Canadian, Australian, and American codes alike do not allow window shading devices to be modeled favorably (or at all) unless they are automated. This stance may be as a result of the concern that building owners are motivated to inflate predicted performance [74]; occupants are not only uncertain but their positive behavior is difficult to disprove. For other codes, the target appears to be more realistic (e.g. partially closed shades discussed in the previous section).

France’s code credits occupants with saving energy, as it assumes manual systems are allowed to be controlled quite effectively. For instance, it assumes window shades are controlled linearly with respect to indoor illuminance, which is quite optimistic considering that shades often remain closed for days or weeks after they are initially closed (O’Brien et al. 2014). It also mandates that operable windows be closed below 8°C outdoor air temperature and increased open opening linearly till 16°C, when the windows are fully open. Windows are only to be opened when mechanical cooling is off, whereas in reality occupants may leave windows open regardless of the mechanical system status. However, for heating systems, a window contact sensor must be provided (presumably to ensure that heating is deactivated or turned down if a window is open).

Numerous reviewed building energy codes (e.g., China, India, USA) require occupancy sensing to turn off devices, thus implying a certain level of distrust (though realism) that occupants will turn it off prior to departure. Similarly, Brazil, Canada, the UAE, and the USA require motion sensors that turn lights off if a space is unoccupied. Canada’s code gives some credit to occupants exploiting daylight, but still favours automation: “Research shows that, where a manual control is installed, the human eye acts as the photosensor and occupants take it upon themselves to lower electric lighting levels if sufficient daylight is available. However, manual controls are not as effective a means to save energy as automatic ones.”

To require or disallow occupants to override automation systems indicates whether the code expects occupants to behave in such a way to save energy. For example, the Indian code does not allow daylight-based lighting controls to be overridden by occupants. In contrast, the Danish code requires that occupants be able to override automated motorized windows. Similarly, the French code requires occupants to be able to override automated window shade controls. The Canadian and American codes allow overrides for various scheduled HVAC and lighting control modes, but the overrides are limited to one or two hours (after which they must be reset), depending on the instance.

4 Discussion

In general, the results of both phases of the research above indicate that occupant-related code requirements are quite simplistic. However, they vary greatly with regards to magnitudes (e.g. occupant density and schedule), simplicity (e.g. fixed schedule vs. dynamic models), crediting occupant for energy savings, and scope. In this regard, it is important to note that one does not expect identical assumptions and modeling approaches with regard to occupants. On the contrary, from the authors' view, it would be ideal if each code reflects the unique culture in its country, while improving standardization and consistency where such differences are not merited. This could, for example, be achieved through an international committee (e.g. the IEA EBC Working Group on Building Energy Codes) as a follow-up to this paper. For some of the current codes' quantitative assumptions such as occupancy density or working hours, it is not surprising to see a large degree of variation across the codes commensurate with cultural, technological, and other contextual factors. However, without knowledge of the empirical basis behind the codes, the present study does not aim to explain the differences between the codes, but to put to the codes' approaches and assumptions in an international context to identify possibilities for improvements in future efforts.

The remainder of this section is forward looking and provides broader insights by reviewing some innovative code requirements, and also providing a series of potential areas for improvement to all codes.

4.1 Unique occupant-related code requirements

As an extension to Phase 2, this section highlights code requirements that were found to be unique and relatively demanding regarding occupants – and could be considered for future codes. The authors do not claim these are effective or more important than more fundamental requirements (e.g., schedules).

Personal or high-resolution day/lighting and HVAC control. Several of the codes restrict the control zone size or area affected by HVAC and day/lighting systems to: 1) reduce the impact that one occupant has on another and 2) reduce energy wastage in partially or unevenly occupied buildings. Many codes (e.g., Australia, Canada, France, USA, and Brazil) restrict lighting control zones to reduce the frequency of having partial or low occupancy but lights on. A seemingly unique requirement to UAE-1 is the requirement that internal window shades be no wider than four meters and directly controllable by occupants. This helps to ensure that occupants can somewhat personalize the level of daylight and glare they are subjected to. China requires that dissimilarly occupied spaces not be served by the same constant air volume (CAV) system. In Denmark, the compliance documentation must explain how individuals are provided with control via readjustment of diffusers for personal ventilation, temperature setpoint, operable windows, and the size of control zones and potential impact on other occupants. The Canadian code offers interesting insights: "Furthermore, occupants are much more likely to use manual controls if they have sole responsibility for a space than if they share a space: the [daylighting credit given for manual lighting controls in daylit spaces] for private enclosed offices is therefore [five times] higher than for other space types with manual controls." These requirements about spatial scope of controllability are particularly critical as we begin to recognize the diverse nature of individual occupant's schedules and preferences for indoor conditions [75, 76].

Usability. There is a limited mention of usability among the reviewed code requirements. A recurring requirement for numerous countries (Canada, US, and New Zealand) is that lights be visible from where they are controlled (e.g., from the light switch) unless safety would be at risk. This ensures that occupants are aware of the lights that they are controlling and are also more cognisant of leaving them on upon departure. In Denmark, indoor thermal conditions are required to be controlled in a simple way. Moreover, if one occupant can negatively affect another's thermal comfort, the range of controllability must be limited.

Demand controlled ventilation. Numerous codes (e.g., Canada, Germany, UAE, USA, Austria) require demand-controlled ventilation, though it is often limited to high-density and relatively large spaces (see Section 3.2.1). For instance, the American code requires DCV in spaces larger than 50 m^2 and occupant densities above 0.25 person/m^2 (much higher than offices). In light of higher occupancy variations than the code schedules (see Section 3.1) imply, DCV is often much more effective than predicted [26]. In Switzerland, the regular occupancy schedule in private and shared offices is to be reduced by 20%. This is sensible (and perhaps not enough), considering various monitoring studies, showing private offices are typically occupied only 50% as much as office building schedules would suggest [77].

Occupancy-controlled lighting. Several of the codes (e.g., Canada, USA) have strict rules against occupancy-on lighting controls (i.e., motion sensors tied to automatically turning on lights). This is particularly important for daylit spaces. Significant evidence [e.g., 78] shows that occupants are unlikely to turn on lights even if there is daylight illuminance that is an order of magnitude lower typical recommended levels. Gilani and O'Brien [79] measured 62% energy savings when occupancy-on lighting controls were replaced with manual-on lighting controls in perimeter offices. These same codes require lights to be automatically turned off after 20 minutes of absence.

Receptacle control. Unique to the reviewed code requirements, the USA code requires centralized receptacle control. The requirement requires that at least half of receptacles in offices be turned off on a schedule or occupancy basis. Considering the growing share of plug loads in building energy end-use breakdowns, this appears to be an appropriate requirement. However, future research is required regarding occupants requiring remote desktop access and their ability to simply plug equipment into uncontrolled receptacles [80].

Occupant engagement. Several of the reviewed codes are quite progressive regarding occupant engagement and feedback. In the case of UAE-1, designers can earn credits for demonstrating "sustainability communication" actions. These include developing a guide for how to use and maintain the building, which covers: description of energy and water efficiency features and how occupants affect them; information on the building's indoor environmental quality (IEQ) and how it is measured and managed; materials and their environmental and social considerations; waste management strategy; recommendations for tenant fit-ups (e.g., lighting) and, details on availability of public transportation and bicycle facilities. Moreover, they must also provide a written plan for distributing the handbook to occupants. Additional credits can be earned by demonstrating the use of digital dashboards, or the equivalent, to provide feedback to occupants about building energy use and how they affect it. Documentation must be submitted at the time of code compliance to show such digital interfaces and how they affect user experience. As for the UAE-2 code, the highest certification level (gold) requires the building operator to develop and provide a clear mechanism for promoting sustainability awareness among building users and rationalize the consumption of energy and water in the building. A similar approach is proposed by the Singapore Green Mark Scheme. A total of three points are allocated to the User Engagement indicator, which refers to the provision of building user guide, sustainability awareness and education program, and other related information.

4.2 Approaches to advance building codes

This section proposes six categories of methods to improve the occupant-related aspects of building codes, building upon work of O'Brien, Ouf, Gunay, Gilani, Abuimara and Abdelalim [81]. As previously discussed, the benefit of new code requirements must outweigh the costs. Key considerations include ability for code users to meet requirements, ability to enforce requirements, cost to comply, and potential negative impacts on policy and other unintended consequences. The following approaches are approximately in the order of simplest to more complex.

4.2.1 Add prescriptive requirements based on the literature

Prescriptive requirements, such as Canada and the USA's requirement that occupants can see the luminaire(s) that light switch control, are most suitably added as prescriptive requirements. Such subtleties are difficult to model in building simulation. Additional areas that would be suitable for prescriptive requirements include usability of buildings and interfaces, occupant feedback, control zone sizes, requirements for window shades and operable windows, etc. To a large extent evidence and justification for new code requirements could be obtained from the literature, though likely focused studies are required as well.

4.2.2 Add prescriptive requirements based on occupant simulation studies

Similar to the point above, new prescriptive requirements could be added on the basis of simulation studies. For example, maximum lighting and HVAC control zone size requirements could be re-evaluated on the basis of more realistic contemporary office occupancy scenarios. These requirements should include both system (lighting, HVAC, envelope, etc.) parameters as well as the technologies and configurations enabling them to be operated efficiently (e.g., demand-controlled ventilation, occupancy-based lighting). For instance, O'Brien and Gunay [26] used stochastic occupancy modelling to evaluate the impact of lighting control zone size, and consequently recommended that lighting control zones be reduced by a factor of five. Given the relatively advanced nature of stochastic occupant models, additional prescriptive requirements could be added to cover other domains, such as lighting, window shades, operable windows, receptacles, thermostats, etc.

4.2.3 Update schedules based on new field studies

While advanced occupant modelling may be beyond the comfort of code committees, schedules already exist in the majority of building codes (as indicated by Phase 1). Accordingly, schedules are a relatively low-risk/low-effort way to update building codes. It is widely accepted that existing schedules are generally not very realistic and quite outdated (e.g., by three or more decades [82]). For example, occupancy is typically much lower than schedules indicate [77]. Societal trends, such as remote working, are expected to further increase this discrepancy, though this may be somewhat balanced by hotelling-style office management [83]. Similarly, plug loads tend to be lower during the day (perhaps because of lower occupancy) and higher during the night than schedules would indicate [84]. While some extensive field studies have been performed to yield new schedules, further studies [e.g., 85] should be performed in different building types and climates to build confidence in these schedules. Moreover, new building automation and sensing technologies (some of which are conveniently required by code, e.g., ASHRAE [15]) should be employed for such studies to reduce costs and improve study size and duration.

4.2.4 Develop schedules that cover a greater scope of occupant behavior based on detailed simulation studies

Existing schedules tend to focus on non-adaptive occupant domains (e.g. occupancy, plug loads) and water, thermostat setpoints, and general lighting. However, window shades, operable windows, and other adaptive opportunities are generally absent by means of schedules. It would be feasible to build climate and building-specific schedules by running simulation studies that involve advanced occupant models. For example, Ouf, O'Brien and Gunay [86] showed that semi-customized lighting and window shade schedules could be built by running numerous annual simulations. They used a decision tree and clustering to reduce simulation results to three different schedules: low, medium, and high.

4.2.5 Require multiple occupant scenarios to be simulated to better represent a range of possibilities

An argument for using fixed and mandated schedules in building energy codes to model occupants is that while there is uncertainty about occupants, at least this approach can offer consistency [24]. However, this approach risks causing designers to optimize buildings for one set of occupant assumptions, while neglecting other scenarios (e.g., low and partial occupancy) [26]. Moreover, occupants and tenants may change over the course of a building, given that buildings often outlast the life of a company, its employees, and the technologies they use. One approach to address this uncertainty is to mandate that several occupancy and occupant-related scenarios be modeled and then set constraints on the aggregate performance (e.g., the proposed building model must perform better than the reference building model for three different occupancy scenarios).

4.2.6 Specify the occupant modeling approach required

Finally, occupant-related requirements could be updated by mandating more advanced occupant modelling approaches. In particular, we recommend modelling approaches that demonstrate the adaptive nature of occupants and that recognize that better building design can positively affect energy-related occupant behaviors. This could be particularly applied for key adaptive behaviors, such as operable windows, window shades, lighting, and thermostats. While not covered by the reviewed codes and standards, a notable example IES LM 83-2012 [68], which mandates that window shades be closed whenever a point on the workplane exceeds 1000 lux. Such rules would reward buildings with appropriately-sized windows and strategically-designed fixed shading that transmits comfortable levels of daylight.

While much of the recent scientific literature is focused on stochastic occupant models [e.g., 87, 88], we argue that they are not suitable for building energy code purposes – at least for the foreseeable future. Stochastic occupant models yield a different result every time a simulation is run, which causes complexity when performance paths of building codes rely on single simulations. Moreover, the definition of these models (which usually involves a model form and coefficients) are not particularly transparent or easy to enforce, unlike basic rules-based models. Despite the trend towards agent-based stochastic models, the collected data that was used to build those models could also be re-used to develop simple rule-based models.

4.3 Adding requirements for building usability

One of the most notable omissions is requirements for occupant usability of buildings and their systems. In particular, this topic includes usability of interfaces (e.g., occupant instructions, feedback, location of interface, nature of interfaces). Usability may not appear to be energy-related, but it plays an important role in how occupants use energy in buildings [89]. While this is a gap in building energy codes, several rating systems (e.g., WELL, LEED) have addressed usability to some extent. These requirements could be incorporated into building energy codes, as they certainly indirectly affect energy. Some example requirements or items for credit in these standards include:

- "Indicator lights at windows and/or online notifications signal to regular building occupants when outdoor air allows for open windows (with various IAQ and temperature conditions)" [90]. This requirement improves usability by providing cues to occupants about advantageous window opening actions, while still providing individual control to occupants [91].
- "All operable windows in regularly occupied spaces comply with the following requirements:
    - Provide enough space to permit occupants to approach and operate them (from both a standing and seated position).
    - Are operable with one hand and with a closed fist and do not require tight grasping, pinching or twisting of the wrist.
    - Require less than 22 N [5 lbs] of force to open [90]."

  This requirement ensures that operable windows are not only provided to meet conditions but that they are usable even by occupants who are constrained to wheelchairs [92].
- "All regular building occupants have control over temperature through either:
    - Thermostats present within the thermal zone.
    - Digital interface available on a computer or phone [90]."

  This requirement acknowledges the importance of personal control over temperature due to both the value of perceived control and the inter-occupant differences in preferences for thermal conditions [93]. Note that many of field implementations of occupant-centric building control studies are focused on bringing occupants back in the control loop [94].
- "In all regularly occupied and shared spaces within the same heating or cooling zone, regular building occupants have access upon request to personal thermal comfort devices (e.g., personalized fans, heated/cooled chairs, and others, except combustion-based space heaters) that provide individual user control of air speed, air temperature and/or mean radiant temperature" [90]. Similar to the point above, this requirement recognizes the value of perceived control and the ability to customize thermal conditions for individual occupants. Moreover, these devices tend to be lower in energy-intensity than centralized HVAC systems.
- Similar to above, "Thermal comfort controls allow occupants, whether in individual spaces or shared multi-occupant spaces, to adjust at least one of the following in their local environment: air temperature, radiant temperature, air speed, and humidity" [95].

It is noteworthy that the above example requirements not only go into significantly more detail than the building energy codes, but they are also supported by an extensive body of literature and ergonomics standards. However, we do not suggest that all requirements of WELL and LEED should be adopted by building energy codes, as they have a different objective.

5 Conclusion

Considering the impact of building energy codes and the corresponding simplicity of the way occupants are handled by them, this paper sought to provide an international review of occupant-related requirements in building energy codes and standards. Ultimately misguided occupant-related code requirements –for prescriptive and performance paths alike— may mislead designers towards suboptimal building designs.

The 23 regions' codes or standards were reviewed in two phases. Phase 1 focused on quantitative requirements relating to schedules, densities, and setpoints, as well as the general code objective, which revealed a wide range of occupant-related values concerning people density, lights, equipment and hot water use to standardize occupants in the path to meet performance targets such as secondary or primary energy use, emission rate or water consumption. The review showed considerable variations across the codes with regard to the occupancy, lighting and equipment power density values. While these can likely be partly assigned to cultural and contextual differences, the study put the occupant-related assumptions in an international context to facilitate the future efforts to develop occupant-centric building energy codes. In particular, the study results suggest that the efforts to explicitly address occupant behavior in the codes cannot overlook the implications of local contextual factors. An obvious next step in research is to carefully trace the roots of each occupant-related code-requirement to understand their origin. For example, if the same schedule values have been used for the past several decades, updates based on more recent measured data should be considered.

Phase 2 was focused on written code requirements. These code requirements were compared with the objective of identifying similarities, differences, and exemplary and noteworthy features. The review concluded that while code requirements and underlying philosophies about occupants are diverse, they are generally quite simplistic and have not kept up with the scientific literature. For example, the majority of performance path (i.e. modelling-based) requirements do not adequately acknowledge design as a way to positively influence occupant behavior because they assume that behavior is the same in reference and design buildings (e.g., through schedules). Moreover, there is a lack of requirements for usability of buildings and their systems. Aside from perceived control for occupants and comfort implications, lack of usability could also have energy implications because occupants who cannot use buildings as they were intended are more likely to take energy-adverse actions to restore their comfort.

For future research, we recommend the following foci:

- More field studies to collect long-term data in a variety of contexts (countries, building types) to improve confidence of both schedules (and densities) and potentially more advanced occupant models (e.g., agent based and dynamic).
- More field and simulation studies to support the updating of prescriptive requirements – especially regarding control zone sizes, control algorithms, and building system usability.
- An international committee to review all aspects of building energy codes, including occupant-related aspects. While there are some inherent differences between different regions' cultures and climates, a more consistent approach whereby the best alternatives are used, would be beneficial. In fact, International Energy Agency's Energy in Buildings and Communities Programme has started a standing committee that is tasked with reviewing national building energy codes.

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A Schedules of occupancy, light and equipment use

Table A.1: The schedules of weekday occupancy for offices given in national building energy codes together with the average schedule (AVG)

Hour of day	Fraction of maximum occupancy density														
	AUS	BRA	CAN	CHE	CHN	DEU	DNK	ENG	FRA	IND	NOR	NZL	SGP	USA	AVG
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0.1	0.01
8	0.15	0	0.7	0.2	0.1	1	0	0.25	0	0.1	0.38	0.95	1	0.2	0.36
9	0.6	1	0.9	0.6	0.5	1	1	0.5	0.57	0.2	0.38	0.95	1	0.95	0.72
10	1	1	0.9	1	0.95	1	1	1	1	0.95	1	0.95	1	0.95	0.98
11	1	1	0.9	1	0.95	1	1	1	1	0.95	1	0.95	1	0.95	0.98
12	1	1	0.5	0.8	0.95	1	1	1	1	0.95	0.38	0.95	1	0.95	0.89
13	1	1	0.5	0.4	0.8	1	1	0.75	0.57	0.95	0.38	0.95	1	0.5	0.77
14	1	1	0.9	0.6	0.8	1	1	0.75	0.57	0.5	1	0.95	1	0.95	0.86
15	1	1	0.9	1	0.95	1	1	1	1	0.95	1	0.95	1	0.95	0.98
16	1	1	0.9	0.8	0.95	1	1	1	1	0.95	0.38	0.95	1	0.95	0.92
17	1	1	0.7	0.6	0.95	1	1	1	1	0.95	0.38	0.95	1	0.95	0.89
18	0.5	1	0.3	0.2	0.95	1	0	0.5	0.57	0.95	0	0.05	0	0.3	0.45
19	0.15	0	0.1	0	0.3	0	0	0.25	0	0.39	0	0.05	0	0.1	0.09
20	0.05	0	0.1	0	0.3	0	0	0	0	0.1	0	0.05	0	0.1	0.05
21	0.05	0	0.1	0	0	0	0	0	0	0.1	0	0.05	0	0.1	0.03
22	0	0	0.1	0	0	0	0	0	0	0.1	0	0	0	0.1	0.02
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0
Sum	9.50	10.00	8.60	7.20	9.45	11.00	9.00	9.00	8.28	9.09	6.28	9.70	10.00	9.20	9.00

Table A.2: The schedules of weekday lighting power for offices given in national building energy codes together with the average schedule (AVG)

Hour of day	Fraction of maximum lighting power														
	AUS	BRA	CAN	CHE	CHN	DEU	DNK	ENG	FRA	IND	NOR	NZL	SGP	USA	AVG
1	0.1	0	0.05	0	0	0	0	0	0	0.05	0	0.05	0.1	0.05	0.03
2	0.1	0	0.05	0	0	0	0	0	0	0.05	0	0.05	0.1	0.05	0.03
3	0.1	0	0.05	0	0	0	0	0	0	0.05	0	0.05	0.1	0.05	0.03
4	0.1	0	0.05	0	0	0	0	0	0	0.05	0	0.05	0.1	0.05	0.03

5	0.1	0	0.05	0	0	0	0	0	0	0.05	0	0.05	0.1	0.05	0.03
6	0.1	0	0.05	0	0	0	0	0	0	0.05	0	0.05	0.1	0.1	0.03
7	0.1	0	0.3	0	0	0	0	0	0	0.1	0	0.05	0.1	0.1	0.05
8	0.4	0	0.8	1	0.1	1	0	1	0	0.3	1	0.9	1	0.3	0.56
9	0.8	1	0.9	1	0.5	1	1	1	1	0.9	1	0.9	1	0.9	0.92
10	1	1	0.9	1	0.95	1	1	1	1	0.9	1	0.9	1	0.9	0.97
11	1	1	0.9	1	0.95	1	1	1	1	0.9	1	0.9	1	0.9	0.97
12	1	1	0.9	1	0.95	1	1	1	1	0.9	1	0.9	1	0.9	0.97
13	1	1	0.9	1	0.8	1	1	1	1	0.9	1	0.9	1	0.9	0.96
14	1	1	0.9	1	0.8	1	1	1	1	0.5	1	0.9	1	0.9	0.93
15	1	1	0.9	1	0.95	1	1	1	1	0.9	1	0.9	1	0.9	0.97
16	1	1	0.9	1	0.95	1	1	1	1	0.9	1	0.9	1	0.9	0.97
17	1	1	0.8	1	0.95	1	1	1	1	0.9	1	0.9	1	0.9	0.96
18	0.8	1	0.5	1	0.95	1	0	1	1	0.9	0	0.3	0.1	0.5	0.65
19	0.6	0	0.3	0	0.3	0	0	1	0	0.5	0	0.3	0.1	0.3	0.24
20	0.4	0	0.3	0	0.3	0	0	0	0	0.3	0	0.3	0.1	0.3	0.14
21	0.2	0	0.1	0	0	0	0	0	0	0.3	0	0.3	0.1	0.2	0.09
22	0.1	0	0.1	0	0	0	0	0	0	0.2	0	0.05	0.1	0.2	0.05
23	0.1	0	0.05	0	0	0	0	0	0	0.1	0	0.05	0.1	0.1	0.04
24	0.1	0	0.05	0	0	0	0	0	0	0.05	0	0.05	0.1	0.05	0.03
Sum	12.20	10.00	10.80	11.00	9.45	11.00	9.00	12.00	10.00	10.75	10.00	10.70	11.40	10.50	10.65

Table A.3: The schedules of weekday equipment power for offices given in national building energy codes together with the average schedule (AVG)

Hour of day	Fraction of maximum equipment power														
	AUS	BRA	CAN	CHE	CHN	DEU	DNK	ENG	FRA	IND	NOR	NZL	SGP	USA	AVG
1	0.1	0	0.2	0.1	0	0	0	0.05	0.11	0	0	0.05	0.05	0.4	0.08
2	0.1	0	0.2	0.1	0	0	0	0.05	0.11	0	0	0.05	0.05	0.4	0.08
3	0.1	0	0.2	0.1	0	0	0	0.05	0.11	0	0	0.05	0.05	0.4	0.08
4	0.1	0	0.2	0.1	0	0	0	0.05	0.11	0	0	0.05	0.05	0.4	0.08
5	0.1	0	0.2	0.1	0	0	0	0.05	0.11	0	0	0.05	0.05	0.4	0.08
6	0.1	0	0.2	0.1	0	0	0	0.05	0.11	0	0	0.05	0.05	0.4	0.08
7	0.1	0	0.3	0.1	0	0	0	0.05	0.11	0	0	0.05	0.05	0.4	0.08
8	0.25	0	0.8	0.2	0.1	1	0	1	0.11	0	0.38	0.9	1	0.4	0.44
9	0.7	1	0.9	0.6	0.5	1	1	1	0.55	0.1	0.38	0.9	1	0.9	0.75
10	1	1	0.9	0.8	0.95	1	1	1	1	0.9	1	0.9	1	0.9	0.95
11	1	1	0.9	1	0.95	1	1	1	1	0.9	1	0.9	1	0.9	0.97
12	1	1	0.9	0.8	0.95	1	1	1	1	0.9	0.38	0.9	1	0.9	0.91
13	1	1	0.9	0.4	0.5	1	1	1	1	0.9	0.38	0.9	1	0.8	0.84
14	1	1	0.9	0.6	0.5	1	1	1	1	0.8	1	0.9	1	0.9	0.90
15	1	1	0.9	1	0.95	1	1	1	1	0.9	1	0.9	1	0.9	0.97
16	1	1	0.9	0.8	0.95	1	1	1	1	0.9	0.38	0.9	1	0.9	0.91
17	1	1	0.9	0.6	0.95	1	1	1	1	0.9	0.38	0.9	1	0.9	0.90
18	0.6	1	0.5	0.2	0.95	1	0	1	0.55	0.9	0	0.3	0.05	0.5	0.54
19	0.25	0	0.3	0.1	0.3	0	0	1	0.11	0.5	0	0.3	0.05	0.4	0.24
20	0.15	0	0.3	0.1	0.3	0	0	1	0.11	0.1	0	0.3	0.05	0.4	0.20
21	0.15	0	0.2	0.1	0	0	0	0.05	0.11	0.1	0	0.3	0.05	0.4	0.10
22	0.1	0	0.2	0.1	0	0	0	0.05	0.11	0	0	0.05	0.05	0.4	0.08
23	0.1	0	0.2	0.1	0	0	0	0.05	0.11	0	0	0.05	0.05	0.4	0.08
24	0.1	0	0.2	0.1	0	0	0	0.05	0.11	0	0	0.05	0.05	0.4	0.08
Sum	11.10	10.00	12.30	8.30	8.85	11.00	9.00	13.55	10.64	8.80	6.28	10.70	10.70	14.10	10.42

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