On the impact of internal gains and comfort band on the effectiveness of building thermal zoning

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A B S T R A C T

Thermal zoning is a commonly adopted building energy efficiency initiative, since thermally segregating conditioned spaces is generally expected to minimise energy losses when conditioning unoccupied spaces. When comparing a partitioned building with widely differing heat gains between zones to an equivalent non-partitioned building, ‘zoning’ might not always beneficial. This paper analyses the fundamental thermal processes involved in these scenarios by firstly undertaking a number of steady state analyses, demonstrating that there are scenarios where the thermal energy required to maintain comfort conditions is less for an open-plan arrangement than for a more highly partitioned building. We then performed dynamical simulations of a simple building, confirming the steady state analyses and showing that, for space heating, connecting the spaces can significantly reduce the energy demand. It was concluded that whenever two zones are both conditioned to the same set-points, thermally connecting zones always leads to an energy demand lower or equal to thermally isolated zones. We then conducted simulations of an archetypal residential building with intermittent conditioning of spaces. The results showed that thermally connecting the spaces can be beneficial in climates from cool to warm temperate, with a decrease in energy demand from 2.2 to 9.9%, while this was not beneficial in a hot and humid climate, with an energy demand increase of 0.2 to 2.3% for the thermally connected scenario.

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1. Introduction

Efforts to improve the thermal comfort of building occupants over many decades has led to increasing overall energy demand for heating, ventilation and air conditioning (HVAC) in the global building stock. To mitigate this increased energy consumption, many energy efficiency initiatives have been developed and implemented over the years. One of the most fundamental initiatives has been the implementation of thermal zoning (i.e. separation/partitioning of thermal spaces) so that the heating and cooling loads can be managed so as to avoid unnecessary energy consumption with respect to maintaining thermal comfort conditions in spaces that may be unconditioned, or may only need intermittent conditioning. Several studies have analysed and presented the benefits of thermal zoning e.g. [1] and there are international standards and guidelines available for regulating the implementation methodologies.

However, there is no universally agreed approach to thermal zoning in building performance simulation (BPS). According to Bembook [2], for example, a thermal zone should approximately correlate to the spatial subdivision, or partitioning of a building, and there are guidelines indicating that a BPS user should choose the number of zones so that they match the number of heating and cooling systems serving the building [2–5]. In addition, Bembook [2] and CIBSE AM11 [4] suggest that two adjacent spaces can be considered as one thermal zone in some circumstances, but they need to have similar heating and cooling set-points, internal gains, solar gains, spatial location and thus the same thermal behaviour without the heating or cooling system operating and similar requirements are specified in ASHRAE 90.1 [3].

BPS software tools, such as EnergyPlus, ESP-r and IDA ICE, enable users to implement thermal zoning independent of space usage with flexible inputs in terms of occupant behaviour and other constraints. Individual thermal management of zones has been studied for mechanically ventilated and conditioned buildings, as well as naturally ventilated ones [6]. The impact of thermal zoning on energy performance in buildings has been extensively studied, mostly through simulations. However, there is as yet no
A detailed multi-zone model.

While the majority of studies, based on intermittent occupancy, show qualitative agreement on energy savings achievable by appropriate zoning strategies (see for example [7–10]), some studies have reported a decrease in performance when the spaces are partitioned [11,12]. For instance, the study presented in O’Brien et al. [11] quantified the effect of the air flow rate of mechanically driven air circulation and thermal zoning on heating and cooling loads and thermal comfort. Results from a residential case study building showed that: (a) solar heat gains were not correctly distributed when inter-zone air flow was restricted; and (b) increasing inter-zone air flow via mechanical means was most beneficial during periods when a given zone was predicted to overheat due to internal gains and other zones required heating.

The effect of three zoning strategies on the energy use in 940 commercial buildings in three climate zones using EnergyPlus was assessed by Chen and Hong [12]. The zoning strategies investigated were: treating each floor as a single zone; a perimeter-core zoning; and a so-called ‘prototype zoning’ approach, which employed building typologies developed by the U.S. Department of Energy. The single zone model gave the lowest energy demand, with 7.5% lower cooling load and 16.9% lower heating load than the perimeter-core zoning approach. Nevertheless, comparing the detailed prototype zoning with perimeter-core zoning, the differences in energy use varied from –12.1% to 19.0%. This variation on the energy performance was attributed to the different shapes employed in the Prototype zoning compared to the perimeter-core, which resulted in large differences in exterior wall area and window area.

Thermal zoning features and methods have generally been investigated in the BPS context to be able to accurately represent the real building performance (see for example Heidell et al. [13]) or to understand the effect of modifying the number of zones on the performance of a detailed multi-zone model [14], as inferred from a recent review by Shin and Haberl [1]. These studies typically compare:

- Monitored building energy consumption against simulated results with different zoning strategies.
- Simulated energy performance of detailed multi-zone models against simulated single (or less number of zones) models.

In these cases, the effect of zoning on simulation accuracy is assessed assuming that merging the zones is a simplification of the multi-zone detailed model.

For example, Georgescu et al. [14] assessed the changes on the simulated heating and cooling load for an educational building when the number of zones where progressively reduced from 191 to 10. Results were reported in terms of error, with 13.3% error on the simulated energy load of the 10-zone model compared to the detailed multi-zone model.

Another study by Smith [15] investigated the effects of zoning strategies on the building energy performance of three different building geometries and four climates zones. Results demonstrated that the choice of zoning can significantly affect the simulated energy performance of the building. Irrespective of the building geometry, the 1-zone and 2-zones per floor strategies showed an underestimation of the energy consumption ranging from 5% up to 25% compared to the building multi-zoned following ASHRAE Standard 90.1 Appendix G guidelines [3]. The results for the cardinal zoning (typically 5-zones per floor) were found to be building geometry dependent. The percentage difference in electricity consumption varied from 25% over-prediction to –8% (under prediction) compared to the multi-zone building. These differences were attributed to the deep plan buildings having zones across multiple orientations.

Despite the fact that these previous studies have confirmed the importance of thermal zoning on the building performance there remains significant doubt as to whether thermally partitioning spaces always results in higher energy efficiency. To this end, this paper describes new insights into the thermal processes involved in thermal zoning and scenarios where distribution of heat gains across multiple zones leads to higher building efficiencies. This is demonstrated using dynamic simulations to assess the effect of zoning on a national home energy rating system, using the Australian NatHERS (nationwide house energy rating scheme) as an example.

2. Simulation case studies

2.1. Two-zone building

The Building Energy Simulation Test (BESTest) is a comparative simulation test method used to determine the quality of a simulation tool through the accuracy and self-consistency of results from the particular tool, or in comparison to other simulation tools. BESTest was developed by the International Energy Agency (IEA) Experts Group [16] and was adopted in ASHRAE Standard 140 for an ASHRAE Standard method of test for building energy simulation software [17]. Because the BESTest procedures are repeatable, one of the buildings described in Henninger and Witte [18], i.e. Case 910 (a high mass building with shading on the north wall) was selected as the basis for our first two-zone case study building. In addition, the case study building was also chosen because its characteristics align with recent studies undertaken by the International Building Performance Simulation Association, i.e. Project 1 under the BOPTEST (Building Operation TESTING) framework [19]. The simple BESTest buildings described above were only single-zone spaces, so our fundamental case study building was developed using two adjacent zones, each being equivalent to a Case 910 building. This building was then modelled in DesignBuilder (with details provided in Fig. 1 and Table 1).

The floor of each zone was assumed to be thermally decoupled from the ground, and each zone had two north-facing windows of area 6m² per window and a 1 m horizontal overhang across the northern wall. It should be noted that the internal loads originally specified for Case 910 in [18] were not employed, as the dependence of the building on internal load schedules and intensities was a key part of the present study.

**Nomenclature**

| Symbol | Description |
|--------|-------------|
| A      | Wall area (m²) |
| I      | Internal gains (W) |
| L      | Losses to the ambient (W) |
| Qₐ     | Mechanical cooling power (W) |
| Qₐₑ    | Mechanical heating power (W) |
| Tₒ     | Outdoor temperature (°C) |
| Tₜₖₑ    | Cooling set-point (°C) |
| Tₜₖₜ    | Heating set-point (°C) |
| U      | Wall U-Value (W/m²K) |
| ΔQₗₑ    | Heat required to raise the room temperature from heating to cooling set-point (W) |

**Equations**

| Equation | Description |
|----------|-------------|
| Heat required to raise the room temperature from heating to cooling set-point (W) | $ΔQ_{Iₑ} = U \times (T_{ₜₖₑ} - Tₙ) \times A$ |
| Heat required to lower the room temperature from cooling to heating set-point (W) | $ΔQ_{ₑₜ} = U \times (Tₙ - Tₜₖₑ) \times A$ |
| Heat required to raise the room temperature from the ground to the ceiling (W) | $ΔQ_{ₜₙ} = U \times (T_{ₜₖₑ} - Tₙ) \times A$ |
| Heat required to lower the room temperature from the ceiling to the ground (W) | $ΔQ_{ₑₜₙ} = U \times (Tₙ - T_{ₜₖₑ}) \times A$ |

**Building Energy Simulation Test (BESTest)**

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2.2. Apartment case study building

The practical case study building was chosen to be an apartment archetype. Its geometry and construction details were the same as used by Bannister et al. [20] and the floor plan and 3-D perspective of this archetype are presented in Fig. 2. The Nationwide House Energy Rating Scheme (NatHERS) is the most common pathway for building designers to comply with the energy efficiency requirements of the Australian National Construction Code (NCC). NatHERS rates residential buildings using a star system; from a star rating of 0 for a building with an envelope that does practically nothing to mitigate discomfort due to the external environment, to 10 Stars for a building that needs no artificial cooling or heating to maintain comfortable indoor temperatures. The star rating is based on a predicted thermal energy demand for cooling and heating (MJ/m²/year) obtained by running a building performance simulation using a NatHERS-accredited BPS tool. Benchmarks maximum thermal heating/cooling requirements as a function of energy star rating have been developed for all geographic climate zones, so as to provide a fair comparison between the very different weather conditions across Australia. NatHERS-accredited BPS tools, such as AccuRate, use the CHENATH engine which has been benchmarked against the BESTest methodology [21].

AccuRate (v2.3.3.13 SP3) was used to model the performance of an apartment archetype. In this software thermal zones were linked to the geometry of the house, and their schedules of operation and internal gain intensities were associated with the different types of rooms in the dwelling. Single-directional or bi-directional air flows through an open door or window are calculated based on the air pressure differences across the opening along its vertical height. Details of the air flow modelling can be found in [22]. The air flow model implemented in AccuRate v2.3.3.13 SP3 is based on the flow model presented by Li et al. [23], with an improvement on the air density calculation. Li et al. found that their air flow model, which used a constant air density, had an error of less than 3% when compared with analytical solutions for single zone and two zone air flows. Ren et al. [22] improved this model by including the variation in air density with changing air temperature.

In line with the NatHERS operational protocol, occupancy schedules varied between day time spaces (living areas and kitchen) and night time spaces (bedrooms and bathrooms), and mechanical conditioning set-points were dependent on the time of the day for heating and on local climate for cooling (Fig. 3). Openings (e.g. internal doors or windows) were occupant-controlled by default, and the logic of operation was determined by the software. In general, the windows and doors were assumed to be open when the outdoor conditions were favourable for natural ventilation, and closed when the building required mechanical heating or cooling to maintain thermal comfort. Windows and doors could also be set as permanent openings, i.e. they remained fully open regardless of the indoor and outdoor conditions. The NatHERS simulation protocol assumes that heating and cooling is available for all the rooms if and when required, except for the bathroom, which had no dedicated heating and cooling systems.

### Table 1

| Parameter Type | Parameter Description |
|----------------|-----------------------|
| **Construction** | Concrete slab with insulation (R = 25.4 m²K/W) |
| **Operation** | 0.5 ACH at normal pressure |

| Parameter Type | Description |
|----------------|-------------|
| **External wall** | Concrete with insulation (R = 1.95 m²K/W) |
| **Windows** | Clear double glazed windows (U = 3 W/m²K) |
| **Floor** | Concrete slab with insulation (R = 25.4 m²K/W) |
| **Roof** | Metal roof deck with insulation (R = 3.15 m²K/W) |
| **Airtightness** | 0.5 ACH at normal pressure |
| **Cooling set-point** | 27 °C |
| **Heating set-point** | 20 °C |

Fig. 1. DesignBuilder model of the BESTest rooms.

Fig. 2. Floor plan of the apartment archetype modelled in AccuRate.

3. Methodology

Different approaches to zoning can result in different BPS predictions of energy performance, which are a result of various factors including fundamental building physics, and/or simulation assumptions and methodologies. The effects of these factors on heating and cooling energy demand are not straightforward and they have received relatively little consideration in the literature to date. In the following we explore the critical role played by room thermal loads and the temperature comfort band chosen. Note, that here ‘comfort band’ is taken to mean the temperature range between the heating and cooling set-points, when neither heating nor cooling is required.
3.1. Two-zone building steady state analysis

To illustrate the fundamental thermal principles operating in buildings with different degrees of thermal partitioning or ‘zoning’, a theoretical case study, or ‘thought experiment’, involving a simple building is presented in Figs. 4 to 7. Here the heat flows in two identical, thermally separated, rooms in a heating scenario are presented. Assuming one room does not have internal gains, the other room can have different internal gains, which can be separated in the following four scenarios:

In Scenario 1, presented in Fig. 4, the internal gains in Room 1 are low enough for both spaces to require heating to maintain the heating set-point. The mechanical heating $Q_{H2}$ required to just maintain the heating set-point in Room 2 is equal to the losses through the building envelope, $Q_0$. In Room 1, the mechanical heating required to maintain the set-point, since the internal gains $I_1 < Q_0$, is equal to $Q_{H1} = Q_0 - I_1$.

When the rooms are thermally connected as in Fig. 4b, the total heating demand to maintain the heating set-point is the same as that with the two rooms thermally separated.

In Scenario 2, where the internal gains are higher than the heat required to maintain the heating set-point in one room and lower than that needed to reach the cooling set-point is presented in Fig. 5.

In Fig. 5a the internal gains are increased to the point where they are now sufficiently high to maintain the temperature of Room 1 between the heating and cooling set-point temperatures with no mechanical heating.

Here we note that the amount of heating required to raise the temperature of the room above from the heating set-point to the cooling set-point is $\Delta Q_{set} = UA(T_{set,cool} - T_{set,heat})$, where $U$ and $A$ are the overall heat transfer coefficient and surface area of the building envelope, respectively. For simplicity we also assumed that the difference in temperature between the heating set-point and the ambient is greater than the difference between the two set-points, thus, $\Delta Q_{set} < Q_0$, however, this restriction is made here only for purposes of a clear explanation of the thermal processes involved.

Consequently, the single-zone configuration in Fig. 5b requires less heating due to the sharing of the internal gains across both rooms.
rooms, as \( Q_{H1} = Q_{H2} = Q_0 - L_1/2 < Q_0/2 \); and we can conclude that in this scenario zoning does indeed influence the total energy required to heat the building.

In any scenario where the internal gains are further increased, as in Scenario 3 presented in the example in Fig. 6, so as to cause a cooling request in Room 1 (\( Q_{I1} = I_1 - Q_0 + \Delta Q_{set} \)), then the single-zone building becomes increasingly beneficial. The maximum benefit is reached when the internal gain in Room 1 is equal to \( 2Q_0 \) and no heating is required when the zones are thermally connected, as presented in Fig. 7.

Thermal comfort may be maintained in the case of thermally connected zones without a need for cooling despite increasing internal loads up to the point where \( I_1 > 2(Q_0 + \Delta Q_{set}) \). In Scenario 4, when \( I_1 \) exceeds this threshold, cooling is required for the thermally connected zones, as shown in Fig. 7b, but the cooling energy demand remains lower than the energy required in Fig. 7a since \( I_1 - 2(Q_0 + \Delta Q_{set}) < Q_0 + I_1 - (Q_0 + \Delta Q_{set}) \). The case in which the outdoor temperature is higher than the indoor temperature logically leads to a cooling requirement for both spaces that is the same regardless of whether the zones are thermally isolated or connected.

It can be therefore concluded that, when two zones are both conditioned to the same set-points, thermally connecting zones always leads to an energy demand lower or equal to thermally isolated zones.

It is noted that such a steady state heat balance analysis may not fully represent the dynamic thermal processes in real buildings, however, it does give the general potential impact of zoning on the heating and cooling energy demands at different internal heat gains and indoor/outdoor temperature conditions.

### 3.2. Two-zone building simulation method

To verify the application of the thermal principles set out above and to determine the effects on building heating and cooling energy demand for a practical dwellings operating under dynamic conditions, the simple two-zone building described in Section 2 was dynamically simulated using DesignBuilder:

- Baseline Model – two thermal zones are separated by an adiabatic internal partition.
- Thermally Connected Model – the two zones are perfectly thermally connected, i.e. merged as a single zone.

Simulations were undertaken using IWEC (International Weather for Energy Calculations) weather data for Melbourne during a week in winter, from the 4th to 10th of July for the four scenarios previously presented in the simplified thought exercise (Section 3.1). The internal loads were varied in accordance with these four scenarios. In all the simulations, the simple two-zone building is assumed to have no internal heat sources, while has solar gains based on the weather data. To establish the scenarios presented in Section 3.1 in this dynamical simulation, different time-varying internal heat gain profiles have to be generated. This was achieved by deriving the average UA value of each room (\( UA = Q_0/(T_i - T_o) \)) from the heat losses (\( Q_0 \)) calculated by the simulation software at night, when solar radiation is not present and there are no other internal gains. This was then used to calculate \( Q_o \) at daytime, when solar radiation was also present. The internal heat gains (\( I_h \)) profiles (which exclude the solar gains) used to generate the four required scenarios in the chambers therefore were:

- Scenario 1: \( I_h = 0 \)
- Scenario 2: \( I_h = (Q_0 + \Delta Q_{set})/3 \)
- Scenario 3: \( I_h = (2Q_0 + \Delta Q_{set})/2 \)
- Scenario 4: \( I_h = 3Q_0 \)

These heat gain profiles (Scenario 2 to 4), together with the solar gains, are shown in Fig. 8.

In addition, the same four scenarios were simulated in a hot summer climate (Cairns) during a week in summer (25th to 31st
of January) to demonstrate the effect of zoning on the cooling demand when the outdoor temperature is higher than the indoors.

3.3. Apartment building case study – dynamic model

The performance of the apartment archetype was modelled using AccuRate. This software models the operation of doors and windows as open when natural ventilation is beneficial and closed when the building requires mechanical heating or cooling to maintain thermal comfort. To understand the effect of zoning on the apartment archetype described in Section 2, the same apartment was simulated under the following scenarios:

- Baseline Model – Operable doors using the building operation mode to determine their position (NatHERS protocol)
- Thermally Connected Model – Internal doors were kept permanently open to increase heat exchange between rooms.

Two levels of building envelope air-permeability were also tested, to evaluate the effect of zoning on buildings with different levels of energy efficiency:

- Low infiltration rate, 7 ACH @50 Pa.
- Typical infiltration rate for newly-built Australian houses based on the work presented in [24], 14.5 ACH @50 Pa.

The simulations were carried out for four Australian climate zones (CZ), as defined in [25]:

- Cool temperate (CZ7, Hobart);
- Mild temperate (CZ6, Melbourne);
- Warm temperate climate (CZ5, Sydney);
- High humidity summer, warm winter (CZ1, Cairns);

4. Results and discussion

4.1. Two-zone building simulation results

This section presents the DesignBuilder simulation results of the BESTest two-zone building, simulated with the four internal heat gain scenario profiles presented in Section 2.2.

The model was simulated as a two-zone building and a single-zone building, as previously described. A summary of the simulation results of this model in the winter Melbourne weather is reported in Table 2. These results confirm the expectations presented in the steady-state scenarios of Section 3.1, showing that in any scenario with high enough internal gains (Scenarios 2, 3 and 4) there is a reduction in the total energy demand, and this reduction is greater as the internal heat gains in Room 1 increase. As presented in examples in Section 3.1, in Scenario 1, where the two spaces have the same internal loads, the results show as expected no difference between the two zoning set-ups. In Scenario 2, where the internal gains make the temperature in Room 1 fluctuate between the heating and cooling set-points, the energy is saved because the heat gains in Room 1, when the rooms are merged, help reducing the demand of Room 2. The energy saved increases with the increase of internal gains, up to Scenario 4, where in the cooling demand of Room 1 and the heating demand in Room 2 are compensating each other when the rooms are merged, leading to a reduction in energy consumption close to 100%. An example of the dynamic temperature and energy demand profiles of the two rooms in the thermally segregated or merged in a single zone is presented in Fig. 9, where the results of Scenario 2 in Melbourne are presented. Here it can be noticed how the excess heat in Room 1 (Fig. 9a) reduces the total heat demand when the rooms are merged (Fig. 9b).

It is therefore clear that thermal separation of the zones in these scenarios is not beneficial in reducing the building heating and cooling energy demand. The results from the simulation in Cairns during the summer period are presented in Table 3. As expected from the discussion in Section 3.1, in cooling conditions, when the outdoor temperature is higher than the indoor one, there is no difference in cooling demand between the two zoning scenarios. The marginal differences reported, approximately 1%, could be attributable to the non-linear behaviour present in the dynamic simulation model which relate to the different levels of internal heat gain, that are not taken into consideration in the simplified heat balance analysis presented in Section 3.1.
4.2. Apartment building dynamic model results

The results presented in this section show the effect of increasing the thermal “connection” between spaces in a multi-zone residential building on its energy efficiency performance, by permanently opening the internal doors for example. These results are particularly interesting as the building modelled implements an on-demand delivery of heating and cooling to each individual thermal zone, which have an intermittent conditioning and occupancy (as presented in Section 2). Further, the apartment has one unconditioned zone, i.e. the bathroom, which has no dedicated mechanical heating and cooling available. Both the intermittent air-conditioning profile and the unconditioned zone should favour thermal separation of zones to reduce the heating and cooling energy consumption of the building. As any normally operating building though, the internal gains are present and the effect of sharing the internal gains is generally not measured or not considered as a reason to “thermally connect” the spaces.

The results from the simulations are presented in Table 4, where the climates are ordered according to the city latitude. The Hobart climate results show that both heating and cooling loads decreased when the internal doors were permanently open, Table 2

| Scen. | Zoning | Heating Room1 (kWh) | Heating Room2 (kWh) | Cooling Room1 (kWh) | Cooling Room2 (kWh) | Heating change (kWh) | Cooling change (kWh) | Total Energy Diff. |
|-------|--------|---------------------|---------------------|--------------------|--------------------|----------------------|---------------------|---------------------|
| 1     | Sep.   | 63.9                | 63.9                | 0                  | 0                  | -0.3                 | -0                  | 0%                  |
| Conn. |        |                      |                      |                    |                    |                      |                     |                     |
| 2     | Sep.   | 0                   | 127.5               | 0                  | 0                  | -29.5                | 0                   | -46%                |
| Conn. |        |                      |                      |                    |                    |                      |                     |                     |
| 3     | Sep.   | 0                   | 34.4                | 3.4                | 0                  | -55.3                | -3.4                | -87%                |
| Conn. |        |                      |                      |                    |                    |                      |                     |                     |
| 4     | Sep.   | 0                   | 63.9                | 99.5               | 0                  | -63.9                | -96.9               | -98%                |
| Conn. |        |                      |                      |                    |                    |                      |                     |                     |

Fig. 9. BESTest simulations results in Melbourne, winter, in internal loads Scenario 2 with (a) perfectly segregated rooms and (b) merged rooms in a single zone.

Table 3

| Scen. | Zoning | Heating Room1 (kWh) | Heating Room2 (kWh) | Cooling Room1 (kWh) | Cooling Room2 (kWh) | Heating change (kWh) | Cooling change (kWh) | Total Energy Diff. |
|-------|--------|---------------------|---------------------|--------------------|--------------------|----------------------|---------------------|---------------------|
| 1     | Sep.   | 0                   | 0                   | 116.4              | 118.6              | 0                    | -0.7                | -0.3%               |
| Conn. |        |                      |                      |                    |                    |                      |                     |                     |
| 2     | Sep.   | 0                   | 0                   | 255.6              | 118.6              | 0                    | 1.9                 | 0.5%                |
| Conn. |        |                      |                      |                    |                    |                      |                     |                     |
| 3     | Sep.   | 0                   | 0                   | 293.6              | 118.6              | 0                    | 3.3                 | 0.8%                |
| Conn. |        |                      |                      |                    |                    |                      |                     |                     |
| 4     | Sep.   | 0                   | 0                   | 412.5              | 118.6              | 0                    | 8.4                 | 1.6%                |
| Conn. |        |                      |                      |                    |                    |                      |                     |                     |
leading to a higher star rating for the building. In particular, it could be noticed that with a low infiltration rate (better performing building), the impact of thermally connecting the zones was higher than for the high infiltration building in terms of change of star rating. It is also noticeable that this higher impact on star rating is mostly due to a larger decrease in the heating energy demand, although the cooling energy savings are reduced. When the internal doors were opened, the star rating increased by 0.1 in the high infiltration model (2.8% reduction in the total energy demand), and by 0.3 in the low infiltration model (8.3% reduction in the total energy demand).

In Melbourne the results are similar to those in Hobart, with the only difference that the low infiltration model benefits from the open doors more than the high infiltration one in both the heating and cooling demand. While the star rating increases by the same amount, 0.1 in the high infiltration model (2.2% reduction in total energy demand), and by 0.3 in the low infiltration model (8.3% reduction in the total energy demand).

In Sydney, the low infiltration model benefits from the open doors more than the high infiltration on the cooling demand rather than the heating. In this case, despite the reduction in cooling and heating is small in absolute values (since the baseline demand for Sydney is small due its mild climate) the star rating increases by 0.1 in the high infiltration model (5.5% reduction in the total energy demand), and by 0.4 in the low infiltration model (9.9% reduction in the total energy demand).

In Cairns, with its hot and humid climate, is the only location that experiences a decrease in performance and star rating when the internal doors are opened. As it is a very hot climate, no heating is required throughout the year, and mechanical cooling is largely necessary to maintain thermal comfort. The difference in cooling demand increase is more prominent in the high infiltration house scenario, where there is an increase of 2.3% in cooling demand when the spaces are thermally connected, leading to a 0.2 star rating decrease. In the low infiltration scenarios the difference is marginal and equal to 0.2%, but still leading to a 0.1 star rating decrease. This difference in cooling demand is due to the benefits of zoning non-conditioned spaces (the bathroom). As discussed in Sections 3.1 and 4.1 a difference close to zero in cooling demand would be expected if there was no intermittent heating and cooling.

The reason for the increase in performance when opening the internal door in the other three aforementioned cases was found to be the benefits in sharing the internal loads. This is particularly apparent when analysing the hourly results of the spaces with larger internal gains, such as the kitchen.

One example of this is presented in Figs. 10 and 11, where the simulation results for Sydney in winter are presented based on the kitchen and living room data, from the beginning of June to the beginning of August, i.e. the winter period in the southern hemisphere.

As it can be noticed in Fig. 10a, in the baseline operation the kitchen tends to overheat mainly due to heat gains from cooking, as it can be seen every day at hour 8–9 and hour 19, and particularly around the day 155 and 190 of the year, where mechanical cooling was required. At the same time, the neighbouring living room (Fig. 10b) requires less heating, as it receives part of the excess heat from the kitchen. This is particularly noticeable by comparing the heating energy from hour 16 to 23, in the days between 190 and 215.

### 4.3 Results discussion

While thermal zoning is perceived as an effective energy efficiency solution for buildings, the results presented in this study showed that thermally connecting spaces provides a more effective solution than zoning in some cases; in particular when the spaces
are always occupied, uneven internal gains are present and the outdoor temperature is lower than the indoor one.

By connecting a space with excessive internal heating load and an under heated space, the overall heating and cooling energy demand of the building can be reduced. When the internal gains are even higher, one space might require cooling while the other requires heating, and thermally connecting the spaces is even more beneficial. Therefore, it is important to consider this effect when designing a building and its heating and cooling system to find the most energy efficient solution. Further, this effect also has a direct impact on energy efficiency rating of buildings, especially when the evaluation is achieved via a building performance simulation study as in Australia.

The results from the simulation of this model were used to demonstrate the effect of the principles described in Section 3 on the energy rating of an archetype apartment. It should be noted that these results are specific to the apartment model studied, with assumptions and simulation settings (e.g., distribution of internal loads, thermostat set point, etc) defined by the NatHERS protocol. The uncertainty in modelling components, such as the internal air-flow model, while small, can affect the magnitude of the heat transfer between zones and thereby the total building energy demand.

5. Conclusions

This paper described a study to examine the relationship between thermal zoning and building energy efficiency performance. The study involved the analysis of (a) a two-zone building in steady state conditions, (b) a dynamic simulation of a simplified, widely-used open source building model and (c) a detailed apartment archetype simulated in the software tool used for residential building energy efficiency rating in Australia.

The results show that while zoning is an effective energy efficiency measure when spaces in a building have intermittent air-conditioning, this is not the case when all the spaces are conditioned at the same time.

The study demonstrated that, when spaces are conditioned to the same set-points, thermally connecting zones always leads to an energy demand lower or equal to thermally isolated zones. Thermally connecting spaces is particularly beneficial when the internal and solar gains are unevenly distributed across zones and when the outdoor temperature is lower than the indoor one.

This finding has also an implications for energy rating scores determined from specific BPS tools, as the results from this study show that in some cases reducing zoning will lead to higher energy efficiency and higher rating scores. Results from the simulation of the model of the archetype apartment, undertaken using the Australian home energy rating system framework, showed that thermally connecting the spaces can be beneficial in climates from cool to warm temperate, with a decrease in energy demand from 2.2 to 9.9%, while this was not beneficial in a hot and humid climate. Zoning the spaces was only found to be beneficial in a hot and humid climate, with an energy demand increase of 0.2 to 2.3% for the thermally connected scenario.

Despite the results from the simulation of this apartment archetype are specific to this model and each building should be anal-
used separately to determine the effect of zoning on its total energy demand, these results showed that the assumptions made in the simulation software become critically important. These assumptions significantly affect the outcome of the rating scores and building designers can opportunistically choose a zoning approach which may have a different impact on the energy consumption of the real operation of the building.

Future work should investigate in more detail whether particular building typologies perform better with internal spaces thermally connected or separated, and whether other parameters affect the relative change in performance through zoning, e.g. climate, construction and the degree to which the building is intermittently air-conditioned.

**CRedIT authorship contribution statement**

**Massimo Fiorentini:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing. **Laia Ledo Comis:** Software, Investigation, Writing - original draft, Writing - review & editing. **Dong Chen:** Conceptualization, Resources, Writing - review & editing. **Paul Cooper:** Conceptualization, Writing - original draft, Writing - review & editing.

**Declaration of Competing Interest**

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

**Appendix A. Supplementary data**

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.enbuild.2020.110320.

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