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Behrendt, Benjamin; Christensen, Jørgen Erik

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CLIMATE CLASSIFICATION FOR THE SIMULATION OF THERMALLY ACTIVATED BUILDING SYSTEMS (TABS)

Benjamin Behrendt, Jørgen Christensen
Department of Civil Engineering
Technical University of Denmark

ABSTRACT

Thermally activated building systems (TABS) provide high temperature cooling and low temperature heating which has a better efficiency compared to traditional heating and cooling solutions. Additionally the moderate required temperature levels for heating and cooling create the opportunity to use alternative (sustainable) energy sources that would otherwise be insufficient.

The design of TABS is however challenging and most often requires a complete simulation of the building. The standard ISO 11855-4 (2011) suggests a simplified sizing method for TABS. The results however omit condensation risk entirely. The proposed climate classification should fill this gap by providing the missing data in a simple manner.

INTRODUCTION

TABS are low temperature heating and high temperature cooling systems. This has a number of advantages if compared to conventional systems. The required temperature levels are more favorable for the use in conjunction with sustainable energy sources such as for instance ground heat exchangers, solar energy (collectors), heat pumps, low temperature district heating and others. The use of TABS can considerably decrease the primary energy demand of a building while at the same time maintaining or even improve the comfort in the building.

The utilization of TABS for cooling of buildings introduces one problem that is mostly foreign to air based cooling systems: Condensation within occupied space. Even though in office buildings the internal humidity load is mostly within acceptable limits the problem could still arise depending on the external environment.

During the design of TABS it is therefore important to evaluate the risk of condensation within the building. If a complete building simulation is undertaken most building simulation tools today recognize potential condensation risks and notify the user. Since simulations of the like are however time consuming it is of considerable value if the usability of TABS could be quickly assessed in a simplified approach. To this end the ISO 11855-4 (2011) suggests the use of a simplified simulation method. This type of simulation however does not consider humidity at all but focuses solely on thermal performance. A possible result of

a simulation with such tool could be that the building may be sufficiently cooled by TABS, a full building simulation would however reveal that the system would likely cause condensation on the controlled surfaces.

To identify this risk it would be beneficial if a climate classification for the use of TABS would exist. This is however not the case as most available climate classifications consider precipitation but not humidity (relative or total). The Köppen-Geiger (Kottek et al., 2006) or the ASHRAE Climate classification (ASHRAE, 2010) are to examples for well established systems, in terms of simulating TABS they are however not quite fitting the needs.

The suggested climate classification is greatly simplified if compared with other established systems such as the Köppen-Geiger or the ASHRAE classification but it incorporates the two important key variables for TABS. The proposed system is based on a combination of degree days and the outside dew point temperature. Compared to the afore mentioned classifications it offers less climatic zones but in return they are closer modeled to the problem at hand.

The current classification is only based on 54 locations in Europe hence its resolution is still too low in some areas. It can however already be used to get a first estimate of what should be expected of a TABS system used in the area.

The method had been tested on a simple office building that has been simulated in various locations (e.g. climate zones) and it has been found that the method works as intended.

Problem statement

The intention is to create a simple climate classification to determine the usability of TABS for a modern building (in accordance to current building standards) throughout Europe (and eventually worldwide). The following points should be answered through the classification. The classification should provide a quick answer to the questions:

Does the building need ...

- ... a heating system?
- ... a cooling system?
- ... a heating and cooling system?
- ... no dehumidification?
- ... intermittent dehumidification?
- ... continuous dehumidification?

In conjunction with the simplified approach for the sizing of TABS as suggested in ISO 11855-4 (2011) this will provide a method to evaluate the usability of tabs.

EXISTING CLIMATE CLASSIFICATIONS

A number of already existing climate classifications have been considered but due to different shortcomings they could not be used.

One of the most promising climate classifications was the Köppen-Geiger system. In the end this system could not be used due to high differences within one climatic zone making it impossible to use it for the evaluation of TABS. It also had shortcomings in relation to the provided humidity data.

Another system that had been considered is the ASHRAE Climate Zones. However in this case insufficient data was provided as climate data only includes precipitation in the USA and humidity is completely omitted. However the ASHRAE Climate Zones have been used in a previous study (Love and Tian, 2009) comparing the use of TABS to a VAV and radiator based system with regard to energy savings. Only US cities have been included in this study.

The degree day method has been used in previous. Since the operation of TABS can be greatly limited by humidity it is important to have a system that pays attention to this aspect. The new introduced system as a combination of heating and cooling degree days as well as humidity can achieve this.

THE NEW CLIMATE CLASSIFICATION

Degree days are defined as the difference of the base temperature and the average daily or hourly outdoor temperature. After both, heating and cooling degree day calculations are explained, the used base temperature is discussed in detail.

Heating Degree Days

Heating Degree Days (HDD) are calculated by defining a base temperature, from which the average daily or hourly outdoor temperature is subtracted. If the value is positive, it is added to the sum of heating degree days. This is repeated for every day or hour throughout the year. Equation 1 shows the heating degree day calculation using average daily temperatures based on hourly temperatures. Equation 2 shows the heating degree day calculation using hourly temperatures. Thus the key difference is that Equation 1 only adds to the HDD if the daily average outdoor temperature is below the base temperature whereas Equation 2 adds to the HDD every time the hourly outdoor temperature is below the base temperature.

The high thermal mass of TABS causes the system to have a high time constant. This high time constant makes it practically impossible to actively react to short term changes in heating demand. For this reason Equation 1 is the appropriate choice. Short term changes in heating demand are compensated through self regulation of TABS. This self regulation is a com-

ination of two things. First the difference in heat capacity of air and typical building materials (e.g. concrete) and second the changing temperature difference between the air and the active surfaces.

$$HDD = \sum_{j=1}^{365} \left(T_b - \frac{\sum_{i=1}^{24} T_{j,i}}{24} \right)^+ \quad (1)$$

$$HDD = \sum_{j=1}^{365} \frac{\sum_{i=1}^{24} (T_b - T_{j,i})^+}{24} \quad (2)$$

Cooling Degree Days

Cooling Degree Days (CDD) are calculated very similar to heating degree days. A base temperature is defined which is then subtracted from the average daily or hourly outdoor temperature. If the value is positive it is added to the sum of cooling degree days. This is repeated for every day or hour throughout the year. Equation 3 shows the cooling degree calculation using average daily temperatures based on hourly temperatures. Equation 4 shows the cooling degree day calculation using hourly temperatures.

For calculating CDD Equation 3 has been used. The argument is the same as for the calculation of HDD.

$$CDD = \sum_{j=1}^{365} \left(\frac{\sum_{i=1}^{24} T_{j,i}}{24} - T_b \right)^+ \quad (3)$$

$$CDD = \sum_{j=1}^{365} \frac{\sum_{i=1}^{24} (T_{j,i} - T_b)^+}{24} \quad (4)$$

Base Temperature

In general, the base temperature - or balance point temperature - is the outside air temperature at which weather-related energy demand would be zero including any gains from occupants, solar radiation, lighting, equipment, etc. - i.e. the average gains are equal to the average heat loss of the building in the given period. Or in simpler terms: No system (heating or cooling) is required, if the outside temperature is equal to the base temperature. This can also be seen from Equation 5 (ASHRAE, 2001).

$$q_{gain} = h \cdot (T_i - T_b) \quad (5)$$

$$T_b = T_i - \frac{q_{gain}}{h} \quad (6)$$

This shows that it is impossible to have one standardized base temperature as buildings vary in their construction (heat loss coefficient), location and use (average gains from equipment, occupants, solar radiation, etc.) as well as desired indoor temperature (thermal comfort requirements).

In addition different base temperatures are currently used in different countries. In Denmark 17°C are commonly used as base temperature for heating degree days with a minimum indoor temperature of 20°C. The remaining 3°C are assumed to be provided through internal and external heat gains. (ASHRAE, 2001; Cap-pelen, 2002) The same base temperature is used in some European countries, in others, like the United Kingdom and Germany the used base temperatures are with 15.5°C and 15°C respectively considerably lower. The USA on the other hand use a higher base temperature of 18.3°C (Energy Lens n.d.; Butala & Prek 2010) for the calculation of cooling degree days less countries have set a base temperature. ASHRAE uses a base temperature of only 10°C, assuming that the remaining heat to reach thermal comfort is supplied through a combination of internal and external gains (ASHRAE, 2001).

For the new climate classification the base temperature used for heating degree days is 18°C and for cooling degree days is 13°C. Compared to the suggestion by Laustsen (2008) only four climatic zones have been defined as illustrated in Table 1.

Table 1: Criteria for the four different thermal climates, based on heating and cooling degree days with a base temperature of 18°C for HDD and 13°C for CDD, based on Laustsen (2008).

| Climate | Heating | Cooling |
|---------------|-----------------|-----------------|
| Heating based | $2000 \leq HDD$ | $CDD < 1000$ |
| Combined | $2000 \leq HDD$ | $1000 \leq CDD$ |
| Moderate | $HDD < 2000$ | $CDD < 1000$ |
| Cooling based | $HDD < 2000$ | $1000 \leq CDD$ |

Humidity considerations

For cooling with TABS it is important to consider the possibility of condensation on controlled surfaces as well as inside of the construction. Where the first is easily spotted, the latter is not as easy to observe. Condensation inside of the slab might lead to future problems and should therefore be avoided. This makes low dew-point temperatures of 14°C interesting. Under extreme conditions it could otherwise happen that mold starts to grow on the controlled surfaces.

Due to thermal comfort requirements (neglecting possible radiant asymmetries) the floor surface temperatures should not be lower than 19°C and wall surfaces should not be cooled below 17°C (Babiak et al., 2007). The presented climate classification distinguishes three different humidity scenarios.

- **No dehumidification** - In this case humidity levels are not likely to cause any problems, even without any dehumidification.
- **Intermittent dehumidification** - The installation of a dehumidification unit is required. However the unit will not need to be operated throughout the cooling season.

- **Continuous dehumidification** - During the cooling period the indoor humidity needs to be controlled most of the time.

Within the 54 evaluated cities (52 in Europe, 2 in North-Africa) no case has been found where continuous dehumidification would be necessary. As can be seen in Table 2 there are however locations like Abu Dhabi, United Arab Emirates, that do require continuous dehumidification.

Degree Days and humidity combined

The new system is now a combination of the four thermal zones with the three humidity scenarios. This generates a theoretical total of twelve climate zones. Based on the 54 European cities that have been evaluated for the classification not all of these zones can be found in Europe. Table 2 shows an example city for each of the climate zones. If no example is given no occurrence of this combination has been found so far.

Table 2: Example cities for each defined category (if any) using base temperatures of 18°C for HDD and 13°C for CDD

| Climate | No Dehumidification |
|---------------|--|
| Heating based | Copenhagen, Denmark HDD: 3562, CDD: 308 |
| Combined | Bucharest, Romania HDD: 3029, CDD: 1071 |
| Moderate | Porto, Portugal HDD: 1506, CDD: 870 |
| Cooling based | Madrid, Spain HDD: 1964, CDD: 1407 |
| Climate | Intermittent Dehumidification |
| Heating based | Strasbourg, France HDD: 2947, CDD: 650 |
| Combined | Milan, Italy HDD: 2640, CDD: 1064 |
| Moderate | - |
| Cooling based | Athens, Greece HDD: 1112, CDD: 2120 |
| Climate | Continues Dehumidification |
| Heating based | - |
| Combined | - |
| Moderate | - |
| Cooling based | Abu Dhabi, UAE HDD: 24, CDD: 5159 |

SYSTEM VALIDATION

In order to validate the established system a number of simulations have been done in BSim. The reference Building used for this study is the same as has been used for an earlier simulation tool comparison by Behrendt et al. (2011). Its dimensions can be seen in figure 1. The building is well insulated and has good glassing and external shading.

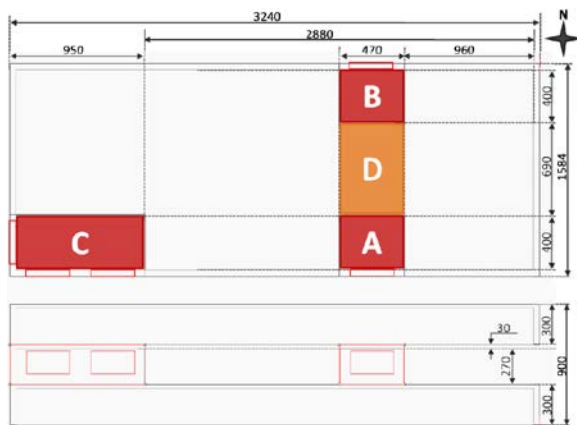


Figure 1: Zone division in the reference building

Table 3 summarizes key values for the building. All loads were present only on weekdays from 8:00 to 17:00 and ventilation was only operating during these hours as well. There is no system operation or internal loads present on weekends. The ventilation system contains a heat recovery system with an efficiency of 80% and during the heating season the supply air is heated to 20°C if the outdoor temperature drops below 16°C (no cooling). During the cooling season the supply air is cooled to 25°C if necessary (no heating). Additional dehumidification is applied as necessary. The heating season was set from 1st of October to 30th of April and from 1st of March to September 30th was considered to be cooling season.

Between the investigated locations only the supply water temperatures as well as used dead-bands have been adjusted to reflect the local demands.

Table 3: Reference building data

| | | Zone | | |
|------------------|-------------------|-------|------|------|
| | | A & B | C | D |
| Floor area | [m ²] | 18.6 | 38 | 31.9 |
| Glazing area | [m ²] | 4 | 12 | — |
| Ventilation rate | [l/s] | 27 | 54.6 | 22.3 |
| TABS installed | | yes | yes | no |
| Loads | | A & B | C | D |
| Occupants | [W] | 240 | 480 | — |
| Equipment | [W] | 160 | 320 | — |
| Lighting | [W] | 93 | 190 | 159 |
| Total | [W] | 493 | 990 | 159 |

The indoor environment was then evaluated according to DS/EN 15251 (2007). The system was considered to be sufficient if the operative temperature remained in category B, or better, for at least 95% of the time. For the validation calculations for all locations have been done. However only a selection is presented in this paper.

Madrid, Spain

According to table 2 Madrid is in a cooling based climate without the need for dehumidification. The simulations done in BSim (see table 4 and 5 for information TABS setup) to verify this show that TABS will be

able to provide adequate cooling throughout the cooling season. As can be seen in figure 2 the operative temperature only exceeds 26°C for about 1% of the time in Zone C. Apart from that there is a slight problem with under-cooling in zones A and B where temperatures drop below 23°C for about 1% of the time.

Table 4: TABS operation key values - part 1

| | | Season | |
|----------------|------|-----------|-------------|
| | | Cooling | Heating |
| T _s | [°C] | 21.5 | 21.5 |
| Dead-band | | | |
| Zone A | [°C] | 23 – 24 | 20.5 – 21.5 |
| Zone B | [°C] | 22 – 24 | 20.5 – 21.5 |
| Zone C | [°C] | 23 – 23.5 | 20.5 – 21.5 |

Table 5: TABS operation key values - part 2

| | | Zone | | |
|--------------------------|-------|------|------|------|
| | | A | B | C |
| Pump on | [H] | 5441 | 4377 | 5541 |
| Solar gains | [kWh] | 969 | 538 | 2742 |
| H ₂ O removed | [kg] | 0.3 | 0.3 | 0.6 |

As table 5 shows only very little (in total 1.2kg) water was removed from the supply air in order to avoid condensation through the entire cooling season. With this it is very unlikely that actual condensation would have occurred, as the surface temperature is usually considerably higher than the supply temperature, thus introducing a considerable safety margin. This was not surprising as can be seen from figure 3 where all hours with dew point temperatures above 14°C are shown. As can be seen the dew point temperature barely exceeds 16°C.

In the case of Madrid most of the cooling is achieved through TABS. The ventilation system is primarily used to supply fresh air to the zones. This can also be seen from table 6 where, during the cooling period, ventilation consumes about 10% of the energy that is used by TABS. In general only limited heating is needed.

Table 6: Yearly energy consumption for Madrid, Spain

| | Zone | | |
|---------------------|-------------------------------|------|------|
| | A | B | C |
| TABS Heating | 0.1 | 1.4 | 0.6 |
| TABS Cooling | 48.4 | 33.6 | 51.2 |
| Ventilation Heating | 0.9 | 1.5 | 1.1 |
| Ventilation Cooling | 4.7 | 4.7 | 4.7 |
| Total | 54.1 | 41.2 | 57.6 |
| | [kWh/m ² per year] | | |

Abu Dhabi, United Arab Emirates

According to table 2 Abu Dhabi is in a cooling based climate with the need for continuous dehumidification. The simulations done in BSim (see table 7 and 8 for information TABS setup) to verify this show that TABS will be able to provide adequate cooling throughout

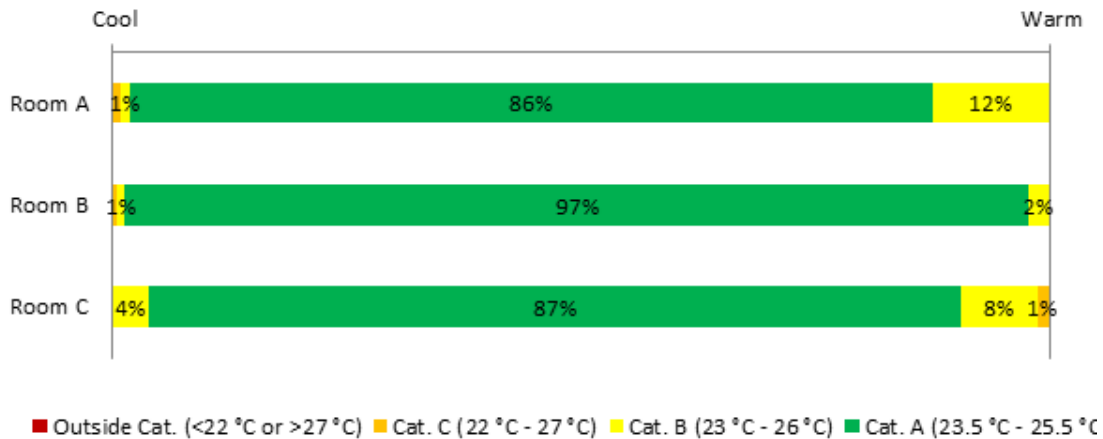


Figure 2: Operative temperature distribution according to the comfort categories for Madrid, Spain

the cooling season. As can be seen in figure 4 the operative temperature only exceeds 26°C for about 2% of the time in Zone C. Also in zone C there is a substantial amount of time (34%) in which temperatures are between 25.5°C and 26°C (cat. B). This is however acceptable for the aim of this validation.

Table 7: TABS operation key values - part 1

| | Season | |
|-------------|---------|---------|
| | Cooling | Heating |
| T_s [°C] | 19.5 | 21 |
| Dead-band | | |
| Zone A [°C] | 23 – 24 | 20 – 24 |
| Zone B [°C] | 23 – 24 | 20 – 24 |
| Zone C [°C] | 23 – 24 | 23 – 24 |

Table 8: TABS operation key values - part 2

| | | Zone | | |
|-------------------------------|--|------|------|------|
| | | A | B | C |
| Pump on [H] | | 3769 | 3706 | 4840 |
| Solar gains [kWh] | | 1003 | 550 | 2912 |
| H ₂ O removed [kg] | | 366 | 366 | 742 |

As table 8 shows that there is a significant amount of water (in total 1474kg removed from the supply air

over the course of the year. Without a continuous dehumidification this would result in considerable condensation on the controlled surfaces. This was also expected from the climate classification and can also be seen from figure 4. In this case the dew point temperature well exceeds 16°C most of the time, making continuous dehumidification during the cooling season necessary.

In Abu Dhabi the TABS are removing roughly three fourth of the heat from the zones, with the remaining energy being removed by the ventilation system. Table 9 shows that there is a considerable cooling load but no heating is required at any time.

Table 9: Yearly energy consumption for Abu Dhabi, United Arab Emirates

| | Zone | | |
|---------------------|-------------------------------|-------|-------|
| | A | B | C |
| TABS Heating | 0.0 | 0.0 | 0.0 |
| TABS Cooling | 102.1 | 85.9 | 116.8 |
| Ventilation Heating | 0.0 | 0.0 | 0.0 |
| Ventilation Cooling | 36.6 | 36.6 | 37.0 |
| Total | 138.6 | 122.5 | 153.9 |
| | [kWh/m ² per year] | | |

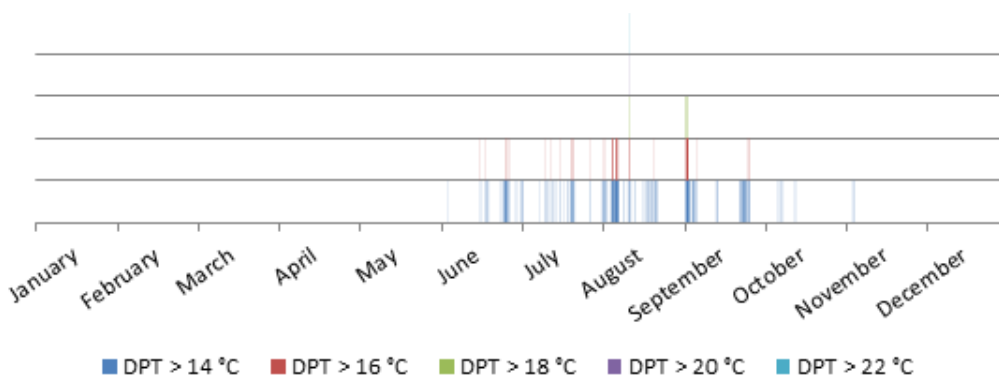


Figure 3: Dew point temperature diagram for Madrid, Spain as example for a cooling based climate without need for dehumidification

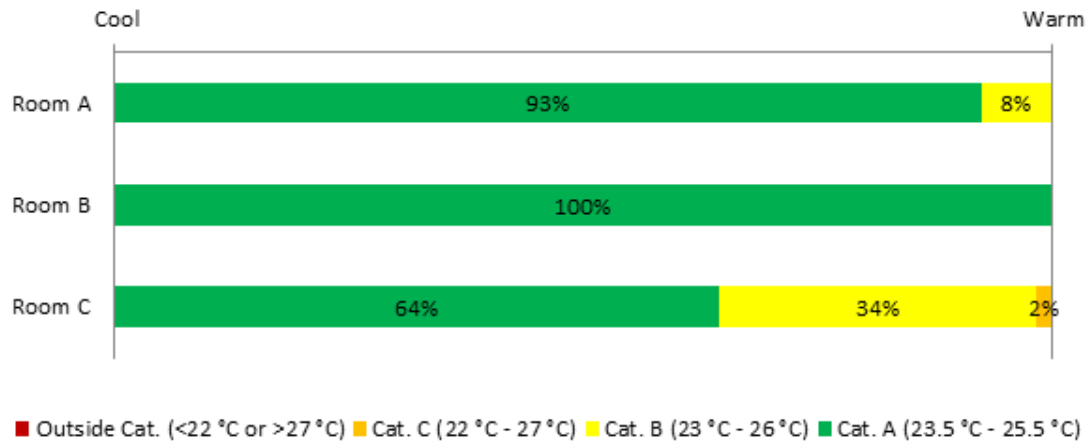


Figure 4: Operative temperature distribution according to the comfort categories for Abu Dhabi, United Arab Emirates

DISCUSSION AND RESULT ANALYSIS

Due to insufficient humidity informations, both the Köppen-Geiger, as well as the ASHRAE climate classification have been rejected. Extending either one of the systems to include humidity levels would likely have resulted in further zone fragmentation (even higher amount of different climatic zones), making them complicated to use.

The new classification offers a considerably simpler method, leaving less room for mix-ups while using the system.

The validation has shown that it is possible to use the new system to predict the need for dehumidification. However as the comparison of the energy consumption of Madrid and Abu Dhabi shows it is not possible to predict what percentage of the load will be removed by TABS and how much the ventilation system has to take care of. In extreme cases it is possible that the air handling unit is removing the biggest part of the load do to dehumidification requirements.

Within Europe only seven out of twelve possible climatic zones have been found. This was not surprising as a heating based climate will only require very lit-

tle cooling (if any) and in turn have very little need for dehumidification. There might however be circumstances where even a heating base climate requires continuous dehumidification during cooling periods. It is however questionable that cooling would be installed in such cases.

Based on the data for the 54 cities Figure 6 has been created. As can be seen most of Europe is either heating (north) or cooling (south) based. However there are some locations within otherwise uniform areas that indicate that the current resolution might not be high enough. As can be seen by Strasbourg (France - No. 15) climatic zones might be completely enclosed by just one other zone. This suggests that is very well possible that an increase on resolution (analysis of more locations/cities) could reveal that the current zoning is imprecise. The included map should therefore only be used with caution but it should reveal good results in close proximity to any of the indicated cities.

The new classification can also be used to evaluate the usability of other systems. Since the system is however set up for the evaluation of TABS additional precautions have to be considered.

The minimum permissible dew point temperature may

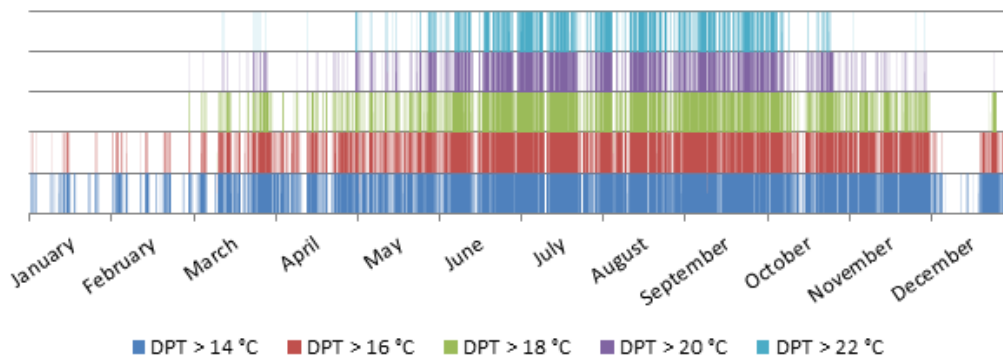
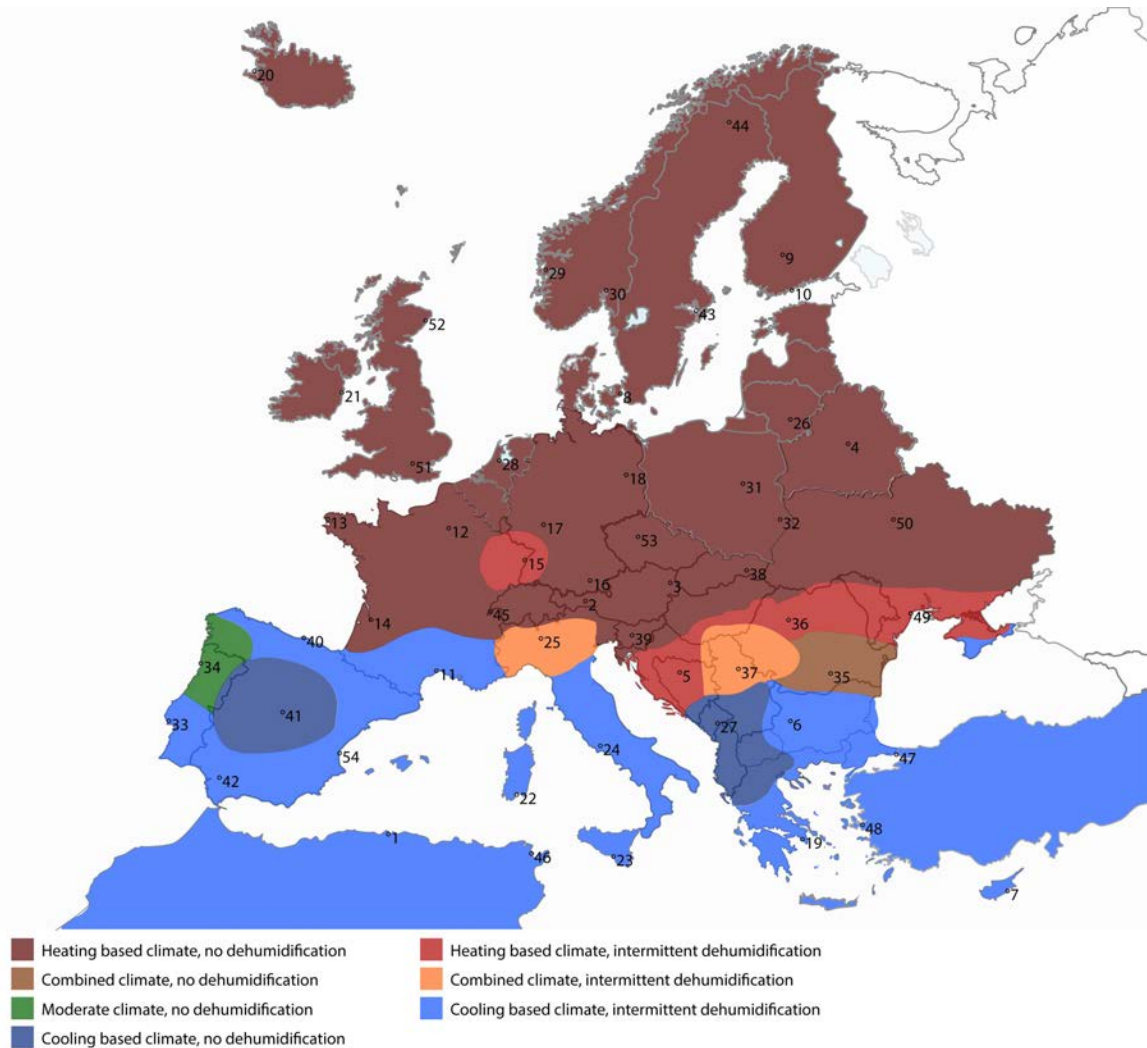


Figure 5: Dew point temperature diagram for Abu Dhabi, United Arab Emirates as example for a cooling based climate without need for dehumidification



- | | | |
|---------------------------------------|----------------------------|------------------------------|
| 1. Algiers, Algeria | 19. Athens, Greece | 37. Belgrade, Serbia |
| 2. Innsbruck, Austria | 20. Reykjavík, Iceland | 38. Kosice, Slovakia |
| 3. Vienna, Austria | 21. Dublin, Ireland | 39. Ljubljana, Slovenia |
| 4. Minsk, Belarus | 22. Cagliari, Italy | 40. Santander, Spain |
| 5. Banja Luka, Bosnia and Herzegovina | 23. Gela, Italy | 41. Madrid, Spain |
| 6. Sofia, Bulgaria | 24. Rome, Italy | 42. Sevilla, Spain |
| 7. Larnaca, Cyprus | 25. Milan, Italy | 43. Stockholm, Sweden |
| 8. Copenhagen, Denmark | 26. Kaunas, Lithuania | 44. Kiruna, Sweden |
| 9. Tampere, Finland | 27. Podgorica, Montenegro | 45. Geneva, Switzerland |
| 10. Helsinki, Finland | 28. Amsterdam, Netherlands | 46. Tunis, Tunisia |
| 11. Montpellier, France | 29. Bergen, Norway | 47. Istanbul, Turkey |
| 12. Paris, France | 30. Oslo, Norway | 48. Izmir, Turkey |
| 13. Brest, France | 31. Warsaw, Poland | 49. Odessa, Ukraine |
| 14. Bordeaux, France | 32. Zamosc, Poland | 50. Kiev, Ukraine |
| 15. Strasbourg, France | 33. Lisbon, Portugal | 51. London, United Kingdom |
| 16. Munich, Germany | 34. Porto, Portugal | 52. Aberdeen, United Kingdom |
| 17. Frankfurt, Germany | 35. Bucharest, Romania | 53. Prague, Czech Republic |
| 18. Berlin, Germany | 36. Cluj-Napoca, Romania | 54. Valencia, Spain |

Figure 6: Map of Europe based on the new climate classification system.
Based on vector map by Dill (2012)

differ greatly from one system to another. For example a chilled beam might already cause condensation on its surfaces while no condensation occurs for TABS when operated at the same supply temperature. However, in this case chilled beams would (with otherwise equivalent geometric properties) have a higher cooling capacity due to its better heat transfer.

Another problem for the use with systems other than TABS could be the choice made for the calculation of HDD and CDD. For systems with low thermal inertia Equations 2 and 4 would be more appropriate to calculate HDD and CDD rather than the here used Equations 1 and 3.

CONCLUSION

For evaluating the use of TABS in different climates, a method for classifying the climates involving heating and cooling degree days and the outdoor dew-point temperature has been put forward and a map of Europe divided into 7 of 12 possible climate zones has been created. The method is simple and works as intended. In conjunction with a simplified sizing method for TABS as suggested in ISO 11855-4 (2011) it is possible to estimate the capabilities of TABS under the given circumstances without the need of a full blown building simulation. This can save time and money as it can be done at early design stages with very little effort.

The current classification should however be further refined. The currently used base temperatures might not be the best choice for modern buildings. The improved insulation and glazing that is required due to current building codes in many countries has a significant influence on the buildings base temperature. Due to different valid building standards around the world it might be necessary to adjust the base temperature accordingly to get the best results.

NOMENCLATURE

- h = heat loss coefficient of the building envelope [W/K]
 T_b = base temperature [°C]
 T_i = average indoor temperature [°C]
 $T_{j,i}$ = outdoor temp. of hour i on day j [°C]
 T_s = Supply water temperature [°C]
 q_{gain} = average gains from equipment, occupants, the sun, etc. [W]
 $\sum(\dots)^+$ = only add to sum if bracket positiv

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