Building Energy and Environmental Performance tool BEEP

Development of a method to compare the true energy efficiency of buildings

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SUMMARY

Regulatory devices for the energy efficiency of buildings currently in use, including the new EU “Directive on the Energy Performance of Buildings” [1] and especially the methods currently proposed in the various member states to determine and judge the energy performance of buildings as required by this directive deal only with energy demand and not with energy efficiency. This paper proposes a method which allows the true energy efficiency of a building design to be determined and thus a real comparison of various building design options. Energy efficiency is understood here as the relationship between the quality of the internal thermal environment in a building and the quantity of energy consumption required to maintain this environment. The proposed method takes into account the interrelationship between energy demand and internal environment and the calculated BEEP value is an indicator for total Building Energy and Environmental Performance.

INTRODUCTION

The true meaning of energy efficiency must take into account the internal environmental conditions as well as the energy demand required to maintain them. In fact, I propose that it is the relationship between the quality of the internal environment in a building and the quantity of energy consumption required to maintain this, which defines the energy efficiency of a building, at least in a thermal sense. The economic importance of the relationship between thermal comfort and productivity is becoming increasingly recognized [2]. The real challenge in energy efficiency is achieving a good indoor environment with a low energy demand. Prospective tenants and buyers of buildings should know what they are getting – a certificate with an energy demand rating means little if information about the quality of the associated internal environment is not made available. The current one-sided approach with concentration on energy consumption can lead to situations whereby seemingly high energy efficiency is only being achieved on paper. If the indoor environment is not acceptable, systems will be adjusted or new systems added to achieve a better environment at the cost of higher energy consumption. A method is needed which allows both energy demand and indoor environment to be quantitatively appraised to allow a real comparison between various options.

METHODS

The goal of the study was to develop a chart which allows the energy efficiency of various building designs to be plotted and thus compared. In order to measure the energy efficiency of the considered options it is necessary to relate the quality of the internal environment to the energy use necessary to maintain this. It is proposed here that the quality of the internal environment be indicated by the number of hours whereby comfortable conditions are not achieved; this in turn is measured by determining how many hours the "Predicted Percentage Dissatisfied" (PPD) is greater than 10%. PPD is the percentage of people likely to be dissatisfied with the thermal environment [3]. In the ISO 7730 a PPD value of less than approx. 10% is recommended [4].

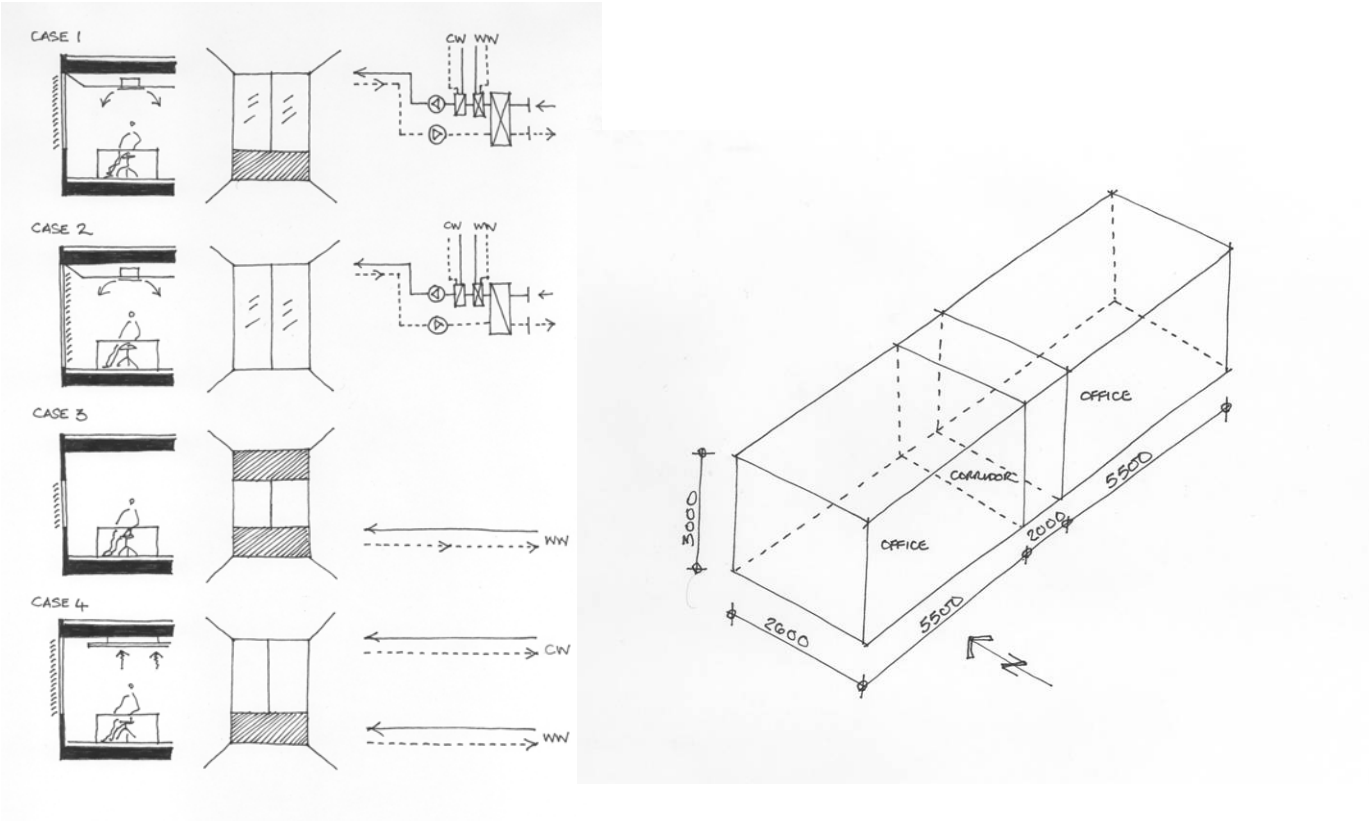

Figure 1. Design options and model geometry

In a second step four design options for a hypothetical office building were examined using dynamic thermal simulation and plotted on the chart as a means of testing the suitability of the proposed method. The options examined are various design alternatives for a hypothetical office building in Vienna city orientated with main facades east and west (see figure 1). The first design option has facades with approx. 70% window area and external blinds and is air-conditioned with non-operable windows. The second is fully glazed with a highly selective solar control glass and internal shading devices. It is also air-conditioned with non-operable windows. The third building has 40% window area, external blinds, operable windows and is heated only. Exposed concrete slabs and night time ventilation are used to limit summertime temperatures. The fourth building has façades with approx. 70% window area and external blinds, exposed concrete slabs, night time ventilation, comfort cooling and natural ventilation. For the thermal simulations a representative slice of the building as shown in figure 1 was used. The following assumptions were made:

- office hours from 9 am to 5 pm
- room setpoint in summer 24°C
- room setpoint in winter 22°C (reduced to 16°C at night)
- normal office internal loads (1 Person per 14 m², 15 W/m² machines, 15 W/m² lights)
- window frame 10%
- no humidification in winter
- supply air condition 20°C all-year round

- no ventilation in the corridor
- ventilation system in operation from 8 am to 6 pm
- nighttime ventilation from 12 pm to 6 am, May to September, assumed constant at 1.5 ac/h
- a constant air change rate of 2 ac/h is assumed for the natural ventilation options
- % window to wall is based on internal wall area (seen from office)
- internal walls are assumed adiabatic

To assume a constant air change rate of 2 ac/h for the natural ventilation options is a simplification and could potentially lead to overestimation of both heating demand in winter and summertime overheating. However cross-checking of the results with previous detailed studies into natural ventilation of offices [5] shows that the results correlate well with previous results based on more complex models. Due to the uncertainties associated with occupant behavior in naturally ventilated buildings it was felt that this approach was adequate for the present purpose. For details on the various design parameters used for the four options see table 1.

Table 1. Parameters

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Window Area as % of indoor wall area	73%	100%	40%	73%
Window U-Value	1.3	1.5	1.5	1.3
Glass g-Value	62%	36%	62%	62%
Glass light transmission	80%	66%	80%	80%
Operable windows	no	no	yes	yes
Solar Shading Position	external	internal	external	external
Solar Shading Control Value	200 W/m^2	200 W/m^2	200 W/m^2	200 W/m^2
Wall U-Value	0.3		0.5	0.3
Suspended ceiling	yes	yes	no	no
Cooling	yes	yes	no	yes
Ventilation	mechanical	mechanical	natural	natural
Air change rate	2.5 ac/h	2.5 ac/h	2 ac/h	2 ac/h
Dehumidification	yes	yes	no	no
Heat Recovery efficiency	70%	50%	none	none
Heating Unit Capacity (W/m^2)	70	70	70	70
Cooling Unit Capacity (W/m^2)	50	50	0	50
Nighttime ventilation	no	no	yes	yes

Heating and cooling loads were calculated using dynamic thermal simulation software. Fan energy was calculated based on 3 W per l/s of supply air, typical for conventional ventilation systems currently installed in European buildings. Lighting energy was estimated using a simple method developed by the author, which uses calculated daylight factors and annual external light availability data to roughly estimate the hours when electrical lighting can be expected to be in use. The primary energy demand thus calculated represents roughly 90% of the total primary energy demand of an average office building (excluding computers, office machines etc.). Items such as domestic hot water, pumps and lifts are not included.

RESULTS

Figure 2 shows the BEEP chart which was developed to allow the energy efficiency of various building designs to be plotted and thus compared. The x-coordinate of a given point represents the primary energy demand of the building design for heating, cooling, lighting and fans and the y-coordinate the percentage of occupied hours in a year with PPD > 10% as an indication of the comfort level achieved.

It is proposed that energy efficiency is expressed as the relationship of the number of hours with comfortable conditions to the primary energy demand necessary to maintain this condition. This is called the BEEP value and is calculated thus:

$$BEEP = \frac{NOH(100 - N)}{100PED} \qquad (1)$$

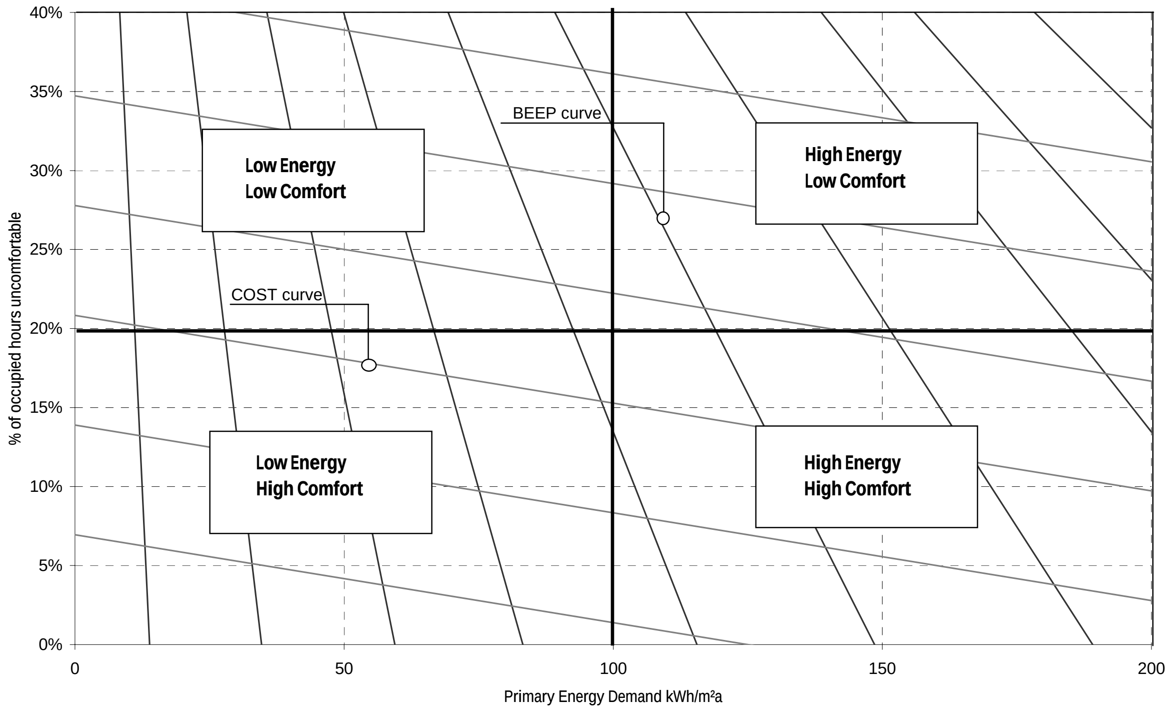

Figure 2. BEEP Chart

where BEEP is the Building Energy and Environmental Performance in hours comfortable per kWh/m²a, NOH is the number of occupied hours in a year, here assumed to be 2080, PED is the primary energy demand for heating, cooling, fans and lighting in kWh/m²a and N is the % of occupied hours with non-acceptable internal environmental conditions (PPD > 10%). To allow a comparison of the economic or financial implication of the considered options in operation it is proposed to sum the energy costs and the effect of the loss of productivity due to poor internal conditions and use this as an indicator of the economic cost of the various options.

$$COST = (EC)(PED) + (PL)\frac{(SC)(N)}{10000} \qquad (2)$$

where COST is measured in €, EC is the cost of a unit of primary energy in EUR/kWh, here assumed to be 0.04 €/kWh, SC are the staff costs and are assumed here to be EUR 7200/ m²a (€12 000 (Salary+overhead+profit) x 12 months / 20 m²) and PL is the assumed loss in productivity in % for the time when PPD is higher than 10%. It is assumed here that a 1% loss in productivity occurs whenever the PPD is greater than 10%. It should be noted that this is probably a gross underestimation of the effect of poor comfort on productivity. The assumption that the loss remains at 1% regardless of how high the PPD is, is also of course a simplification and probably an underestimation of the effect. Roelofsen states values of approx. 3% productivity loss at 10% PPD rising to nearly 20% at 60% PPD [6]. However for the purpose of providing an indicator such as proposed here for use in the comparison of options, it was felt that it may be better to initially underestimate this effect. As the results will show, even a constant value of 1% weighs in heavily when compared to energy costs. Further research should be undertaken into the application of the available data on productivity loss dependent on comfort in a method such as proposed here.

The resulting BEEP chart can be thought of as comprising four areas as shown in figure 2. The goal of building designers should of course be the bottom left area. Often decisions are between the bottom right and the top left areas. Obviously the top right area is to be avoided. Lines connecting BEEP points with equal values are called BEEP curves. Buildings which lie on the same BEEP curve may be said to be equally energy efficient. Lines connecting COST points with equal values are called COST curves. Buildings which lie on the same COST curves may be thought of as having similar economic implications in operation. The higher the BEEP value is, the higher the energy efficiency of the solution. A lower COST value means lower costs in operation. 100 kWh/m²a was taken as the boundary value between high and low energy solutions. This is the value used to define a low energy building in a governmental support program for energy efficient building in Germany [7]. A value of 20% of the occupied hours uncomfortable was chosen as the boundary value between high and low comfort. While this may seem high, one must remember that a large proportion of office buildings in Europe have no passive or active cooling and will thus be probably uncomfortable for large portions of the summer. Obviously these values are to some extent by nature arbitrary and will need to be adjusted after further research work. Table 2 shows the results of the dynamic thermal simulation of the four design options described above, including the BEEP values, which were calculated as described above. The primary energy value obtained from the simulation of the representational slice was multiplied by a factor of 0.85 to convert the value to kWh per m² total floor area of the building. This factor is based on typical values for the relationship between office and total floor areas and between energy demand in the office areas and in the other areas of the building.

Table 2. Results

	Energy Demand	**Comfort**		**BEEP**
	Primary Energy kWh/m²a	Hours PPD>10%	% of occupied hours	Value
Alternative 1	110	13.0	0.6%	19
Alternative 2	150	615.0	29.6%	10
Alternative 3	100	564.0	27.1%	15
Alternative 4	87	174.0	8.4%	22

Figure 3 shows the break-down of the primary energy demand for the various options. In figure 4 the four alternative solutions are plotted on the BEEP chart. When the alternative solutions are ranked in terms of both BEEP value and COST values the results are surprising when compared with a ranking done on intuition. Interestingly, alternative 1 can be seen to have a higher BEEP value and therefore a higher total energy and environmental performance than alternative 3, which may not have been apparent before being plotted on the BEEP chart. From an economic point of view alternative 1 can be seen to be by far the most efficient, also not immediately apparent before plotting on the BEEP chart. Before finalizing a decision, capital costs and the costs of system maintenance etc. would of course need to be considered. Alternative 2 is the worst type of solution; high energy and low comfort. In terms of costs in operation alternative 2 and 3 are similar, also an unexpected result. Of course the capital costs associated with alternative 2 will be higher. Alternative 4 is a low energy high comfort solution and has the highest BEEP value. Considering that alternative 1 will also be more expensive in terms of initial costs than alternative 4 and that the absolute energy demand of alternative 4 is considerably lower than alternative 1, alternative 4 may be judged to be the best solution. The relatively large percentage of time however, whereby the internal environment is not comfortable, needs to be considered. On the other hand, many solutions exist for low energy high comfort buildings which may be expected to perform considerably better than alternative 4. Note also that if natural ventilation was reduced in winter and increased in summer the comfort performance of alternative 4 (and alternative 3) could be expected to improve (see assumption above for natural ventilation). In other words there is potential with alternatives 3 and 4 to improve comfort and energy performance by optimizing natural ventilation strategies. Note that whilst the energy demand from the alternatives 3 and 4 are similar, the total performance of alternative 4 as measured by the BEEP value is significantly higher.

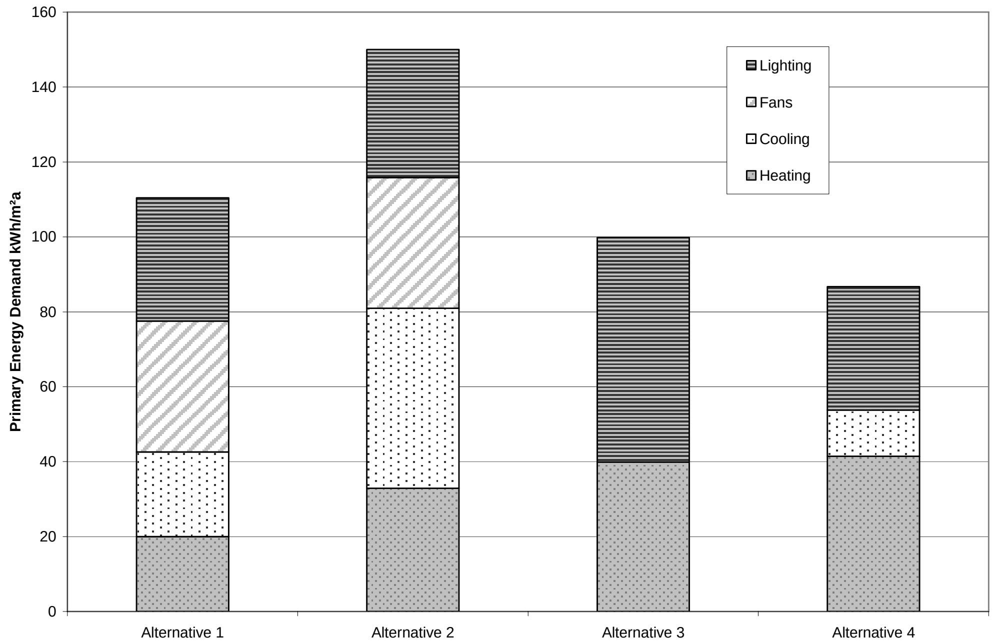

Figure 3. Primary energy demand of the various options

An interesting question poses itself with regard to alternative 3. What would happen, if the building was upgraded at a later stage with a cooling system to improve comfort? This option was also simulated and the result is shown in figure 4 as point 3´. The cooling system is the same as that used in alternative 4. It can be observed that although comfort is significantly improved and the BEEP value is also improved (slope of the improvement curve is steeper than the BEEP curves), the total energy and environmental performance is still less than for alternatives 1 and 4. The energy demand of the upgraded alternative 3 is very similar to 1, yet the attained comfort level significantly lower. This result demonstrates that the BEEP value in such a case should be calculated for both the present condition and the condition after an upgrading to include systems which provide a certain minimum level of comfort.

DISCUSSION AND CONCLUSIONS

The method presented here outlines an approach which could form the basis on which further work could be carried out with the ultimate goal of developing a comprehensive way of comparing the energy efficiency of building design options. The examples here were used as a means of initially testing the method. The results obtained are not intended in any way to provide conclusions on the appropriateness of the various design solutions studied. The results do indicate however that we need to compare options comprehensively and understand energy efficiency not as energy use alone but as the relationship between energy use and value in terms of the quality of the internal climate achieved. This should be part of a total approach in which capital and running costs, functionality and architectural quality etc. of the various options are also compared with one another. The economic curves are primarily displayed to indicate tendencies and to show the vast difference between the energy and economic efficiencies (demonstrated by the different slope of the curves). An increase in energy cost would change the slope of the economic curve and it is interesting to note, that based on the data considered here, the energy price would need to increase by a factor of approx. 15 before the slopes would roughly coincide and decision making based on total energy and environmental performance and decision making based on cost would lead to the same solution. It must be remembered that capital costs have not been factored-in. The goal of any design should be a high BEEP value positioned in the bottom left area. Note that the higher the BEEP number, the steeper the curve; i.e. large differences in comfort and small differences in energy demand.

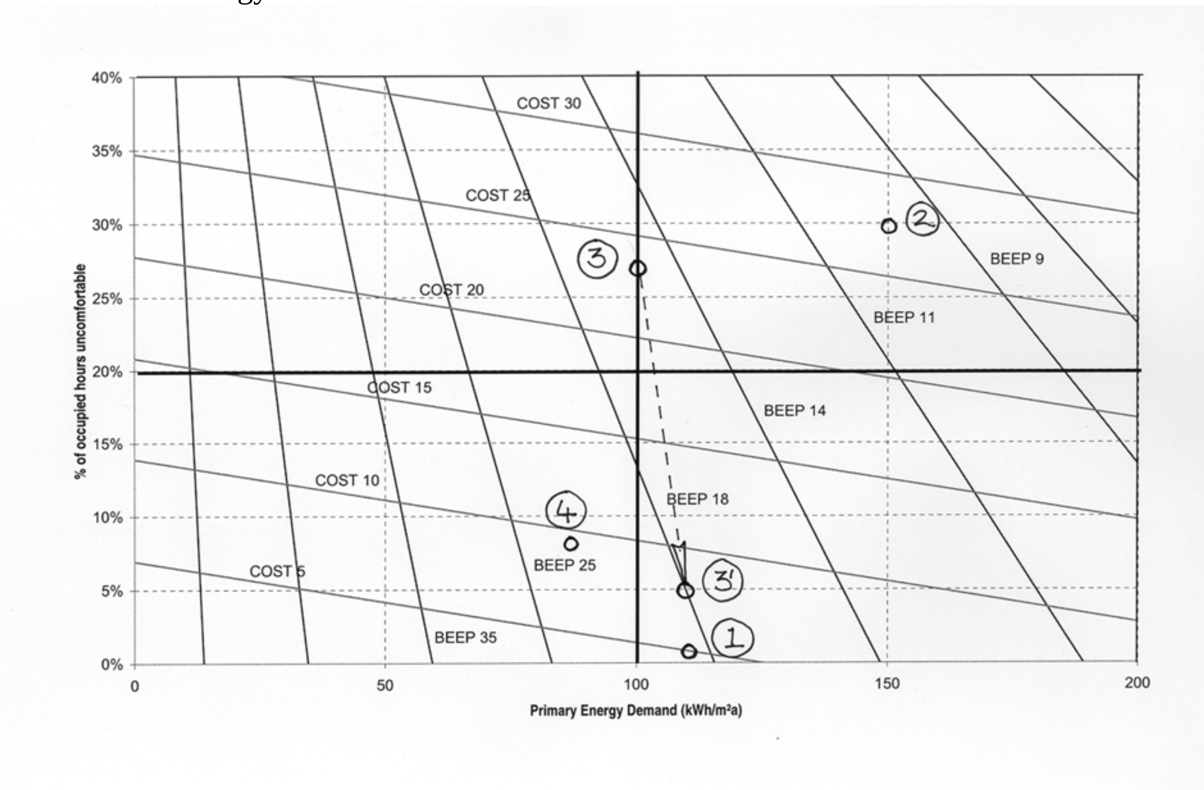

Figure 4. Results

The proposed tool could be developed to be put in use not only as a means of demonstrating the energy efficiency of building designs at the planning permission stage (similar to the energy certificate as required by the new EU directive) but also as a design tool to compare various options during the design stage. Items such as energy production (photovoltaic, wind energy, solar cooling) and system configurations such as underground fresh air ducts are not considered in the illustrated case studies but could and should be included in the final planning instrument. A more complex instrument can be imagined whereby the x-axis is represented by total primary energy demand over the total life cycle of the building (including embodied energy etc.) with the y-axis representing the total internal environment achieved including factors such as air quality, lighting levels and acoustics but also psychological issues such as daylight, operable windows etc. The capital costs could be factored into the economic curves.

Contemporary engineering design firms use dynamic simulation to design buildings as standard procedure. It seems questionable, whether the right approach is to develop spreadsheets for energy calculations for the production of energy certificates, which is what is happening all over Europe right now, instead of accrediting commercial dynamic simulation software programs. Further research is necessary to determine the range of appropriate values in the BEEP chart and to produce BEEP charts for different applications. A series of charts could be produced for different building uses (office, apartments etc.) for various climatic regions. Further research should also look at ways to measure comfort which would be appropriate to be used in such an approach. The simulation software used in the study here calculates the PPD value for the centre point of the room. It should be investigated further whether this relatively primitive indicator is adequate for the intended purpose or alternatively whether a better one could be employed. Further research on the exact nature of the relationship between PPD and performance would also be valuable. Future work could also improve the complexity of the natural ventilation model (see above). Note also that research has shown that comfort perceptions in naturally and mechanically ventilated buildings are different [8]. This aspect has not been considered yet in the approach used here.

The upgrading of alternative 3 with cooling shows the danger of the current methods concentrating only on energy demand; a seemingly low energy building may after upgrading to rectify comfort problems be less energy efficient than a relatively conventional fully air conditioned building. In terms of conserving energy or possibly even from an ecological point of view, concentrating on reducing energy demand is possibly a legitimate approach but is it really sustainable? Achieving sustainability is complex and consideration of the economic and social aspects may mean that conserving energy at the expense of a lower quality of internal environment is not the most sustainable approach.

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