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Assessment of productivity loss in air-conditioned buildings using PMV index

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Abstract

This theoretical study reports on the assessment of productivity loss in air-conditioned office buildings using the PMV approach and makes use of Wyon's reviews [D.P. Wyon, P.O. Fanger, B.W. Olesen, C.J.K. Pedersen, The mental performance of subjects clothed for comfort at two different air temperatures, Ergonomics 18 (1975) 358–374; D.P. Wyon, Individual microclimate control: required range, probable benefits and current feasibility, in: Proceedings of Indoor Air '96, Institute of Public Health, Tokyo, 1996; D.P. Wyon, Indoor environmental effects on productivity. IAQ 96 Paths to better building environments/Keynote address. Y. Kevin. Atlanta, ASHRAE, pp. 5–15] as the basis to compare and to relate how the productivity loss could be minimised through improved thermal comfort design criteria. The finding shows that task-related performance is significant correlated with the human perception of thermal environment that in turn is dependent on temperatures. Different combinations of thermal criteria (air velocity, clo, metabolic, etc.) can lead to similar PMV value and the PMV equation is useful to predict productivity loss that is due to the rate of change in thermal conditions. The study also highlights the issues that remain to be resolved in future research.

Keywords: Productivity; PMV index; Air-conditioned offices

1. Introduction

Air-conditioned office buildings aim to provide a thermally acceptable environment for human comfort and work that would in turn enable better work productivity and less thermal dissatisfaction. The initial investment cost of an air-conditioning system is the usual first criterion in its system selection. This is a limited approach because it can be costly in the building economic life cycle if the air-conditioning operation and maintenance cost and the impact on office workers' productivity are not duly considered.

A literature review has identified the following findings: (1) the salaries of office workers are many times the cost of operating a building in developed countries; (2) there is a potential monetary gain due to improved workers' productivity if there is a shift in focus towards the provision of better indoor climate conditions; (3) improving working efficiency in thermal indoor environment is deemed to be the most important environmental factor in office productivity study. Woods [4] has determined that the salaries of workers in the US office buildings have exceeded the cost of building energy, maintenance, annualized construction and rental by a factor of 100. Skåret [5] has published a similar study in Norway and estimated that increased productivity due to an improved indoor climate is at least 10 to 100 times greater than the operational and maintenance costs.

More recent US studies such as [6,7] have estimated that the yearly potential gain of productivity increase due to the reduction of respiratory infection would equal US$ 6–14 billion while a reduction of sick building syndromes (SBS) could yield around US$ 15–38 billion. Most significantly, improved working efficiency could yield US$

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20–200 billion. Similar findings have been published elsewhere in developed countries, such as a reported Finnish study by Seppanen [8] that estimated a loss of 2.7 billion Euros due to poor indoor climate conditions in Finland. In Asia, a recent study by Gan and Tan [9] has emphasized the negative consequences of a poor indoor thermal environment and stated that the use of life cycle costing approach is necessary to mitigate the monetary implication of thermal comfort and productivity in tropical air-conditioned buildings. The productivity loss issue is therefore prevalent in poorly designed air-conditioned enclosures regardless of external climate variation and thus a primary aim in this study is to design quality indoor thermal conditions that are suitable for the envisaged tasks in office spaces, thus promoting better productivity.

This theoretical study reports on the assessment of productivity loss in air-conditioned office buildings using the predicted mean vote (PMV) approach and makes use of Wyon's reviews [1–3] as the basis to compare and to relate how the productivity loss could be minimised through improved thermal comfort design criteria. This 'retrospective' interpretation, by means of PMV parametric analysis, also helps to re-examine the nature of productivity loss reported in earlier studies.

2. Thermal environment

Thermal comfort is a fluid concept and is derived from the actual requirement of people. A human being's thermal sensation is related to the thermal balance of his body as a whole. Using the first principle of adaptive thermal comfort approach, the subject will secure his own comfort through behavioural adjustment. The balance is influenced by his metabolic heat production, physical activity, clothing and the four environmental parameters: air temperature, mean radiant temperature, air velocity and air humidity. At the outset, occupants in an air-conditioned building could normally adapt to the indoor thermal environment through physiological means to attain their own comfort. When these factors are known, the thermal sensation for the body as a whole can be predicted by the predicted mean vote calculation. There could possibly be different combinations of thermal criteria at thermal neutrality (PMV = 0) that could give rise to the same work performance (productivity). One such example is reported by Wyon et al. [1] where the conditions of 0.6 clo value at 23.2 °C air temperature and 1.15 clo at 18.7 °C air temperature are cited to lead to similar productivity level.

Hence, the PMV concept [10] is relevant as a tool in the assessment of productivity loss for the rate of change in thermal comfort criteria. This could provide a better insight into the thermo-physics of the heat exchange between an occupant and his environment; and the impact on productivity in an indoor air-conditioned office environment. Several other studies have shown that very moderate heat stress can negatively affect mental performance [3]. In the case of a warm thermal environment, the blood vessels would normally vasodilate, increasing the blood flow through the skin and at higher thermal load one begins to perspire. In the absence of conscious effort, the human body might tend to adapt through lowering of internal heat production and this reduces or even avoids perspiration. This subconscious behavioural adjustment could mean a lower arousal and results in a slower work rate. This is the responsiveness of human thermoregulatory system towards external variation in climate, work condition and perceived sensations.

3. Productivity measure

It should be noted that optimal performance (productivity) does not necessarily occur under optimal thermal comfort conditions and this is supported by evidence in an early study [11] where subjects were performing mental work at air temperatures in the range 20–30 °C. A more recent report by Wyon [3] has summarized numerous thermal effects on performance in laboratory environments. Productivity loss is presented as a function of room temperature in different tasks. The main findings are two-fold: (1) for thinking tasks, the rate of working was reduced by 30% at 27 °C when the average neutral temperature was 21 °C and remained constant at 70% for higher temperatures above 27 °C and (2) for typing tasks, performance decreased to 70% over 4 °C and remained at 70% at higher temperatures. Thus, productivity loss is strongly dependent on the nature of the performed task. The approach makes use of two main tasks: typing and thinking. The best approach is to fit the general pool of job descriptions by using the time weighting factors for the tasks.

These past findings provides the impetus to model the simulated subjective responses of occupants in buildings, using the PMV parametric analysis, with respect to the rate of change in thermal conditions and the impact of the changing thermal conditions on both the thinking and typing tasks where the thermal neutral balance situations are fully documented. Wyon's results [1–3] are therefore used and reconstructed in this study to create a generic productivity loss model using the PMV index as a 'navigating' search and assessment tool. The neutral temperature concept is used in this assessment of productivity loss in air-conditioned office buildings.

4. Base case comparison to new simulated situations

Table 1 reports the results of the parametric analysis that is carried out at a room temperature of 21 °C and relative humidity of 50%, in a condition that is somewhat akin to Wyon's review [3]. The Cases 1–4 in Table 1 are examples of the possible thermal neutral conditions in the test. In the

Table 1
Comparison of PMV values at different temperature differences from the neutral conditions in the selected cases

	Estimated conditions for Wyon's review (base case)	Other simulated cases			
		1	2	3	4
DT_{rad}	0 °C	0 °C	0 °C	−2 °C	2 °C
v	0.15 (m/s)	0.15 (m/s)	0.25 (m/s)	0.15 (m/s)	0.15 (m/s)
clo	1.16	1.2	1.25	1.23	1.03
M	1.2	1.1	1.2	1.2	1.2
Temperature difference using a starting base temperature of 21 °C	Reconstructed PMV results	Other simulated cases – PMV results			
0	0	0	0	0	0
+1	0.21	0.21	0.21	0.19	0.23
+2	0.42	0.43	0.42	0.39	0.46
+3	0.63	0.65	0.63	0.59	0.68
+4	0.84	0.87	0.85	0.79	0.91
+5	1.06	1.09	1.07	0.99	1.14
+6	1.28	1.32	1.28	1.19	1.38

DT_{rad}: temperature difference (K) between room temperature and mean radiant temperature; v: air velocity (m/s); clo: clothing value (clo); M: metabolic rate (W/m^2); PMV: predicted mean votes.

selected situations (Cases 1–4), the basic assumptions are as follows:

- air velocity is 0.15 m/s (except case 2: 0.15 m/s);
- radiant temperature is assumed to be equal to the room temperature (except Case 3: DT_{rad} = −2 °C and Case 4: DT_{rad} = +2 °C);
- metabolic rate is 1.2 MET (except Case 2: 1.1 MET);
- relative humidity is 50%;
- room (air) temperature is 21 °C.

Based on these values in the selected cases, the requested clo values are calculated at the base temperature level of 21 °C to reach thermal neutrality.

In the base case, the clo value has been adjusted to 1.16 to reach the thermal neutral conditions (PMV = 0). At the same way in Cases 1–4, the requested clo values are calculated to reach thermal neutrality.

The effect of the temperature rise from the neutral conditions for PMV index is slightly different with the different combinations of thermal criteria. The biggest difference occurs when there is deviation between the radiant temperature and the room temperature. Cases 3 and 4 in Table 1 demonstrate a change in the radiant temperature to attain the thermal neutrality at a room air temperature 21 °C. Anyhow, the PMV values at different room air temperatures of Cases 1 and 2 differ very little from the base case which is estimated to describe the conditions in the reviewed study.

This finding has demonstrated the followings:

- different combinations of thermal criteria (air velocity, clo, metabolic, etc.) lead to similar PMV values at different temperature levels when the radiant temperature is assumed to equal to the room temperature;
- the reconstructed conditions are reasonable accurate for use to predict the PMV-productivity loss analysis and generalize the previous temperature correlation to cover PMV and productivity interdependence.

5. PMV prediction of thinking and typing tasks in office

The above base case comparison has shown that the PMV parametric analysis approach is possible to create the causal

Table 2
PMV prediction of thinking and typing tasks at different temperatures

Temperature difference from base temperature of 21 °C	PMV prediction	Predicted percentage dissatisfied, PPD (%)	Wyon's productivity loss in thinking (%)	Wyon's productivity loss in typing (%)
−1	−0.21	6.3	0.0	0.0
0	0	5.0	1.9	4.9
+1	0.21	6.0	5.4	13.5
+2	0.42	9.0	10.1	23.2
+3	0.63	14.0	15.3	30.0
+4	0.84	21.0	20.6	32.8
+5	1.06	29.0	25.7	33.4
+6	1.28	38.0	30.0	33.5

relationship between the PMV index and results of the productivity loss for thinking and typing office tasks that are reported by Wyon [3] (Table 2).

Using the predicted PMV results, the peak level of the productivity (assume = 100%) occurs when PMV value is −0.21 at a temperature of 20 °C. The PPD in this case has a low value of 6.3%. This hypothetical benchmark is aimed to offer a better insight of thermal responses at the corresponding higher temperatures. The results show that, as the temperature increases above the neutral temperature of 21 °C for the envisaged productivity losses in thinking and typing, the corresponding PMV values move from 0 (neutral sensation) to 1.28 (warm sensation). At a temperature of 24 °C, the productivity loss in typing task exceeds 30% with a predicted PMV value of 0.63 (slightly warm sensation). This is significantly different compared to a thinking task where 30% or more productivity loss only starts to occur at a higher temperature of 27 °C.

This finding implies the followings:

- task-related performance is significant correlated with the human perception of thermal environment that in turn is dependent on PMV and PPD values;
- the value of the productivity loss in thinking is quite close to PPD value and in typing about two times higher than PPD value when PMV is less than 0.65;
- normally accepted PMV value of +0.5 leads about 12% productivity loss in thinking and 26% loss in typing.

Using the mathematical expression of Productivity Loss, $y = c_0(\mathrm{PMV}) + c_1(\mathrm{PMV})^2 + c_2(\mathrm{PMV})^3 + c_3(\mathrm{PMV})^4 + \cdots + c_n(\mathrm{PMV})^n$. The following two Eqs. (1) and (2) are derived for typing and thinking tasks (Fig. 1).

For typing task:

$$y = -60.543x^6 + 198.41x^5 - 183.75x^4 - 8.1178x^3 + 50.24x^2 + 32.123x + 4.8988 \quad (1)$$

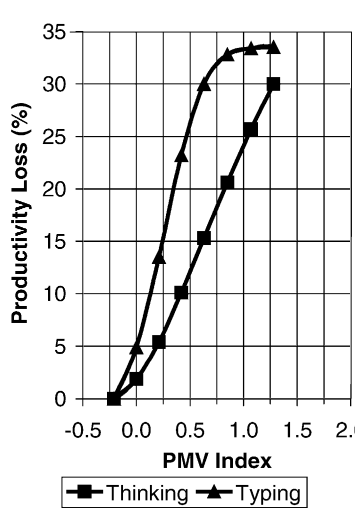

Fig. 1. Curve fitting of thinking and typing tasks.

For thinking task:

$$y = 1.5928x^5 - 1.5526x^4 - 10.401x^3 + 19.226x^2 + 13.389x + 1.8763 \quad (2)$$

Using the curve fitting equations for thinking and typing tasks, it is possible to calculate the productivity loss as a function of PMV, and as a function of PPD using the typing and thinking tasks in Eqs. (1) and (2), respectively as the boundary constraints. The results are shown in Figs. 2 and 3 below.

The envelope of curves shown in Figs. 2 and 3 arising out of the mathematical expressions derived in Eqs. (1) and (2) is fairly accurate to predict the productivity loss vis-à-vis the traditional PMV and PPD approaches.

The nature of the task is a key determinant for the rate of productivity loss. The productivity of the worker decreases at a sharper rate in typing tasks than thinking tasks. For example, if the share of thinking and typing is 50:50 with a PMV value of 0.5, the productivity loss is about 6% higher than pure thinking task.

It is noted that an approximate linear correlation between PPD and productivity loss (≤20%) occurs for thinking tasks. Conversely, in typing tasks, the productivity loss (≤20%) can be almost twice as much as the PPD. (See Fig. 3 comparison for typing task: PPD =15% and productivity loss = 30% and thinking task: PPD = 15% and productivity loss = 15%.)

6. Neutral temperatures and its impact on productivity

The acceptable PMV range is usually between −0.5 (slightly cool sensation) and +0.5 (slightly warm sensation). In tandem with the acceptable PMV range, the respective neutral temperatures of 21, 23 and 25 °C would produce a temperature range of +2.5, +2.0 and +1.5 °C, respectively. This condition is only valid when all other parameters are constant.

In practice, there is a possibility to adjust clothing insulation at lower temperatures and in turn this helps to increase the neutral temperature range. At higher temperatures, this is a limited possibility because the clothing value has to conform to the social milieu. For example, the necessary clo value would be approximately 0.84 at 23 °C and 0.53 at 25 °C. Adjustment methods, such as a move relaxed clothing norm that result in lower clo value, approximate to 0.50 clo, could be used to achieve a higher neutral temperature, but it is not possible in all cases.

Figs. 4 and 5 show that the decline of productivity at the different neutral temperatures for both typing and thinking tasks. The envisaged productivity for typing tasks will decline to 70% when the temperature difference between room temperature and neutral temperature is 3 °C. For thinking tasks, the tolerance threshold is higher than that

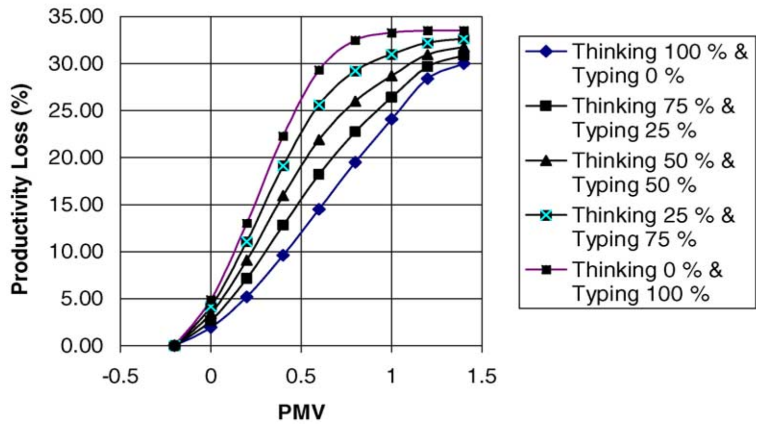

Fig. 2. Productivity loss as a function of PMV for different combination of tasks.

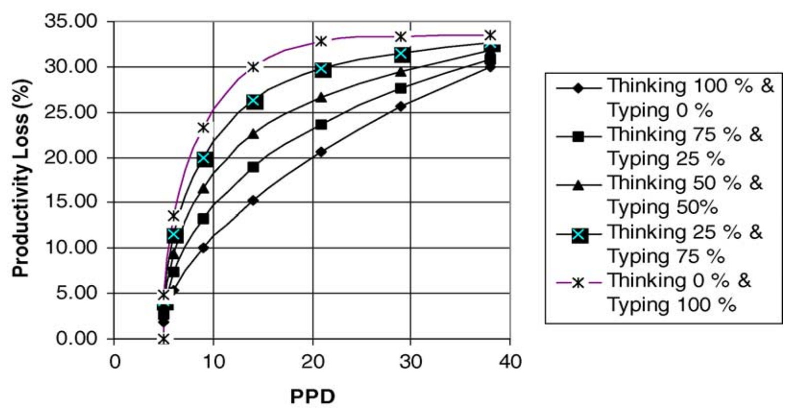

Fig. 3. Productivity loss as a function of PPD for different combination of tasks.

of typing tasks. The temperature difference for a 30% lost of productivity is 4–6 °C depending on the neutral temperature.

7. Productivity impact of relative humidity

Relative humidity may also affect productivity. A maximum relative humidity between 50 and 65% is normally provided at the design stage. A higher relative humidity affects the perceived indoor air quality and thus affects thermal comfort. Fig. 6 psychrometric chart is used to illustrate the changes that would occur from an air temperature of 25 °C and relative humidity of 50%. The optimal productivity is around 24 °C at a predicted PMV value of −0.21 (Fig. 6). The first line illustrates that the productivity loss is under 5% and the second line shows a 15% productivity loss. In Fig. 6 shows ASHREA comfort range.

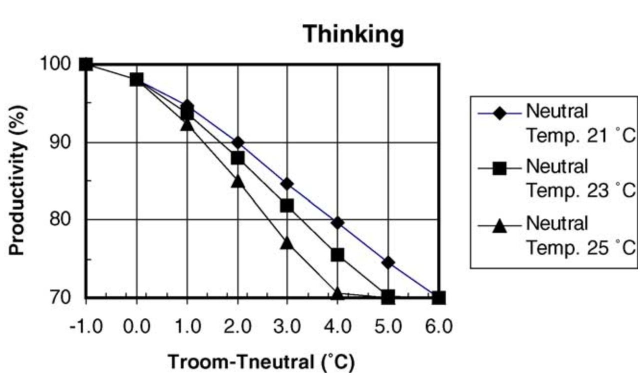

Fig. 4. Neutral temperatures and their impact on productivity for a thinking task.

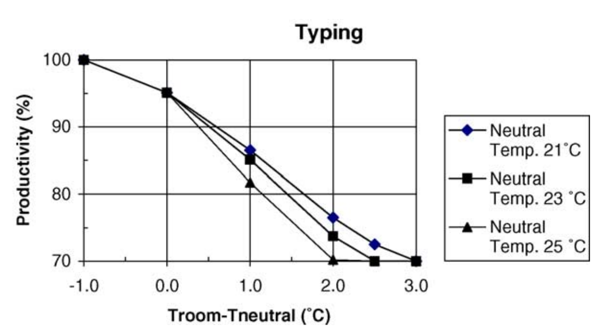

Fig. 5. Neutral temperatures and their impact on productivity for a typing task.

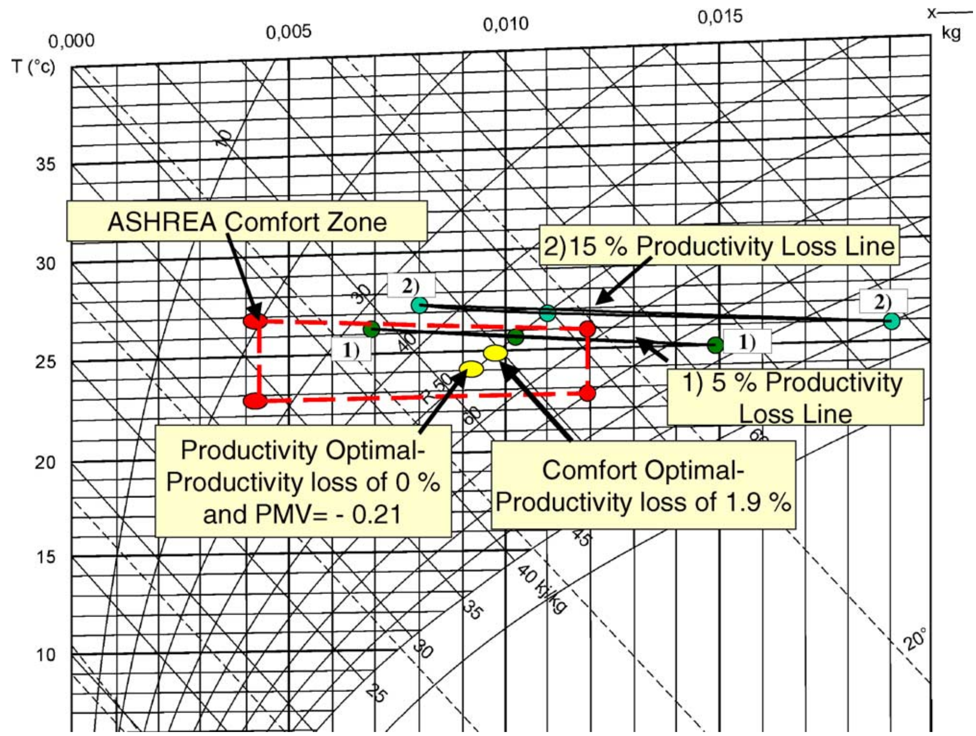

Fig. 6. Psychrometric chart illustrating optimal comfort and productivity loss lines of 5 and 15% compared with the ASHREA comfort zone.

The productivity loss of 5% is equivalent with 0–1.5 °C temperature rise depending on the relative humidity. A 15% productivity loss means a 1.0–2.5 °C temperature rise. It should be noted that Fig. 6 illustrates slightly stronger correlation between the productivity loss and the relative humidity than ASHREA describes. Based on the used model, the room temperature should be about 0.5 °C lower at high humidity. This means that the ASHREA limit: room temperature 26 and 17 °C dew point should be instead 25.5 and 17 °C.

The effect of the humidity is higher when the neutral temperature is higher. Table 3 shows the effect of the humidity when the thermal neutral condition is 25 °C and 50%. At the same temperature level of 25 °C, the productivity loss increases about 2% when the humidity increases from 50 to 75%. At the 27 °C level, a decrease of 5% in productivity occurs.

Table 3
Effect of relative humidity on productivity (25 °C and 50% is the thermal neutral condition and at 24 °C and 50% the productivity is maximum)

Relative humidity at temperature 25 °C (%)	Productivity loss (%)	Relative humidity at temperature 27 °C (%)	Productivity loss (%)
35	0.7	35	12.1
50	1.9	50	15.0
55	2.4	55	16.1
65	3.4	65	18.0
75	4.8	75	20.0

8. Cost implication of productivity

The initial investment cost of an air-conditioning system is the usual first criterion in system selection. This is a limited approach because it can be costly in the building economic life cycle if the air-conditioning operation and maintenance cost and the impact on office workers' productivity are not duly considered: (1) The salaries of office workers are many times the cost of operating a building in developed countries; (2) there is a potential monetary gain due to improved workers' productivity if there is a shift in focus towards the provision of better indoor climate conditions; (3) improving working efficiency in thermal indoor environment is deemed to be the most important environmental factor in office productivity. Fig. 7 shows the influence of the temperature difference

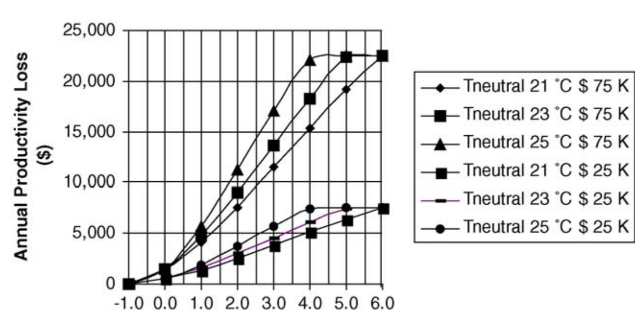

Fig. 7. Cost implication of productivity loss at different neutral temperatures.

from the neutral conditions for different annual salary costs and different neutral conditions. Two different salaries are used in the figure.

Fig. 7 shows that a small difference of 2 °C between room temperature and neutral temperature could result in more than 10% productivity loss. In monetary terms, this is about US$ 3000 with US$ 25,000 salary and about US$ 10,000 with US$ 75,000 salary for a drift of 2.0 °C. If we consider a period of 10 years, the productivity loss is equivalent to one year's salary. The life-cycle cost of HVAC system for a period of 10 years is about US$ 200/m^2. Using the spatial planning and use of 10 m^2 per person, a comparison between the productivity loss and HVAC life-cycle costs indicates that the productivity loss of a 2 °C temperature difference from the neutral conditions could easily be 2.5–5 times higher than the cost of the system over the life cycle. At this design criteria, the envisaged productivity loss is approximately US$ 2000 per person (10 m^2 per person × US$ 200/m^2) for a 10 m^2 of space in office buildings each year.

9. Inferences from current study

- Previous laboratory studies [2,3] are relevant to a neutral temperature range between 20 and 27 °C. The productivity loss at a temperature beyond 27 °C has been assumed to be constant.
- The level of the neutral temperature is an important factor to indicate the rate of the productivity change (increase or decrease) when the room temperature would increase.
- The acceptable PMV range is usually between −0.5 and +0.5. However the PMV value of +0.5 leads significant productivity loss.
- In future experiments or tests, PMV values should be fully documented.
- The current PMV estimation is based on the causal relationship between temperatures and productivity; and is limited to experiments that have been carried out in temperate environments. The true implication for hot-and-humid tropical climates in air-conditioned buildings remains relatively unknown.
- Though relative humidity is a less important factor for thermal comfort-productivity loss in temperate climates, this is a crucial factor to understand the actual thermal comfort requirements in the hot-and-humid climates that in turn impact the level of productivity in offices.
- ASHREA comfort range slightly underestimates the influence of the humidity at high humidity level.

10. Conclusion

As a general rule, the productivity loss when thinking is less severe than the productivity loss when typing in a warmer environment. Task-related performance is significant correlated with the human perception of thermal environment that in turn is dependent on temperatures. Different combinations of thermal criteria (air velocity, clo, metabolic, etc.) can lead to similar PMV values. The PMV equation is useful to predict productivity loss that is due to the rate of change in thermal conditions. The reference temperature (neutral temperature) setpoints for typing and thinking tasks may be helpful to assess productivity loss in different climates but nonetheless require further verification. This is especially true in the hot-and-humid climates, particularly those in the Southeast Asia region, where there is a pressing need to evaluate thermal comfort standards due to an escalating demand for air-conditioning.

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