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Forecasting Productivity under Thermal Environment Variations

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Abstract
Many attempts have been made to establish mathematical models reflecting the relationship between the thermal environment and construction labour productivity. Once established, the models were used to forecast the change in productivity due to thermal environment variations. The models, however, failed to accurately capture the complex nature of such a relationship for a number of reasons, including a consideration of the nature of the task being performed and the effect of all known variables of the thermal environment. This paper presents an advanced thermal environment/productivity forecasting model that takes into consideration all thermal variables such as air temperature, mean radiant temperature, relative humidity and metabolic rate. Also, the developed model is capable of reflecting the nature of the construction task being performed. The paper reports on experimental as well as field data gathered to assess the predictive power of the developed model.

Keywords
Construction, Thermal Environment, Thermal Comfort, Productivity, Mathematical Models.

1. Introduction

Many studies that identified factors influencing construction workers' productivity attempted to quantify their individual effects. One of these factors is the thermal environment variations which affect the efficiency of the workers and reduce their productivity. Although the literature abounds with models and formulae developed to predict the change in productivity due to thermal environment variations, most are inadequate because they address only a part of the whole thermal environment parameters. For instance, these models account for a combination of no more than three basic thermal environment parameters (i.e. air temperature, relative humidity and wind velocity).

The efficiency of a human worker depends on the working conditions and the skill level of the worker. The working conditions, in turn, depend on the atmospheric condition, which is a combination of site location and thermal environment. Many researchers have discussed the impact of thermal environment on productivity, yet it is still unclear how the thermal environment impacts upon productivity (Thomas *et al*., 1999). As the air temperature rises, heat becomes a definite hazard and the body's heat-regulating centre reacts with a number of responses, in order to dissipate internal and absorbed heat, to maintain the body's required temperature of 37°C (Brooks *et al*., 1996). When a human is exposed to a cold thermal environment, the body also responds to prevent lowering of the body temperature.

In summary, humans tend to balance heat between their body and the environment in order to keep the inner body temperature constant. The effect of air temperature and/or relative humidity on the productivity of selected construction tasks is well documented (Bilhaif, 1990; Srinavin, 2002).

While the effect of heat stress on mental performance has been a traditional subject of inquiry for ergonomics and human factors specialists, it still remains less clear than the effects on physical performance. Lorsch and Abdou (1994) argue that most mental tasks are unaffected by heat within physical limits of tolerance and that, over short periods, motivated workers can sustain their productivity even under adverse environmental conditions.

Another psychological factor that affects human performance is the level of arousal. Studies have suggested that elevated or depressed levels of arousal may affect human performance, which in turn affects productivity (Franken, 1998). A sensation of hot, comfortable and cold may be considered as arousal factors (Petri, 1996). Uncomfortable heat, or example, may affect performance by drawing attention from the task. Arousal and distraction are the psychological processes which most likely account for the effects of uncomfortably warm temperatures on performance (Mook, 1987). The conclusion that could be drawn from these studies is that productivity is intrinsically related to temperature. When temperatures reach uncomfortable levels, productivity is reduced.

2. Thermal Comfort

Thermal comfort is a subjective condition of mind that is expressed by a satisfaction with the thermal environment. The thermal environment incorporates those characteristics of the environment which affect a person's heat loss. In terms of bodily sensations, thermal comfort is a sensation of hot, warm, slightly warmer, neutral, slightly cooler, cool and cold. From the physiological point of view, thermal comfort occurs when there is a thermal equilibrium in the absence of regulatory sweating between the heat exchange of the human body and the environment (Fanger, 1970). The primary factors which influence thermal comfort are: 1) air temperature, 2) relative humidity, 3) air movement, 4) radiant heat, 5) metabolic rate and 6) clothing ensemble (Sundstrom and Sundstrom, 1986).

Over the years, a number of empirical and analytical indices were developed to reflect subjective responses to different combinations of temperature, air movement, humidity and radiant source of heat. These indices permit comparison of the thermal comfort levels provided by different environments. A review of these indices indicates that the thermal comfort index (PMV) has the capability to integrate the effect of the above six thermal environment parameters and provides a single value as a thermal index. Therefore, the PMV index (ISO9920, 1995) has been selected as the most appropriate tool for developing the proposed productivity-thermal environment model, as described in the following section.

3. Model Development

A method which is based on a combination of the arousal theory (effects of physical environment on productivity) and the first law of thermodynamics (thermal balance between human body and its environment) was established (Srinavin, 2002). This method is premised on the assumption that a set of climatic, task and clothing parameters, which satisfies the heat balance equation between the body and its thermal environment, produces optimum comfort. The method also argues that productivity can be predicted as a function of the PMV which, in turn, is treated as an arousal. So, productivity should improve if the PMV value, which is a combination of the thermal environment, the task being performed and the workers' clothing, provides a stimulation that brings the workers' arousal into the optimal range. On the other hand, productivity should decline if the PMV value moves away from what is optimal for the task under investigation.

In order to relate the PMV value to construction workers' productivity, a large amount of data is needed. Through an extensive review, a total of more than 200 data sets, representing seven different construction tasks were identified and collected from the published literature (Srinavin, 2002). These obtained data were used to correlate the calculated PMV value to the reported workers' productivity by means of a polynomial regression analysis technique. This has resulted in three different mathematical regression models represented by equations 1, 2 and 3 for predicting productivity for light, moderate and heavy construction tasks, respectively. It should be noted that maximum productivity values, calculated using any of these equations, should not exceed 100% (i.e. If calculated P > 100%, take P = 100%). The coefficient of determination (R^2) obtained from the regression analysis were 0.97, 0.95 and 0.95 for equations 1, 2 and 3, respectively.

$$P_L = 102 - 0.80PMV - 1.84(PMV)^2 \quad (1)$$

$$P_M = 102 + 1.19PMV - 2.17(PMV)^2 \quad (2)$$

$$P_H = 83 + 21.64PMV - 9.53(PMV)^2 + 0.91(PMV)^3 \quad (3)$$

4. Model Validation - Experimental

To validate the above three relationships and to minimise the effect of working skills and the complexity of actual construction tasks, an experimental programme was specifically designed to include simplified tasks categorised into three levels of activity, according to the metabolic requirement of each task. Exact metabolic rates were determined by measuring an individual's oxygen uptake/ consumption, using the open circuit spirometry (Morris *et al.*, 2002). The clothing insulation parameter was estimated for every subject using the values suggested by the International Standard Organisation (ISO9920, 1995). All of the remaining four thermal environment parameters: air temperature, mean radiant temperature, relative humidity and wind velocity were measured using the relevant commercial instruments as suggested by the International Standard Organisation (ISO7726, 1985).

Fifteen healthy male volunteers at the age of between 24 and 36 years participated in the study. No attempt was made to select the subjects according to physical characteristic or age. Each subject was clearly informed of the experimental tasks to be performed. Subjects completed one of the four selected tasks in a climate chamber in random order. The chamber conditions were set for nine conditions within a range of 15-45°C air temperature and 40-70% relative humidity, with a circulating air velocity of 0 to 0.5 m/sec. For the first three thermal environment conditions, the thermal environment was set to yield a low PMV index for all three levels of the task. For conditions number four to six, the thermal environment condition was set to give a moderate PMV index; while the last three conditions were set to give a high PMV index for those light, moderate and heavy tasks. While the subjects performed their tasks, the thermal environment parameters were measured and recorded every 10 minutes. The average value of each recorded variable was used in the calculation of the PMV index. Productivity was determined when the subject finished the task. Since each task has its own unit of productivity, the different units of productivity needed to be standardised to allow a comparison to be performed. The method used for standardising measured productivity was to transform them into a common scale. This transformation was done by setting the highest productivity obtained for each simplified construction task as the optimum productivity (100%). The rest of the productivity data were calculated proportional to this optimum value.

A correlation analysis was carried out to compare the experimental (actual) and the predicted productivity values. In this analysis, pairs of data sets, at a similar PMV value, were compared. Correlation coefficient values of 0.896, 0.822 and 0.777 were obtained for light, moderate and heavy tasks, respectively. These correlation coefficients are considered significant at the 0.01 level.

The collected data for the light task are shown in Figure 1, which presents a plot of the observed (actual) productivity and the predicted productivity (using Equation 1) against the PMV values. Figure 1 shows that productivity starts to decreases as the PMV increase from the comfort zone (approximately PMV zero). The observed values reach up to 100% at the range of comfort zone and start to decrease beyond this range. This range may be considered as the optimum thermal environment for light tasks at which subjects perform most efficiently. This plot also shows the variation of the actual productivity across a wide range of PMV index (0.7 to 4.5). Indeed, the actual productivity values scattered between plus 15% and minus 5% lines with the majority are close to the latter implies that Equation 1 has a relatively high level of accuracy in predicting productivity under the variation of the thermal environment. Comparable accuracy levels were obtained for the other tasks.

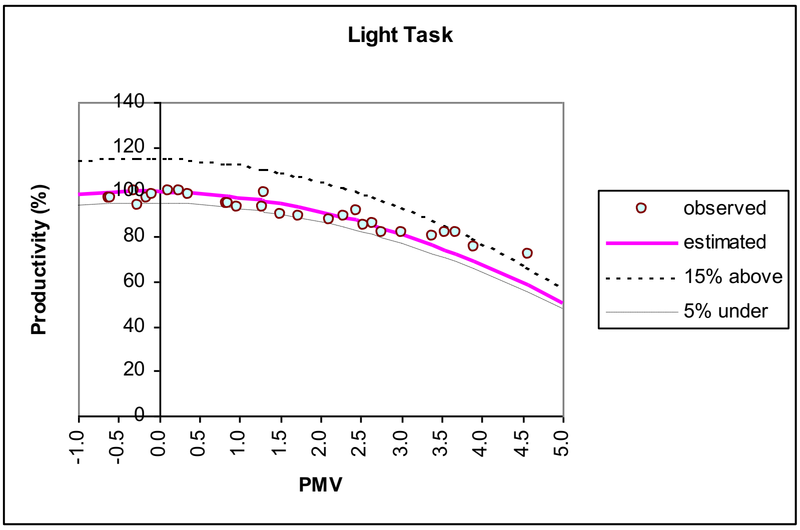

Figure 1: Comparison of estimated and observed productivity values for light tasks

5. Model Validation - Fieldwork

Productivity data and thermal environment data, collected from four construction project sites, were used for model validation. The fieldwork required the measurement of productivity and thermal environment. The field investigation focused only on those tasks that could be quantified at the end of the working day. The selected tasks were painting, brick laying and manual excavation which represented light, moderate and heavy tasks, respectively. Since each activity has its own unique unit of productivity, the units of measure must be standardised. In order to avoid the wide range of productivity units, the measured productivity was transformed to a common scale (i.e. percentage). The average workers' productivity was assumed to be the amount of work produced per working day, divided by the number of workers and the time involved. It was important to specify input and output when comparing productivity. The input in this investigation consisted of the number of workers and the time used. The output was the amount of work performed by the worker, which could be measured in terms of the unit of work per work-hour. The time used by the worker to perform a task is the productive time that is determined from the activity sampling.

The collected data for the light task (wall painting) are shown in Figure 2 where it can be seen that the lower PMV value, the higher the productivity. The observed (actual) productivity value reaches maximum value (100%) in the PMV range from 1.2 to 2.2 and starts to decrease beyond this range. Therefore, this range may be considered as the optimum thermal environment for light construction tasks, in which construction workers perform most efficiently.

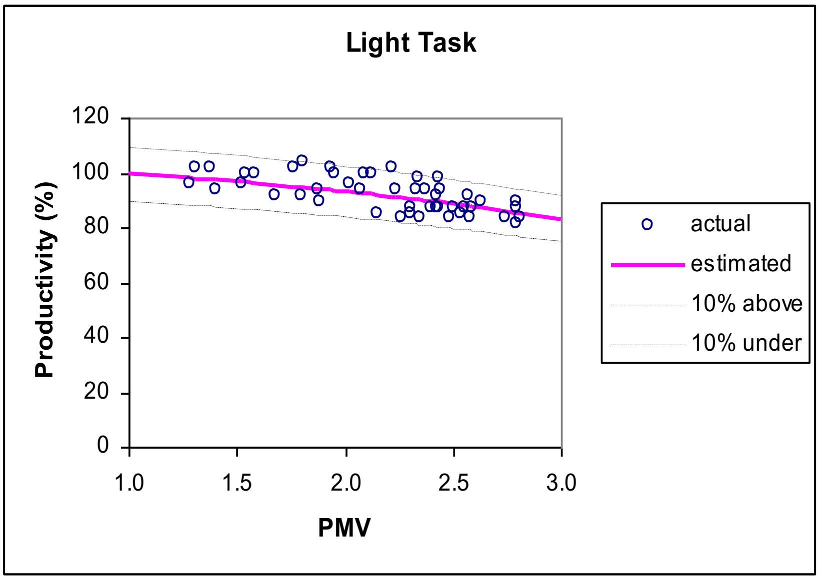

Figure 2: A Plot of the Estimated Productivity against the Actual Productivity of the Painiting Task

Figure 2 presents a plot of the estimated productivity using Equation 1 against the collected productivity data from the construction sites. This plot represents a variation in the productivity of the painting work across a certain range of PMV values (PMV 1.2 to 2.8). From the above figure, it can be seen that the actual productivity values are scattered between the plus and minus 10% lines. This implies that the developed model for light construction tasks has an accuracy of ±10% in predicting the workers' productivity under the variation of thermal environment within the PMV range investigated.

6. Conclusion

This paper reported on a research investigation where workers' productivity is linked to a set of climatic, task and clothing parameters via the utilisation of the predicted mean vote (PMV) thermal comfort index. A large amount of data was gathered from the literature, and was used to develop three different regression equations for predicting productivity due to changes in the thermal environment. The predictive power of these equations was successfully tested against actual data obtained experimentally covering simplified tasks with different levels of physical demand.

Furthermore, a comparison between productivity values predicted by the developed model and those that were obtained from construction sites was used. Such a comparison is considered an effective technique for performing a validation (Bilhaif, 1990). From the fieldwork investigation, it was found that different construction tasks or activities are influenced at different levels of the thermal environment. This conclusion is important because it indicates that changes in workers' productivity are a function of the nature of the construction task. Additionally, activities that have a complicated nature appear to be associated with greater reductions in workers' productivity than simple tasks. The results also confirm that different activity levels (i.e. the metabolic rate) have different reductions in workers' productivity. It was also found that light construction tasks are more sensitive to the thermal environment than are the heavy tasks. The field work data were collected under hot and humid climate of Thailand, and so could not cover the full range of thermal environments. A stronger validation of the models may be made by using the data collected from other countries that have a wider range of thermal environments.

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