ELSEVIER

Energy and Buildings 24 (1996) 167–177

ENERGY
AND
BUILDINGS

Implications of indoor climate control for comfort, energy and environment

Ardeshir Mahdavi, Satish Kumar

Department of Architecture, Carnegie Mellon University, Pittsburgh, PA 15213, USA

Received 16 July 1995; accepted 5 February 1996

Abstract

This paper critically examines the underlying premises of indoor climate control technologies and the HVAC industry (heating, ventilating, air-conditioning). It questions whether 'total environmental control' is possible, effective and desirable. The paper also reviews the methods and terminology of thermal comfort science focusing on the question of predictability of people's environmental preferences. The paper concludes with a review of recent critical observations and ideas that transcend conventional control technologies and corresponding comfort standards toward new vistas in environmental design.

Keywords: Thermal comfort; Human ecology; Environmental control systems; Energy and entropy; Built environment; Comfort

1. Introduction

In the last few decades the notion of environmental control (particularly the thermal environment) has emerged as a mega-industry. This as such remarkable development appears to be (at least implicitly) based on two basic assumptions:

(i) total indoor environmental control is possible and effective regardless of the outdoor climatic conditions;

(ii) maintaining a predefined set of environmental conditions assures the comfort and satisfaction of the inhabitants.

These assumptions must be critically reviewed, if one hopes to gain an understanding of the status quo and an idea of possible future developments in the area of environmental control. Toward this end, human ecology can provide not only a suitable epistemological framework, but also original insights as to the desirable directions in future research.

2. Control and entropy

Human beings have always actively shaped their habitats, or as Banham maintains, deployed technical resources and social organizations, "in order to control the immediate environment: to produce dryness in rainstorms, heat in winter, chill in summer, to enjoy acoustic and visual privacy ..." ([1], p. 18). One may refer to this act of shaping (or gestalting), if prepared consciously and in an organized manner, as environmental design. Utilizing the conceptual framework of human ecology [2,3], one could derive a provisional cybernetic view of this design activity:

"As a process, designing involves the development of a set of related (coherent) formal (spatial) configurations, and organizational (functional) layouts, as well as the concrete (physical) realization thereof, with the (a priori expressed and/or a posteriori deducible) 'intention' of favorably influencing the relationship between the ecological potency of human beings and the ecological valency of their surrounding outside world, while responding to requirements implied by both 'real' (first) and 'symbol' (second) functions" ([4], p. 531).

Ecological potency denotes here the totality of the characteristics of human beings in their distinctions realized at the respective point in time and considered in their significance as related to the encounter with their surroundings. Ecological valency denotes the totality of the characteristics of the surrounding outside world in their distinctions realized at the respective point in time and considered in their significance to the relevant human beings. It is important to understand that the above definition is not the continuation of the behavioristic error on a higher strategic level. It is not implied that a perceived imbalance in the (ideally homeostatic) relation between ecological valency and ecological potency triggers design activity, quasi in the way behaviorists thought stimuli trigger responses.

PII S0378-7788(96)00975-9

Based on the historical evidence of evolving human habitation patterns, one could probably imply a trend away from (human) 'self-adaptation' toward adaptation of the surrounding context. In this context, the evolution of the building activity appears as a set of variations on a theme dedicated to the nature of the interrelations between the ecological potency of human beings and the ecological valency of their outside surrounding world:

"First, there is man's habit of changing his environment rather than changing himself. Faced with a changing variable (e.g. temperature) within itself which it should control, the organism may make changes either within itself or in the external environment ... In evolutionary history, the great majority of steps have been of an intermediate kind in which the organisms achieved change of environment by change of locale ..." ([5], p. 445).

In fact, one could interpret the periodic migration of nomads (biannual change of location in pursuit of a better climatic 'match') as motivated by the differential between ecological potency and ecological valency. In this context, nomads' active change of location can be seen in contrast to the creation of permanent built structures that provide artificial conditions more responsive to attributes of the ecological potency. Starting from this point, the evolutionary development of the building activity appears to be that of successive increase in the 'environmental' adaptive efficiency (i.e. increased potential for creating and maintaining artificial and adaptable surroundings).

Certain products of the so-called 'traditional architecture' demonstrate intermediate cases where buildings allow for the reduction of human exertion and provide a more adaptable valency context [6]. A good example of this adaptive strategy is the traditional '2-zone' house on the north coast of Oman that integrates a winter residence and a summer residence (thus involving a mild form of biannual migration). The characteristic differences of the constructions of these two units (e.g. the lightweight construction and the air permeability of the summer residence and the rather massive and well-insulated construction of the winter residence) allow for maintaining more or less acceptable potency/valency relations for various prevailing local climatic conditions.

Given the limited availability of energy resources prior to the industrial revolution, judicious (environmentally responsive) design of building structures practically remained the only way to alleviate the impact of the climatic extremes on human habitation. Numerous examples of contextually adopted vernacular architecture in various climatic regions are known and well-documented [6–9].

As from the late nineteenth century, efforts toward augmented control over 'environment' have been increasingly directed toward the use of more or less energy-intensive building service technologies. Fanger's reflections on the definition of thermal comfort fit in this context:

"Creating thermal comfort for man is a primary purpose of the heating and air conditioning industry, and this has had a radical influence on the construction of buildings ... and thus on the whole building industry. Viewed in a wider perspective, it can perhaps even be maintained that man's dependence on thermal surroundings is the main reason for building houses at all, at least in the form in which we know them today" ([10], p. 14).

This 'industry-based' approach to creating thermal comfort can be seen as the continuation of the efforts toward the reduction (or even elimination) of 'man's dependence on thermal surroundings' while further reducing the need for human exertion. This implies in human ecological terms that desirable valency attributes are intended to be achieved not by 'passive' methods (nomad's long-distance migration, or 'mini-migrations' within two-zone traditional houses, or static structural features of the built habitat), but by controlling the thermal comfort parameter in spaces through 'power-operated' mechanical means.

Celebrating the achievements of 'power-operated solutions' (air conditioning units), Banham wrote:

"... we now dispose of sufficient technology to make any old standard, norm or type habitable anywhere in the world. The glass skyscraper can be made habitable in the tropics, the ranch-style split level can be made habitable anywhere in the US" ([1], p. 288).

The intentional leitmotiv (purposive consciousness in Bateson terms) of the recent trends toward the so-called 'intelligent' buildings appears to be the provision of even more control while further reducing the need for exertion. A typical example of this view is expressed in the following newspaper excerpt addressing 'intelligent' features of an office building erected by a Japanese construction company that intends to offer the very latest in workplace comfort:

"Employees will each carry an identification card that holds personal data on his or her favorite room temperature and level of brightness. These cards will transmit the data on an electric wave to sensors installed in the walls. The sensors will then detect who is nearby at one given time, and automatically set the appropriate level of lighting, heat or air conditioning" [11].

Based on the prior discussion, one may now confidently conclude that, firstly, there has been a significant increase in human control over the 'immediate' surroundings, and, secondly, the degree of this controllability has increased sharply due to (relatively) recent availability of power-operated mechanical means for environmental control. The question is, however, if one can justifiably conclude that total indoor environmental control is possible and effective regardless of the climatic context?

As shown earlier, no doubt is expressed in the 'Architecture of the Well-tempered Environment' as to the assumption that mechanical systems would provide for comprehensive control and total comfort. Nor is the question raised if these systems de facto deliver what they have promised or are expected to deliver. Faced with this question and having the advantage of historical hindsight, we may actually speak of a 'control myth'.

In the best of all worlds, a competently designed, installed, operated, and maintained mechanical system could theoretically provide a high level of indoor environmental control, given a static building use scenario. Alas, there is abundant empirical evidence that many mechanical building service systems (particularly the HVAC installations), due to a wide range of circumstances (extremely inappropriate 'structural' solutions, bottom-line oriented poorly designed service systems, incompetent execution, poor maintenance and operation, post-installation changes in building use and occupancy, lack of systems integration, etc.), do not provide the expected and required range of environmental conditions [12–14]. Cases of poor performance due to misplaced and/or defective thermostats, deficient zoning and control options, inflexible load capacities and distribution patterns, mislocated air-intake and exhaust openings, short-circuiting supply and return air paths, etc., can be listed ad nauseum. Recent literature is filled with damaging accounts of air quality problems (e.g. stale air, high levels of pollutants' concentration), hygienic deficiencies (e.g. mold growth), discomfort complaints, and the range of problems associated with the 'sick buildings syndrome' (SBS) [15,16].

As to the question of 'effectiveness', Banham provides a few references to the implications of the widespread use of mechanical means for thermal conditioning of the indoor environment. However, these are limited to first-cost economical matters. Repeated references to 'abundant timber' and 'abundant fuel' in North America indicate a rather uncritical internalization of 'cheap-fuel economy' as the all decisive design context. Architects are primarily criticized not because they failed to offer energy-conscious (e.g. passive) alternatives to the emerging energy-intensive air-conditioning technology, but mainly on their failure to rapidly and 'neatly' integrate them in their designs ([1], p. 192).

Further, we find comments on the incapability of the designers to break with the "tyranny of the ancestral and restrictive vernacular" and to fully embrace the "attractiveness of the sealed and necessarily mechanized envelope of glass slab office towers":

"The present generation of experts on tropical architecture ... seem to regard the glass skyscrapers that have appeared in developing countries as mere status symbols ... They may well be succeeded by a generation of experts on architecture in the temperate zones who wish that our Western civilization had been capable of making as bold a break with its ancestral vernaculars as the Africans have been" ([1], p. 288).

We have extensively quoted these sadly outdated passages, as they appear to be, surprisingly, still representative of the implicit mind-set and actual decision-making patterns of most building clients, designers, and engineers. Still in 1995, a publication can appear that de facto summarizes the millennia tradition of refined passive building methods of indigenous cultures with such statements as the following:

"Once upon a time, our ancient ancestors were superstitious concerning the forces of nature. Their indoor environment was determined to a large extent upon the conditions outside. As knowledge began to replace superstition, our ancestors fashioned the first crude indoor environmental control" [17].

North America is, despite the energy crisis of the seventies (of which Banham could not know, while contemporary authors should certainly remember) and despite the ecological movement, still a 'cheap fuel economy'. And fully air-conditioned energy-hungry 'glass skyscrapers' still appear (in fact with increasing frequency) in developing countries [18].

Be that as it may, an enormous price has been and is being paid for the 'power-operated' approach to increased environmental control, namely an explosive growth in the exploitation of the planet's finite energy resources (particularly non-renewable fossil fuels):

"The United States has already misallocated something like two hundred million tons of cooling capacity and 200 peak gigawatts of power supply to run it, at a total marginal cost approaching $1 trillion, through failure to optimize the buildings' capacity that was installed" [19].

Moreover, this excessive energy consumption is accompanied by an accelerated environmental degradation. Commenting on the devastating effects of the North-Americans' 'conspicuous consumption' and their daily energy 'potlatch' (so that the "Thunderbird may keep things rolling along"), Prins maintains:

"The rest of the world has to pay a pretty heavy price on their behalf, perhaps least contentiously in foregone future options on wasting assets being consumed now (e.g. four million barrels of oil per day to feed the Thunderbird, as against one million for Africa, Asia and Latin America combined) ... More and more it appears that the price is most meaningfully displayed as the proportionate American contribution to general pollution, of which perhaps the single best index is of the emission of 'greenhouse gases' which contribute to global warming ... Expressed as tons of carbon per person per year released into the atmosphere, the USA today leads the world at over 3.75 tons ... If we care to continue this global experiment at this rate, we shall soon enough find out the answer. Unfortunately, by that moment it will be, by definition, too late to do anything about it" [20].

In cybernetic terms, the industrial approach has been able to selectively decrease the entropy in the subsystem human habitat (e.g. through maintaining large indoor–outdoor temperature gradients even under extreme climatic conditions and inside poorly designed building structures). However, this has been achieved by an accelerated entropy increase in the encompassing system that includes human habitats, namely the planet earth.

There is ample evidence implying that the pace and magnitude of man's impact has most probably surpassed the maximum adaptation rate of the ecosystems. And the vast energy requirements of a largely power-operated built environment are not an insignificant component of a general approach to 'civilization' that is responsible for such circumstances as the rapid depletion of planet's limited fossil fuels, high levels of tropospheric ozone, the damage to the stratospheric ozone layer, the continuous increase in carbon dioxide concentration (contributing to the greenhouse effect and the global warming risk), rapid global deforestation, large-scale pollution of air, water and soil, extinction of whole animal and plant populations, etc. Bateson appears to have referred to all this, when he wrote:

"... the power ratio between purposive consciousness and the environment has changed rapidly in the last one hundred years, and the rate of change in this ratio is certainly rapidly increasing with technological advances. Conscious man, as a changer of his environment, is now fully able to wreck himself and the environment — with the very best of conscious intentions" ([5], pp. 445–446).

3. Is 'comfort' predictable?

It should be clear at this point that the power-operated energy-intensive approach to (thermal) environmental control has, on many occasions, failed to provide the targeted conditions. Furthermore, the state of art in design and operation of most mechanical air-conditioning systems must be regarded as ineffective in any evaluation framework that goes beyond measures that are indifferent ecologically and short-term (first cost-based) economically. Let us assume now, for argument's sake, that there are building service systems and technologies that in fact maintain *exactly* and *effectively* a predefined set of environmental conditions throughout the *entire* interior spaces of buildings. We still have to deal with the question if there is, in fact, a 'predefined set of environmental conditions' that, if offered, would assure the comfort and satisfaction of the inhabitants.

In order to answer this question, one would have to address the historical development of thermal comfort indices. A brief review of this background reveals two basic trends:

(i) the 'scientific' approach to thermal comfort research has aimed at identification of measurable environmental indicators with the hope of correlating those with people's perception and evaluation of thermal conditions (thermal sensation vote);

(ii) historically, a trend may be postulated toward identification of an increasing number of comfort-relevant environmental (and occupancy) indices and an increasing level of refinement and detail in their description.

Looking back to the late nineteenth century, the room air temperature appears to have been the primary candidate for the description of thermal requirements, although, initially, without systematic studies on its actual relevance for human evaluation purposes. Baldwin simply stated that it is 'usual' to maintain a temperature of 70 °F within a room ([21], p. 34). The same unreflective attitude regarding the preferable temperature range is also present in Corbusier's 'eternal' attachment to an 18 °C air temperature:

"Every nation builds houses for its own climate. At this time of international interpenetration of scientific techniques, I propose: one single building for all nations and climates ... The buildings of Russia, Paris, Suez or Buenos Aires, the streamer crossing the Equator, will be hermetically closed. In winter warmed, in summer cooled, which means that pure controlled air at 18 °C circulates within forever" ([22], p. 64ff).

A major systematic effort toward multi-criteria comfort description frameworks started in the early 1920s at a research facility in Pittsburgh. Experiments involving human subjects were conducted in a controlled context, and the so-called *effective temperature* was derived, which combined the effects of air temperature and relative humidity into one index. Effective temperature is defined as an index which combines into a single number the effect of dry-bulb temperature, humidity and air motion on the sensation of warmth or cold felt by the human body. The numerical value is that of the temperature of still saturated air which would induce an identical sensation [23].

The post world war II economic recovery and the rapid growth of the HVAC industry in the late 60s and early 70s led to a flurry of activities in the field of thermal comfort research. Significant contributions were made, among others, by Fanger and Gagge toward development of comfort indices that would reflect the combined effects of various environmental variables. Their comfort indices are structured in such a way that a given value of the index corresponds to a particular thermal state of the body. However, they differ in the way they define this state. Nonetheless, both Gagge's *standard effective temperature* (SET) and Fanger's *predicted mean vote* (PMV) aim at integrating all the relevant environmental and personal variables toward predicting the occupant's thermal comfort conditions.

Fanger introduced the so-called PMV, which was based on a steady-state model of a human body (in a state of thermal equilibrium with negligible heat storage). The earlier comfort indices were generally the result of statistical analysis of a limited set of experimental data. Each index therefore strictly applied to the range of physical conditions that was covered during a specific set of experiments. Fanger tackled the problem of producing a comprehensive comfort index by starting from the premise that it is possible to define the comfort levels in physical terms that are pertinent to the body's thermal regime. In this perspective, the state of long-term thermal balance is the necessary condition for thermal comfort, i.e. the rate of body's heat loss to the environment must be equal to the rate of heat production in the body. Fanger used classical heat transfer theory and empirical studies to derive the general comfort equation which captured four environmental variables (air temperature, mean radiant temperature, air velocity and relative humidity) and two personal variables (activity level and clothing). The representation of all the six variables and their relationship to the thermal sensations in the comfort equation was a very significant step as it provided for a way to evaluate any thermally controlled environment. McIntyre very succinctly notes this contribution:

"Fanger's recognition that the comfortable levels of skin temperature and sweat rate were affected by activity level allowed the construction of the very successful general comfort equation, which can be applied over a range of conditions" ([24], p. 177).

The satisfaction of the general thermal comfort equation is a necessary condition for maintaining thermal comfort. The comfort equation as such does not specify people's level of discomfort where this condition is not met. Fanger, therefore, derived a relationship between people's thermal sensation, as expressed on ASHRAE's 7-point scale, and the thermal variables occurring in his comfort equation. The assumption was that "the thermal sensation at a given activity level is a function of the thermal load of the body, which is defined as the difference between the internal heat production and heat loss to the actual environment for a person hypothetically kept at the comfort values of the mean skin temperature and the sweat secretion at the actual activity level" ([10], p. 111). Toward this end, PMV is thus defined as the mean response of a large group of people according to the ASHRAE thermal sensation scale. The complex expression to calculate PMV is actually a curve-fit which was constrained to pass through the point for sedentary activity. This partly explains the good agreement between the values predicted by Fanger's comfort equation and the experimental studies that were conducted later using sedentary subjects. From PMV, one can further derive the predicted percentage of dissatisfied (PPD) using a diagram [10] or an expression [25] which predicts the percentage of dissatisfied people for the environment under consideration.

Gagge et al. defined the new effective temperature called SET using a two-node (core and body) model of a human body [26]. This concept assumes a dynamic exchange of energy between the two compartments through direct contact and thermoregulatory controlled peripheral blood flow which is dependent on ambient conditions [27]. Mean skin temperature and skin wettedness define the thermal state of a person in this model. It is reasonable to say that thermal sensation based on SET depends on skin wettedness in a hot environment and skin temperature in a cold environment.

The evaluation of SET for a given set of conditions requires a two-node dynamic mathematical model of thermoregulation. Instead of assuming a steady state condition, Gagge et al. assumed that a transient energy balance exists between the two nodes [26] and that the rate (time dependent dynamic nature) of heat storage equals the net rate of heat gain minus the heat loss. The rate of change in internal energy can be written separately for each compartment in terms of thermal capacity and time rate of temperature change in each compartment [27]. SET is calculated as the temperature of an isothermal environment (where air temperature is equal to mean radiant temperature, relative humidity is 50% and air is still) in which a person with a standard clothing insulation would have the same heat loss at the same mean skin temperature and the same skin wettedness as in the actual environment and with the actual clothing insulation under consideration. Although SET is probably the most general thermal comfort index, it was particularly designed for dealing with the effects of high humidities and temperature.

Our schematic review of the evolution of thermal comfort research demonstrates a process of continuous refinement of increasingly comprehensive predictive models based on classical heat transfer, the body's physiological processes and statistical analysis of human perception. In particular, Fanger's PMV and Gagge's SET form the basis of such internationally reputed standards as ISO 7730 [25] and ASHRAE Standard 55-92 [28], respectively.

The important question that now arises is the applicability of these models and their derivative standards in real world situations. Certain basic problems in model validations are due to the empirical nature of most of the required input parameters. Many empirical constants must be derived experimentally and, despite years of research, there are still problems in accurately predicting their values. One example is the convection coefficient which can be calculated in multiple ways [24,27]. Skin temperature and skin wettedness, two variables which need to be calculated to obtain SET (in Gagge's model), are assumed to be uniform over the whole body which may not be the case in an actual situation.

However, an even more important problem may be related to the requirements of 'controlled' parametric studies. Much as the researchers would have liked to base their findings on 'real-world' situations, these requirements have often led them to perform their experiments solely in climate chambers where the factors influencing thermal comfort can be selectively measured and closely monitored. This controlled research design which may have permitted the relative importance and interactions of several independent variables to be disentangled involves, unfortunately, the risk of reducing the complex comfort evaluation process to rather simplistic stimulus-response patterns [29]. Environmental psychologists and experts in human ecology have long contended that the result of laboratory studies should be applied with care, as they often involve crude oversimplifications of the interactions between people and their surroundings [3,30,31].

In this context, it may be helpful to mention the results of certain field studies that have been conducted to answer specific questions regarding the applicability of 'universal' comfort prediction models and their derivative prescriptive standards. As already discussed, Fanger's largest contribution was the introduction of a comfort model with 'generic' character which was sorely missing in earlier field studies. A number of recently conducted field studies [32–35] involved the comparison of the results obtained from field data with predicted values using comfort standards.

The results of these experiments have not always conformed to those predicted by comfort standards. Thus, the thermal comfort researchers have been confronted with the problem of accounting for this discrepancy in a consistent and scientific way so that either changes can be incorporated in the standards or some alternative approach can be found toward enhancement of the thermal conditions for occupants in real world situations.

Numerous potentially contributing factors have been suggested to explain the above-mentioned discrepancies. These include:

(i) difficulties in accurate estimation of certain empirical constants and coefficients that are utilized in the underlying mathematical algorithms of comfort prediction models;

(ii) difficulties in precisely determining occupancy factors (such as activity levels, clothing insulation, furniture effects) in real world settings;

(iii) field complexity of certain environmental factors (asymmetric radiant fields, complex air movement patterns and related occurrences of draft and turbulency, significant vertical temperature gradients, etc.);

(iv) interference effects of certain personal factors that comfort models may have ignored unjustifiably (differences in age, gender, ethnic and cultural background, etc.);

(v) dynamism and variance of both environmental conditions (*ecological valency* in human ecological terms) and occupants' status, activities and behavior in the field (*ecological potency* in human ecological terms);

(vi) possible synergistic interactions between thermal conditions and other relevant surrounding factors (visual parameter, acoustic conditions, etc.) in view of the overall (informatory) environmental evaluation.

One might argue that, principally, all of these issues may be interpreted as 'noise' phenomena in the inherently statistical relationship that comfort models imply between environmental (and occupancy) factors on one side and the thermal sensation vote on the other side. In fact, the statistically relevant relationship between the Fangerian terms PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) implies that even under given 'optimal' thermal conditions ($PMV = 0$), PPD would be non-zero. This may have been part of the reason why certain comfort standards [28] assume that thermal comfort requirements for an indoor space are fulfilled if no more than 20% of the occupants are dissatisfied with thermal conditions in the environment.

However, there are serious problems with this attitude. As mentioned earlier, field studies indicate that actual dissatisfaction rates may be higher than those foreseen in the standards. Considering the evidence collected in the field and given the fundamental complexity, variance and dynamism of the relationship between people's ecological potency and the ecological valency of their surroundings, it is safe to postulate a certain 'systemic' limit in predictability of thermal comfort and thus in provision of maximum thermal satisfaction in *uniformly* conditioned indoor environments. Furthermore, even if it would be possible to confidently predict that a certain percentage (say 80%) of the inhabitants will be thermally comfortable given a set of predefined thermal conditions, we would still have to seriously question the admissibility of the simple exclusion of a large number of people as thermal 'outcasts'.

4. In search of new paradigms

Looking back to our initial questions, we have come now to some sobering conclusions. All is not well with the design and operation of mechanized indoor environment control systems which, in some instances, even fail to provide their — rather narrowly defined — target environmental conditions. Furthermore, there is most probably a 'system-immanent' limit in the percentage of people who would be thermally comfortable in a *centrally* and *uniformly* conditioned space no matter how carefully the thermal parameters are selected and maintained.

These views are shared by an increasing number of researchers, engineers and designers in search of, or in the process of experimenting with, new approaches and alternative ways in dealing with the problem of defining and providing adequate thermal conditions in the built environment. In this context, we will focus on two recent groups of ideas/efforts that we label — somewhat arbitrarily — 'exoteric' and 'esoteric'.

The 'exoteric' approaches do not question as such the notion of thermal comfort and even the possibility of measuring it through thermal sensation votes utilizing well-known 'psycho-physical' scales. They also appear to accept the 'classical' terminology of thermal comfort research concerning the matrix of those environmental variables and occupancy factors that are believed to be relevant to people's perception and evaluation of the thermal conditions. What these approaches question is the appropriateness of *uniform* environmental conditioning in all but single-occupancy spaces. In fact, one abandons altogether the notion of minimizing the number of dissatisfied in uniformly conditioned spaces and allows instead for a flexible multi-zone context that can be differentially and dynamically controlled by individual occupants. This involves, from the human ecological point of view, 'intelligent' building hardware, energy systems and control technologies to provide high levels of personal control and thus a potentially wider range of possibilities to maintain adequate relationships between inhabitants' ecological potency and their surroundings' ecological valency.

In the domain of office design, implementation efforts have been focussed on occupant-controlled task conditioning systems. These systems have been variously referred to as 'task conditioning', 'localized thermal distribution' and 'personal air-conditioning' in technical literature. As in the case of task lighting, the controls for these systems rest partly or entirely with the occupants. Typically, the occupant is given the possibility to manipulate a number of environmental variables (particularly air temperature, volume and velocity) in the near vicinity to satisfy her personal thermal comfort requirements [36]. One such system provides direct access to supply air (speed, direction and temperature of air can be controlled). An infrared sensor continuously monitors occupancy for automatic on/off control if the user is absent for 10 min. An optional under desk radiant heat panel is capable of providing localized heating [37]. By giving freedom to occupants to adopt their immediate surroundings, one hopes to specifically counteract problems arising out of inter-individual differences. At the same time, this process of partly transferring the controls to occupants may, psychologically, elevate the level of satisfaction with the thermal conditions while relaxing the requirements concerning the 'comfort variables' of the ambient environment.

As compared to large uniform conditioning systems, user-based environmental control systems undoubtedly represent a major step forward. There are, however, still some points of concern, that future research must address. (a) User-based systems sometimes treat the environmental factors in a rather 'sterile' (almost reductionist) manner. For example, in desk-top user-based systems, 'air flow' is typically maintained through highly directional micro-terminals reminiscent of overhead air nozzles in airplane cabins. (b) Furthermore, this 'reductionist' mode of dealing with environmental factors is realized in hermetically sealed buildings with no or little 'immediate' environmental contact with the outside world. (c) The functionality of user-based systems is technically achieved by adopting a thermally asymmetrical conditioning mode (air movement and radiation are directed on some parts of body and not on others) and more research is required to fully understand the overall long-term implications of this approach [36]. (d) A task-based local concentration of environmental services may further intensify the confinement of workers already limited in their spatial movement due to small workplaces configurations such as office cubicles.

At the heart of many of these concerns is probably a sense that even user-based systems (at least in their current technical realizations) do not sufficiently address the potential implications of differential stimuli (e.g. certain fluctuations of environmental patterns), environmental contact and informational factors (semantic attributions, social and cultural expectations, etc.) for the inhabitants' overall sense of well-being.

In order to deal with these questions at some reasonable level of resolution, we now turn our attention to certain 'esoteric' views and approaches that share a common feature: they all, to various extents, challenge, question or transcend all or certain aspects of the premises behind the classical thermal comfort models and the associated technological approaches toward environmental control.

4.1. Energy and information

Human ecology postulates the relevance and importance of both *matter-energetic* and *informatory* aspects of human–environment interactions for the perception and evaluation processes [2,3,38]. This is even recognized, at least theoretically, by ASHRAE's own definition of thermal comfort as "that condition of mind that expresses satisfaction with the thermal environment" [28]. According to human ecological terminology, a material-energetic aspect as well as an informatory aspect can be assigned to every entity, state, process. The material-energetic aspect refers to the assumption that there is nothing called 'existing' unless some amount of matter and/or energy is involved. The informatory aspect refers to the assumption that matter/energy has a certain distribution in space and time which can be understood as a structure. An information content can be correlated to this structure. In practice, the matter-energetic aspect is considered more commonly, perhaps because it can be quantified more conveniently. However, these two aspects are complementary and inherent to any environmental relationship.

Classical thermal comfort research has treated people as a rather passive 'element' of the thermal exposure conditions. However, due to their internal information processing and the resulting actions, human beings can potentially affect external entities which in turn affect their internal 'model environment' [2,38]. The (explicit or de facto) reduction of these systematic relations to mechanistic 'stimuli-response' chains may result in significant conceptual and strategic shortcomings in environmental design activities.

(i) The complex pattern of surrounding factors may be taken into consideration only to the extent of its description in terms of easily measurable (energetic) variables (such as air and mean radiant temperature, relative humidity, etc.).

(ii) The informatory aspect of environmental relationships may be ignored or insufficiently considered. This informatory aspect accounts in many cases for the significant differences between people's individual mental representations (and the derivative evaluations) of the same 'objective' circumstance in the outside world.

(iii) The inhabitants may be viewed in dissociation with their experience and background, status and goals, and treated merely as 'generators' of statistically relevant data.

(iv) The dynamic interactions between two autonomous activity centers ('inhabitants' and 'surroundings') may be conceptually ignored and practically hindered.

Similar concerns have been voiced by many other researchers while commenting on the possible explanations for the afore-mentioned discrepancies between the result of field studies and comfort model predictions. They argue that the perception of thermal comfort may be affected by personal and contextual factors not imagined and thus not considered by the experimenters. In particular, they maintain that the perception process is not solely governed by the so-called environmental 'stimuli' and the primary physiological 'responses'. Rather, it must be studied in the broader context of cognition, memory, expectation, and intentional behavior [39–41].

4.2. Challenging the universality assumption

In the first half of this century, there was a general understanding that comfort-zone requirements should be different for summer and winter. Several studies in the USA and in England reaffirmed these differences [42,43]. However, in the 1960s, there were a series of laboratory experiments at the ASHRAE climate chamber at Kansas State University in which large samples of college age subjects wearing standard clothing and having normal metabolic rates recorded neutralities at the same temperature irrespective of seasons. This universality hypothesis was emphasized by Fanger on the basis of two experiments in Copenhagen on a small group of 'tropical travellers', winter swimmers, and meat packers. According to Auliciems:

"It is not often realized that the claims of its universal applicability were based on remarkably limited and rather incompletely reported preference studies of only 16 travellers from Copenhagen and 32 Danes" ([44], p. 18).

Based on the results of various field studies [32,33,45], it is becoming increasingly difficult to dismiss the possibility that acclimatization might play a role in thermal perception of inhabitants (particularly those living in hot and humid regions). In fact, in a survey of field studies conducted over the last 40 years, Humphreys found that the neutral temperatures preferred by people ranged from 17 to 30 °C [46]. In another study, the preferences of indoor temperatures were shown to be from about 14 °C in Japan to 17 °C in Norway to 21 °C in Sweden; three countries with similar energy prices and similar average household incomes [47]. In a further study conducted in Bangladesh in naturally ventilated buildings (with negligible air movement), the preferred air temperature of people performing sedentary activities and wearing clothes with a 0.5 clo value, was found to be 28.9 °C. This temperature is significantly higher than the value predicted using the comfort model [48]. Empirical studies have also shown that human perception of thermal comfort is somewhat dependent on the outdoor temperature: "People are attuned to outdoor events, and thermal satisfaction is maximized when indoor conditions vary according to seasonal and weather conditions" [44]. The results from these field studies suggest that people may have a tendency of adjusting to the climatic conditions. Thus the notion of universality of thermal comfort and its endorsement by international standards need to be critically reevaluated:

"The hypothesis has been extrapolated as equally applicable to human beings around the world regardless of race, culture or climatic experience (Fanger 1973a, b). Certainly the hypothesis is still being fostered by the International Standard Organization 7730 (1984), equipment manufacturers' handbooks, and the prestigious ASHRAE (1992) handbook" ([44], p. 16).

4.3. Mechanical versus natural control

The models and standards of thermal comfort are based on the underlying assumption of a controlled environment. There are two aspects of this assumption which need further examination as they have direct implications on the expectations of the people in such an environment:

(i) is it reasonable to apply the standards developed for mechanically controlled buildings to naturally ventilated indoor environments?

(ii) is it reasonable to ignore the potential effects of positive or negative connotative associations with a specific building service technology or building construction approach on people's perception of air quality and thermal environment?

The first question is particularly important in the context of those countries where only a small percentage of buildings are equipped with mechanically controlled environmental systems. The present international standards lead to the rather questionable conclusion that the majority of population in these countries are de facto living in substandard environments.

Two studies directly compare thermal comfort perception of two groups of people (one working in naturally ventilated buildings and the other in air-conditioned buildings) with identical cultural, climatic and linguistic background. In the study conducted in Singapore, the neutral temperature was found to be 28.5 °C in naturally ventilated buildings, but only 24.2 °C in air-conditioned buildings [33]. In a similar study conducted in Thailand, "it was found that the upper temperature bound for a Thai comfort standard, instead of being the currently accepted level of 26.1 °C, should be as high as 31 °C for office workers accustomed to naturally ventilated spaces, and as high as 28 °C for those accustomed to air-conditioning" [32]. As people spend a significant amount of time in indoor environments, one might explain these significant differences as the result of the previously mentioned acclimatization effect. Nonetheless, one might also speculate that the 'total environmental quality' in a naturally ventilated building represents a radically different evaluation context, thus also affecting the overall calibration of thermal expectations.

This speculation is also somewhat relevant to the second question above. The presence of negative associations with mechanically conditioned environments are well-documented [15,44]. It is conceivable that peoples' dissatisfaction with certain indoor climatic conditions is in part due to their negative view of the mechanical equipment, absence of personal control, sealed windows, etc. We will further explore this notion in the following discussion of comfort and pleasantness.

4.4. Comfort and pleasantness

Thermal neutrality in the previously mentioned ASHRAE thermal sensation scale denotes a thermal condition in which people do not wish the environment to be warmer or cooler. However, as Kuno mentions, "there are situations when we can feel pleasantly cool or warm" [49]. Following this line of thinking, Kuno developed a two-dimensional model of thermal sensation to clarify the distinction between comfort and pleasantness. According to this model, the experience of thermal pleasantness results from the body's physiological inertia in dealing with quick (or discontinuous) changes in ambient conditions that are initially experienced as uncomfortable. As a consequence, one must experience the 'uncomfortable zone' before entering into the 'pleasant zone'. According to Kuno, this two-dimensional nature of thermal sensation semantics is clearly expressed in Japanese language, where 'Dan' and 'Ryou' involve connotative references to the experiential hues of thermal pleasantness.

The importance of 'differential stimuli' for the underlying physiological and psychological basis of perception have been known for a long time. Previous research has emphasized the importance of differential sensory information for visual and acoustical perception [3] . Still, the prevailing paradigm of active ('power-operated') HVAC systems has been to strictly provide and maintain the neutral thermal state according to the 'one-dimensional' thermal sensation scale of the classical thermal comfort theory.

In this context, Kuno's most valuable contribution may be his reference to the potential of passive building design approaches which rely on the utilization of daylight and solar radiation, contextually adopted building massing and orientation, clever enclosure design including windows for natural ventilation and shading devices, evaporative cooling methods, use of thermal mass inertia for dynamic load shifting, etc. There is no doubt regarding the superiority of these passive techniques in view of energy conservation and ecological sustainability.

However, a "passive system cannot eliminate discomfort completely ... If the degree of discomfort is used for evaluation of environment, the passive system can never be superior to the active system" [49]. Kuno suggests that, in order to have a fair comparison between active and passive systems, one must take pleasantness into the consideration, as "neutral environments have no pleasantness". Kuno believes — probably correctly — that arguments pertaining to energy conservation and global environment will not change the preferences of those adopted to actively conditioned environments. So he suggests that 'health' should be used as an argument, and that "it is better for healthy people to experience a little discomfort".

We sympathize with Kuno's position, although we can literally visualize flocks of 'experts' that ask for the exact definition of pleasantness together with a precise numeric scale and an extensive statistical analysis of the correlation of pleasantness index with measurable health parameters. Alas, even if all that could be demonstrated, the 'experts' would probably guaranty that active systems could be adapted to emulate the natural fluctuation of passive systems in a much more 'reliable' and 'optimized' form (meanwhile applying the same basic energy-intensive technologies).

Let us afford one more speculation here. We referred previously to the SBS in cases of highly controlled and hermetically sealed indoor environments. On the other hand we mentioned the comparatively positive evaluations of naturally ventilated buildings. It is not far from human ecology's notion of 'individual information processing' if one suggests that minor levels of discomfort may be less of a cause for negative evaluation and complaints if they are not associated with incompetent design and poor maintenance, but with the 'natural' forces of environment. As was already known to Chuang Tzu over two millennia ago:

"If someone is crossing a river in a double-hulled vessel and an empty boat comes and strikes against it, even though he may be a quick-tempered person, he will not be angry. But if there is a person in the boat he will shout to him to steer clear. If his first shout goes unheeded, he will shout again. If the second shout goes unheeded, he will shout a third time, and that will certainly be followed by a stream of abuse. In the previous instance he did not get angry but in the present instance he is angry, because the previous boat was empty but this one has a person in it" ([50], p. 190).

4.5. Anthropological perspective

In a refreshingly original contribution, Prins deals with air-conditioning from a cultural and ethical perspective. He questions the notion that "air-conditioning makes life in hot places more agreeable". In fact he sees the trust of classical thermal comfort research as "pseudo-scientific procedures applied to value judgement" and "trapped inside its normative framework" [20,51]. According to this view, the demand for space cooling by North Americans (and those affected by their 'cultural imperialism') cannot be derived from physiologically grounded essential ('Category I') human needs but must be explained instead as the result of a self-reinforcing process of cultural signification and addiction. The cultural significance is seen in the associative message of air-conditioning: "For just as powerfully as it pushes away the shadows of the past, the poor of the present and the hostility of Nature's cycles, air-conditioning exuberantly expresses the achievement of the American dream, its message adding technological to agricultural abundance" [20]. Its addictive power lies in air-conditioning's capability to rapidly teach the body 'to hate the heat'. Prins sees in physical addiction to air-conditioned air "the most pervasive and least noticed epidemic in modern America".

In this context, Stern formulates a significant question: "if coolth is an acquired preference, what are the resistances to reversing it?" [20]. Besides the persuasiveness of the evocative power of American consumer culture and physiological acclimatization phenomena, other — socially originated — resistances create, according to Stern, barriers to reducing space cooling demand:

"Cities create new addicts. By an ingenious positive feedback system, air-conditioning heats the outside air, creating demand for air-conditioning among people who did not want it before. Competition enforces addiction. ... Competition ratcheted up the standard of coolth, and keeps it there. And major long-term social transformations perpetuate addiction. Air-conditioning was responsible in considerable part for the migration of millions to the Sun Belt of the American south and west. These populations now depend on air-conditioning, and express their dependence through their large and growing cadre of elected representatives, who are motivated by constituent pressure to vote against energy taxes, restrictions on consumption of electricity in summer, on any other policy option that would raise the cost or limit the availability of coolth'' [52].

We believe it is a mistake to label thermal comfort research as 'pseudo-scientific', but it would equally be a mistake not to seriously consider compelling evidence implying possible social and cultural 'conditioning' of human preferences and expectations pertaining to the indoor climate. In particular, Stern's reference to a 'positive feedback' reminds one of the implications of another important and equally wasteful mass industry of twentieth century, namely the automobile industry. Here again, the popularization of a technology was accompanied by an extensive cultural conditioning enforcing positively charged connotations (mobility, independence, freedom, etc.). And just as air-conditioning in the 'Sun Belt', the automobile industry made forms of habitation and commuting possible that entirely rely on it and thus perpetuate its existence [38,53,54].

5. Epilogue

From our discourse, a rather unsatisfactory view of the conventional HVAC technology emerges.

(1) Its aim at provision of often centrally controlled and uniform thermal conditions in indoor spaces is inherently problematic considering the differential and dynamic nature of inhabitants' ecological potency.

(2) It relies almost exclusively on a thermal comfort science which, despite many valuable contributions to our understanding of people's thermoregulatory system, is still limited and nearly static in capturing relevant environmental and personal parameters and is inconclusive in terms of the universal validity of its statistical predictions regarding desirable thermal regimes for indoor environment.

(3) In its first-cost dominated commercial realizations, it has in many instances difficulties in providing even that limited and narrowly defined set of environmental conditions and controls for which it is supposedly designed.

(4) It operates in a wasteful manner, is energetically entropic, and contributes significantly to environmental degradation. It is a '*brute force*' engineering solution which undercuts the demand for more effective (e.g. passive) 'soft energy' technologies: it may be cheap to build, but ''ecologically, financially and ultimately morally expensive to run'' [20].

The case for the non-sustainability of this circumstance becomes even stronger if some current global socio-economic tendencies and developments are considered.

(1) Population growth, already a serious concern in the sixties [13], has reached devastating dimensions. An increasing number of countries (particularly in the rapidly developing Asia–Pacific region) strive to reach living standards and styles set by industrialized countries, thereby uncritically adopting similar energy intensive and wasteful approaches to environmental control. Apparently the combined 'cola- and auto-colonization' impact has left no room in minds and actions for Gandhi's wisdom of *atma-nirbharta* (self-reliance), the most fundamental of all recipes for sustainable development.

(2) The fragile nature of the air-conditioning technology (similar to the equally energy-hungry automobile industry) and the afore-mentioned *circulus vitiosus* of a *brute force* engineering approach and its addictive power in generation of demand poses a constant threat to global socio-political stability. The operation 'Desert Storm' was a telling pretaste of what is at stake politically: ''By 2020, if present trends continue, over two-thirds of world oil will be pumped from the Middle East, compared to just a quarter today'' ([55], p. 5).

(3) The continuation and further spread of the current practice in building construction and mechanized indoor climate control undoubtedly intensifies the degradation of already stressed sensitive ecological systems. A major portion of primary energy consumption in industrialized countries is due to heating, cooling, ventilating and lighting of buildings. Moreover, construction, operation and demolition of buildings constitutes the largest source of CO_2 emission in these countries. Recent proposals and actions toward oil exploration in the last heretofore protected regions in North America or elsewhere are deeply troubling indications of the ongoing ecological destruction.

All this, and the current — rather regressive — developments in environmental matters and policies may cause one to believe in the futility of efforts toward environmentally responsive building design methods and indoor climate control strategies. In fact, it appears that the latter would only have a chance in the rather unlikely case that long-term ecological thinking and ethical considerations would prevail. However, responsible professionals in the building science and engineering community will have to persistently point to the problems on the current environmental control practices and strongly promote fundamental course corrections, even if the realization of sustainable alternatives, discussed in this paper and documented elsewhere [6–9,19,53–58], often transcend mere technological considerations and depend on broader political and cultural factors.

References

[1] R. Banham, *The Architecture of the Well-tempered Environment*, The Architectural Press, London/The University of Chicago Press, 1969.

[2] H. Knötig, Some essentials of the Vienna School of Human Ecology, *Proc. 1992 Birmingham Symp.; Austrian and British Efforts in Human Ecology*.

[3] A. Mahdavi, Integrative Strukturanalyse, *Habilitationsschrift*, Vienna University of Technology, Austria, 1988.

[4] A. Mahdavi, From restraints to preferences: reflections on evolving design support environments, in R. Trappl (ed.), *Cybernetics and Systems '94*, World Scientific, Singapore, 1994.

[5] G. Bateson, *Steps to an Ecology of Mind*, Ballantine Books, New York, 1972.

[6] A. Mahdavi, Traditionelle Bauweisen in wissenschaftlicher Sicht, *Bauforum 132, 1989*, pp. 34–40.

[7] N.B. Bahadori, Natural cooling in hot arid regions, in A.A.M. Sayigh (ed.), *Solar Energy Applications in Buildings*, Academic Press, New York, 1979, ISBN 0-12-620860-3.

[8] K. Dunkelberg, *IL31-Bambus Bamboo*, Information of the Institute for Lightweight Structures, University of Stuttgart, Germany, 1985.

[9] M. Ziff, The influence of environmental control systems on interior architecture, *ASHRAE J.*, (June) (1995) 72–78.

[10] P.O. Fanger, *Thermal Comfort Analysis and Applications in Environmental Engineering*, McGraw-Hill, New York, 1970.

[11] A. Waller, Being here, *Mainichi Daily News*, Sept. 1, 1993.

[12] V. Loftness and V. Hartkopf, The effects of building design and use on air quality, in J.E. Cone and M.J. Hodgson (eds.), *Occupational Medicine: State of the Art Reviews*, Vol. 4, No. 4, Hanley & Belfus, Philadelphia, PA, 1989, pp. 643–665.

[13] W.L. McGrath, The human habitat of the future, *ASHRAE J.*, (June) (1995) 82–85.

[14] P.R. Morey and D.E. Shattuck, Role of ventilation in the causation of building-associated illnesses, in J.E. Cone and M.J. Hodgson (eds.), *Occupational Medicine: State of the Art Reviews*, Vol. 4, No. 4, Hanley & Belfus, Philadelphia, PA, 1989, pp. 625–642.

[15] J.E. Cone and M.J. Hodgson (eds.), *Occupational Medicine: State of the Art Reviews (Problem Buildings: Building-Associated Illness and the Sick Building Syndrome)*, Vol. 4, No. 4, Hanley & Belfus, Philadelphia, PA, 1989.

[16] H. Knötig, I. Kurz and E. Panzhauser, 'Sick buildings' — a phenomenon of internal information processing?, *Proc. INDOOR AIR '87*, Vol. 2, 1987, pp. 497–504.

[17] B. Nagengast, Environmental control, taken for granted: past, present and future, *ASHRAE J.*, (June) (1995) 65–68.

[18] A. Al-Temeemi, Climatic design techniques for reducing cooling energy consumption in Kuwaiti houses, *Energy Build.*, *23* (1995) 41–48.

[19] A. Lovins, The super-efficient passive building frontier, *ASHRAE J.*, (June) (1995) 79–81.

[20] G. Prins, On condis and coolth, *Energy Build.*, *18* (1992) 251–258.

[21] W.J. Baldwin, *Outline of Heating, Ventilating and Warming*, New York, 1899.

[22] Le Corbusier, *Précisions*, Paris, 1930.

[23] F.C. Houghten and C.P. Yaglou, Determining equal comfort lines, *J. ASHVE*, *29* (1923) 165–176.

[24] D.A. McIntyre, *Indoor Climate*, Applied Science, London, 1989, ISBN 0-85334-868-5.

[25] Moderate thermal environments — determination of the PMV and PPD indices and specification of the conditions for thermal comfort, *ISO Standard 7730*, Geneva, Switzerland, 1984.

[26] A.P. Gagge, J.A.J. Stolwijk and Y. Nishi, An effective temperature scale based on a simple model of human physiological regulatory response, *ASHRAE Trans.*, *77* (1) (1971) 247–262.

[27] Physiological principles for comfort and health, *ASHRAE Fundamentals Handbook*, ASHRAE, 1993, Ch. 8, pp. 8.9.

[28] Thermal environmental conditions for human occupancy, *ANSI/ASHRAE Standard 55-1992*, ASHRAE, 1992.

[29] D.A. McIntyre, Chamber studies — reductio ad absurdum?, *Energy Build.*, *5* (1982) 89–96.

[30] H.M. Proshansky, Methodology in environmental psychology: problems and issues, *Human Factors*, *14* (1972) 451–460.

[31] J.A. Russel and L.M. Ward, Environmental psychology, *Ann. Rev. Psychol.*, *33* (1982) 651–688.

[32] J. Busch, A tale of two populations: thermal comfort in air-conditioned and naturally ventilated offices in Thailand, *Energy Build.*, *18* (1992) 235–249.

[33] R.J. de Dear, K.G. Leow and S.C. Foo, Thermal comfort in the humid tropics: field experiments in air conditioned and naturally ventilated buildings in Singapore, *Int. J. Biometeorol.*, *34* (1991) 259–265.

[34] G.E. Schiller, E.A. Arens, P.E. Bauman, C. Benton, M. Fountain and T. Doherty, Thermal environments and comfort in office buildings, *ASHRAE Trans.*, *94* (2) (1988) 280–308.

[35] R.J. de Dear and M. Fountain, Field experiments on occupant comfort and office thermal environments in a hot-humid climate, *ASHRAE Trans.*, *100* (2) (1994) 457–475.

[36] F.S. Bauman, H. Zhang, E.A. Arens and C.C. Benton, Localized comfort control with a desktop task conditioning system: laboratory and field measurements, *ASHRAE Trans.*, *99* (2) (1993) 733–749.

[37] Personal environments — environmental control for individual workspaces, *Publication No. 2771*, Johnson Controls, 1994.

[38] A. Mahdavi, Acoustical aspects of the urban environment, *Aris; J. Carnegie Mellon Department of Architecture*, Carnegie Mellon University Press, Pittsburgh, PA, 1992.

[39] H. Helson, Adaptation-level theory: 1970 and after, in M.H. Appley (ed.), *Adaptation-level Theory*, Academic Press, New York, pp. 5–17.

[40] W.H. Ittelson, Environmental perception and contemporary perception theory, in W.H. Ittelson (ed.), *Environmental and Cognition*, Seminar Press, New York, pp. 1–19.

[41] D.A. McIntyre, Chamber studies — reductio ad absurdum?, *Energy Build.*, *5* (1982) 89–96.

[42] T. Bedford, Environmental warmth and its measurement, *Medical Research Council Memorandum No. 17*, HMSO, London, 1946.

[43] C.P. Yaglou, Indices of comfort, in L.H. Newburgh (ed.), *Physiology of Heat Regulation and the Science of Clothing*, W.B. Sanders, Philadelphia, PA, 1949.

[44] A. Auliciems, Thermal comfort, in N.C. Ruck (ed.), *Building Design and Human Performance*, Van Nostrand Reinhold, New York, 1989, ISBN 0-442-27847-0.

[45] N. Baker and M. Standeven, Thermal comfort in free running buildings, *Proc. 11th Passive and Low Energy Architecture Int. Conf., Dead Sea, Israel, 1994*, pp. 25–32.

[46] M.A. Humphreys, Field studies of thermal comfort compared and applied, *Build. Serv. Eng.*, *44* (1976) 5–27.

[47] L. Schipper, A. Ketoff and A. Kahane, Explaining residential energy use by international bottom-up comparisons, *Ann. Rev. Energy*, *10* (1985) 341–405.

[48] F.H. Mallick, Thermal comfort in tropical climates: an investigation of comfort criteria for Bangladeshi subjects, *Proc. 11th Passive and Low Energy Architecture Int. Conf., Dead Sea, Israel, 1994*, pp. 47–52.

[49] S. Kuno, Comfort and pleasantness, *Pan Pacific Symp. Building and Urban Environmental Conditioning in Asia, Nagoya, Japan, 1995*, Vol. 2, Part 2, pp. 383–392.

[50] V. Mair (translator), *Wandering on the Way; Early Taoist Tales and Parables of Chuang Tzu*, Bantam Books, New York, 1994.

[51] G. Prins, Reply to comments on 'On condis and coolth', *Energy Build.*, *18* (1992) 267–268.

[52] P.C. Stern, The preference for coolth — comments on 'On condis and coolth', *Energy Build.*, *18* (1992) 259–266.

[53] H. Knoflacher, *Zur Harmonie von Stadt und Verkehr: Freiheit vom Zwang zum Autofahren*, Böhlau, Vienna, 1993.

[54] J.H. Kunstler, *The Geography of Nowhere: The Rise and Decline of America's Man-Made Landscape*, Simon & Schuster, New York, 1993.

[55] M. Brower, *Cool Energy: Renewable Solutions to Environmental Problems*, MIT Press, Cambridge, MA, 1992, ISBN-0-262-02349-0.

[56] H. Fathy, *Natural Energy and Vernacular Architecture*, The University of Chicago Press, Chicago, IL, 1986, ISBN-0-226-23917.

[57] B. Anderson (ed.), *Solar Building Architecture*, MIT Press, Cambridge, MA, 1990, ISBN - 0-263-01111-5.

[58] A.B. Lovins, Energy efficient buildings: institutional barriers and opportunities, in *Strategic Issues Paper*, E Source Inc., Rocky Mountain Research Associates, Inc., Boulder, CO, 1992.