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DESIGN STRATEGIES FOR ENERGY-EFFICIENT OCCUPANT CONTROL OF THE ENVIRONMENT IN BUILDINGS

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Introduction

In the Keynote Address to ICBEM'83, Szokolay made a case for the consideration of both occupant control and "objective" (largely automatic) control of the environment, pointing out that occupant control offered the greatest conservation potential but was less predictable and that occupant controls had to be tailored to the occupants, not vice versa (1). He looked forward to relevant papers in the 'human factors' session, but in essence there were none. Consideration of occupants in such papers is usually restricted to their role as receivers of the environment; instead papers typically discuss the fine tuning of the comfort conditions to be established by a building's plant. This pattern of thinking dominated the energy conferences of the 1970s where there was a concentration on improving the plant. Despite the growing interest at that time in systems theory, the occupants were ignored and building fabric characteristics were seen only as parameters to plant operation. Little change of pattern is evident in even the more recent conferences, where discussion has centred on making plant more efficient, rather than the whole system of building plus occupants.

Automatic control of the environment for energy conservation purposes has been implemented with an increasing tightness of that control, accompanied by a minimizing of air change rates in completely sealed buildings. The facade is often designed for thermal opacity, this having the advantage of decreasing the perimeter zone for air conditioning and increasing the floor area able to be served from central plant. The problems that have been encountered with tightly-controlled environments include: concern that laboratory-derived control set-points do not take account of many factors that influence environmental comfort; significant occupant dissatisfaction with the tightly-controlled environments and with the lack of remedial access to system controls; the production of a bland, soporific environment from the uniformity of temperatures and lighting and the low air change rate; and the emergence of a 'sick building syndrome' in which some occupants become chronic suffers of headaches, sore throats, lethargy and other ailments.

Study of such problems reveals two issues: a perceived preference for some naturalness in the internal environment and a desire by occupants for some access to control of the environment. Ideally the naturalness should be achieved by designing buildings to be suitably responsive to and admissive of the external environment, and by less tight control of the internal environment by the building services system. The usual argument against this is that such a strategy would lead to increased energy consumption. A similar argument opposes surrendering some measure of environmental control to the occupants. It is also argued that occupants would be less likely to achieve 'optimum' comfort conditions, although it has been conjectured (1) that occupant access to controls is more important than the actual physical state of the environment in ensuring that the occupants are satisfied with their comfort state.

The key to the success of such an approach is ensuring the effectiveness of the occupant control actions and their compatibility with the overall energy efficiency of the building. Effective occupant action requires their understanding how to use the controls, which implies an understanding of the performance of the whole environmental control system. It also requires that the occupants achieve satisfaction with the effects of their actions, which has implications for the provision of tangible feedback and for the response time of the system to each potential control action. If adequate understanding of system performance or adequate feedback cannot be practicably provided in the building design, occupant control actions may have to be provided through a hierarchy of controls, with control tasks shared between the occupants and automatic sensors/effectors (and possibly some provision for either to override the other). These considerations will be discussed shortly.

A secondary factor in the successful implementation of this approach to building design is an adequate prediction of the performance of the system at the design stage. The environmental control system embodying both occupant and automatic control over a 'natural' internal environment is much more complex than the tightly-controlled, plant-determined environments for which good simulation models are available. An approach to modelling the more complex systems will also be discussed.

Variety in the environmental control system

A significant attribute which occupants bring to the control of the environment is an ability to deal with systems, such as the natural environment, which display high variety. The cybernetic concept of *variety* (2) is a measure of the complexity and variability of a system. Each state of the environmental system can be represented by the set of values of all the system variables for that state. The variety of the system will be the number of states in which it may exist. This number will depend upon the range of values of each of the variables and on the number of possible combinations of these values which in turn depends upon the amount of interaction between the variables.

In the case of a system, such as that of the physical environment, where the variables are continuous within their ranges rather than adopting discrete values, a measure of variety might be obtained by imposing a stepped scale on the range of each variable, analogous to the rating scales used in psychometric studies. If the number of steps in each scale corresponds to the number of separate intervals of values of the variable able to be discriminated by the occupants of a building, this measure of variety would become particularly meaningful.

When the variety of a system is less than the maximum possible number of combinations of values, the system is exhibiting constraint.

The *variety reduction* which this constraint brings about may be through a decrease in the ranges of values which the variables take or through a decrease in the interrelatedness of the variables. In general, environmental comfort requires only variety reduction in the form of a restriction of the ranges of variables so that they lie within the 'comfort zone'. Comfort *per se* does not depend upon a reduction in the interrelationships between environmental variables. Nor does it depend upon such a restriction of the ranges of environmental variables that a single mode of system behaviour is sufficient; that is, that no adaptive control action is necessary (such as switching on a light or opening a window). If variety reduction includes a reduction of interrelationships between variables or the elimination of adaptive behaviour, it will be the result of a requirement or side-effect of the control measures employed.

It can be demonstrated (3) that a system which displays adaptive behaviour must consist of weakly joined subsystems in order to reach equilibrium in a reasonable adaptation time. The terrestrial environment is observed to consist of sparsely joined subsystems but much weaker joins are found in an internal environment which is controlled by plant, assisted by the relative responsiveness of the building enclosure to each variable including the blocking of some inputs and the provision of an artificial substitute. Complementing this, both the building occupants' physiological sensory mechanisms and constructed monitoring devices display dispersion but much more so in the latter case. The connections that exist in people's sensory mechanisms produce a much richer repertoire of behaviour. The specialization of monitoring subsytems ensures greater efficiency for each device. The appropriateness of this specialization is, however, dependent upon the maintenance of constraints on the environment.

A formal way of stating the above is that, in general, electromechanical controls possess responses of very low variety. Since a system displaying a particular amount of variety can only be effectively controlled by a system displaying an equal or greater amount of variety, it is clear that low variety controls can only effectively handle a low variety environment. Conversely, the high variety 'natural' environment preferred by a building's occupants can be appropriately controlled by the high variety responses of those occupants, or by a combination of occupant and automatic control which retains the high variety contributed by the occupants.

Nevertheless, building occupants are often denied any role in environmental control. This decision is usually on the grounds that the occupants will either cause the building and its plant to perform less efficiently (especially in energy terms) or make their own task performance less efficient by this distraction. However, this takes a very narrow view of the way this role might manifest itself. In principle, the control model derived from cybernetics indicates no negative effects from occupant interaction, only the positive advantage of increasing the variety of responses available. The application of cybernetics concepts will need to be extended to see how such occupant interaction might appropriately be achieved.

Conditions for occupant involvement in environmental control

Some insight into the 'protocols' people employ in repeated control actions can be gained from the now classic studies of the human operator in industrial process control (4). However, environmental control is not a primary but a secondary task and building design should ensure that action is required infrequently and that the actions available are not time-consuming. Studies of environmental control as a secondary task appear largely restricted to teacher control of classroom environments (e.g. 5). These show different control strategies being employed in apparently similar situations, with widely different energy consequences. There is a clear need for more research to develop an environmental system which will lead to a similar control strategy for all occupants which is also energy efficient. It would be fundamental to this work to ensure that the environmental system was understood clearly by the occupants.

The fact that we are not physiologically equipped to sense energy consumption means we remain largely ignorant of the consequences in energy terms of the control actions we take. This suggests that the environmental control system will have to be designed either to ensure that occupants receive the necessary information or to restrict the achievable states to those compatible with energy conservation. The latter may be implemented through a hierarchical control system.

The clarity of expression of the environmental control system of older buildings, and the physical immediacy of the system adjustments which could be made by occupants, has been superseded in plant-controlled buildings with two polarized solutions: fully exposed servicing or the concealment of servicing above a suspended ceiling. These aesthetics-based approaches do not convey adequate information for effective occupant control. Although to some extent the recent buildings which have incorporated extensive passive control can be seen as a reversion towards traditional modes of control, it does not follow that a complementary clarity of system expression can be regained automatically. The physical forms can seldom be the same and the demands being made of the controls will be more sophisticated. At the same time the opportunity exists here for using advanced technical design to provide built solutions that are simpler and more easily responded to by people.

In cybernetic terms, the key problem with modern forms of the environmental control system is that the flow of information within the system is poorly managed compared to the flow of energy. This statement recognizes that the occupants are part of that system. In most present systems the flow of information is rudimentary, given the potential complexity of the system. In turn, the energy flows are forced to be simple, imposing a subsystem structure which relegates occupants to being recipients of the environment rather than involved with its control.

The provision of information to the occupants, and the complementary access to appropriate controls, has implications for both the form of the building and the form of the controls on plant and fabric. Allowing a degree of occupant control requires that the occupants be provided with information not only of the disturbances that need to be responded to but also of the appropriate response to make under the circumstances.

Control action decisions taken by the occupants will take account of two important criteria: *anticipated response time* and *anticipated satisfaction* to be achieved. Some systems provide a rapid response (switching on lights; increasing fan speed) while others can be very slow (some heating systems). However, what is important is the time taken for information about the response to be received. An adapting system must obtain information on the effectiveness of its behaviour. An occupant will not be satisfied until that information indicates a successful control action. The information need not be about the variable being controlled. The information from a slow response heating system could be visual (a red glow) or aural (a humming sound), inducing satisfaction from the *anticipated* effect.

Anticipated satisfaction may be increased by a more elaborate control action which may take longer to implement. The two criteria may therefore need to be counter-balanced in any control action decision by an occupant. Together they form an *effectiveness* criterion which is complemented by a third basic criterion, that of the *efficiency* of the human input to the system (the human energy input compared to the size of change produced in an environmental variable or to the length of time that variable is maintained at a preferred value). Efficiency may be enhanced by a form of hierarchical control.

An important characteristic of occupant control is that it is adaptive and uses information which cannot be 'built into' the system by a designer. A cybernetic approach enables systems to be devised which are capable, in principle, of going beyond the range of actions foreseen by the designer. A similar effect is achieved in what would otherwise be deterministic control systems by the informal intervention of affected people. Just as the low variety of the decision-making process at the formal company board meeting is augmented by the high variety interaction at committee meetings, at the Friday evening 'happy hour' and through informal contacts (6), so too can low variety environmental controls be augmented by the highly redundant responses of the building occupants to match the level of variety in the environmental disturbances.

Hierarchical forms of environmental control

Superordinate restriction of control states

Both the situation state (the set of values of the environmental variables) and the control state (the settings of the control mechanism) can be evaluated as satisfactory or unsatisfactory. An unsatisfactory control state could be one that involved a high energy consumption, even if it was able to achieve a satisfactory situation state. The control of energy consumption may be sought superordinately by constraints placed on the available control states through the design of the building fabric, and the plant, or through an override placed on the controls (as in some present forms of light switching). Here, the building designer or building manager is acting as master controller to ensure energy criteria are met.

Amplifying regulation

An alternative hierarchical control system seeks primarily to optimize the efficiency of the human input to control (defined above) by replacing active adaptation with a process of selection; that is, using a small amount of regulation to achieve a large amount of regulatory system behaviour. Cybernetically, this "amplifying regulation" (2) takes the form of a master controller performing a small amount of selection and leaving one or more subcontrollers to carry out the detailed interactive control (7). This places the occupant of a building in a superordinate role with respect to automatic control. Energy conservation would then be achieved by the automatic control (the subcontrollers) in their programmed responses to the commands of the occupants (singly or collectively the master controller).

Computer-based control interface

Combining the above forms of hierarchical control would see the direct link from occupants to subcontrollers replaced by an indirect link via a computer. The computer would respond both to the occupants and to a programmed set of criteria (including energy-use goals), and would take account of both before instructing the subcontrollers. One attraction of this approach is that the occupants need no detailed understanding of the subcontrollers. Their input to the computer could be information about their comfort or desired changes to environmental variables.

Rudimentary desk-top devices for transmitting 'comfort votes' have been used in field studies of thermal comfort. More sophisticated equipment could be developed, perhaps geared to the increasing use of networked desk-top computer terminals which could be linked to a building management system in an overall "intelligent building" approach. Verbal statements such as "I am a little too warm" can be interpreted by an application of fuzzy set theory (8,9) and algorithms developed for a fuzzy logic controller to provide appropriate responses. The system can be designed to be self-organizing with adaptive fuzzy control developing new or better algorithms on the basis of the successfulness of initial algorithms (10). Such self-adaptive control should be able to acquire the variety of responses inherently available in occupant control but without direct occupant intervention (although this latter may be a source of dissatisfaction with this approach).

Local and background control

To provide occupants with some hands-on fine-tuning of their immediate environment, control can be separated into two components: occupant control of local systems and automatic control of a background system. This is already well-established in task/ambient lighting installations and offers exciting prospects as a form of low level air supply providing both personal supply and displacement room ventilation. The local/background concept avoids using energy to maintain comfort conditions through the whole volume of a space. It should be feasible also to design the background system to sense useage of the local systems and to adapt the more explicitly energy conscious background system in such a way as to reduce energy-inefficient use of the local systems.

The satisfaction derived from direct contact with controls and from the immediacy of the effect produced will be greater if the local system is floor-sourced, employing a raised floor, rather than ceiling-sourced, necessitating remote controls and sometimes less immediate effects.

Modelling environmental performance

It has been suggested that the present computer evaluations of energy consumption in buildings may, in the near future, be required to be applied to simulations of the environmental performance of proposed buildings to ensure compliance with energy standards (11). If so, there is a very real danger that the acceptableness of designs will be determined by what can be adequately modelled. Occupant participation in environmental control may be precluded by the limitations of the testing procedure.

Modelling occupant control actions is difficult within the conventional theoretical framework. As is typified by the common resort to either a fully exposed or a concealed environmental services system, it appears that in order to solve a problem which is not well understood the solution space is usually reduced substantially by a constraint imposed from outside the system. To avoid this, a much sounder theoretical framework is required which considers the dynamics of the system comprising not only the building and the physical environment but also the actions of the building's occupants. One approach to this more general theoretical base has been outlined above. A wider ranging and more detailed discussion is provided elsewhere (12).

Without a simulation model which recognizes that the occupants are an integral part of the control system, the search for new forms of environmental control is restricted to the working out of ideas in architectural and engineering practice. Research is restricted to fine-tuning non-occupant forms of control. The key to simulating occupant control actions lies in developing adequate algorithms in a subroutine of the computer model. As with the occupant-computer interface described earlier, this is best done with fuzzy set theory. The use of fuzzy algorithms and the testing of fuzzy models has been well documented (13) and the application to environmental models is discussed elsewhere (14).

Conclusions and Prospects

Basic cybernetic concepts in communication and control have been demonstrated to lead to the development of design strategies for producing 'natural', higher variety environments in buildings with a degree of occupant participation in the control system. Energy efficiency can be maintained by a hierarchical structure in this system, and this has the advantage of requiring less understanding by the occupants of how the whole environmental system works. Techniques for incorporating occupant control actions into simulation models of environmental performance have been validated. Such models provide a basis both for evaluating alternative control systems and for research leading to the development of new control strategies, including less plant-intensive forms.

The insights gained from setting up the model must be used to examine building regulations with a view to their restructuring to recognize the interrelations in a general environmental control model. This will ensure that the regulations do not impose a structure on a designed control system which is in conflict with the 'natural' control system. A comprehensive environmental model, developed to guide both design and research, will have only its application to research unfettered so long as design is constrained by regulations and professional lore (including the present demarcation of professional tasks) which are based on concepts no longer considered relevant to the control situation. The construction of the model must therefore be accompanied by the investigation of ways of ensuring that the results of the research may be readily assimilated into design practice.

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