MOVEMENT DYNAMICS IN OFFICE ENVIRONMENTS

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Keywords: office environmental design, physical activity

Abstract

This research explores the relationship between the indoor environment and physical activity and sets out to highlight how motion inside buildings can be described as a dynamic system that may be prescribed by design. Our work builds on an exploratory study carried out in a cellular workplace at the Computer Laboratory of the University of Cambridge in order to identify the energy cost of movement in different office spaces. Movement has been recorded using an accurate indoor location system and analysed alongside measured energy expenditure. Our goal is to show that it is possible to estimate human energy expenditure at the design stage without the need for specialised medical equipment. Based on our existing knowledge of the importance of environmental-behavior interaction on productivity we believe that increases in movement duration and intensity may have a beneficial effect on both the office organisation and occupant health and wellbeing.

1. Introduction

This research concerns itself with physical activity and health as well as with the effects of office architectural design on the levels and characteristics of movement. Our founding contention is that the design of the environmental layout, very often led by concerns for managerial wellbeing and organisational success, pays little or no explicit attention to the importance of the occupants' wellbeing in space and health. Stampfer et al. (2000) and Wannamethee et al. (2000) have shown that a sedentary lifestyle can lead to obesity-related illnesses and long term ailments including respiratory and cardiac deficiencies, type II diabetes, colon cancer and osteoporosis. In the belief that physical activity is a function of space, and based on recent theories of workplace design, the aim of this work is to stave off this tendency through design. We present a simple model for predicting energy expenditure based on movement and validate this model by comparison to actual movement traces with expenditure recorded by an established medical device. In future, such a model could be incorporated into computer software to influence design decisions.

2. Research Methodology

In this study the topography of the layout, the dynamics of movement, and human energy expenditure are all objectively measured. This allows an exploration of the relationship between occupants' journeys within the office environment and their energy expenditure. The data collection took place over 5 to 7 working days at the University of Cambridge Computer Laboratory in a set of cellular offices on the second floor. Eighteen participants volunteered for the study; the population was predominantly male, aged from 20 to 60 years old, with height and weight ranging from 1.67m to 1.96m and 54kg to 94kg respectively.

All participants wore an Active Bat to record their movement within the office environment. The Active Bat system is an ultrasonic indoor location system which relies on sensors installed throughout the ceiling of the office space to produce an estimation of the location of the Active Bat by multilateration. The system is capable of tracking multiple Active Bats simultaneously and, with a clear line of sight between the Active Bat and the ceiling sensors, can estimate the position of an Active Bat with an error of less than 3 cm 95% of the time (Addlesee et al. 2001, Harter et al. 1999).

In addition to an Active Bat, all study participants wore a GTIM Actigraph (Westerterp 1999, Celler et al. 2004) which previous studies have shown provides an accurate record of energy expenditure. The Actigraph uses accelerometers, a digital band pass filter and an embedded microcontroller to record the intensity of physical activity. Since both the Actigraph and the Active Bat System record the times at which readings are taken, data from these systems can be compared and the relationship between physical activity level and location can be explored empirically.

In addition to quantitative measurement, a qualitative assessment method was also used. Interviews with an indicated high reliability index were conducted using the short version of the International Physical Activity Questionnaire (IPAQ 2005). The structured questionnaires were given to the research participants in order to gain a better understanding of occupants' perception of activity levels during the study. A number of semi-structured questions were also posed to gain a better understanding of the relationship between levels of physical activity and the architecture of the office space.

The ultimate goal of this work is to identify and measure human energy expenditure and find out why we move, where we go and how often – i.e. popular destinations of office journeys. We hypothesise that it may be possible to estimate human energy expenditure at the design stage. Our ultimate goal is to design a software tool for architects to estimate human energy use based only on plans of the building and a suitable profile of the building occupants. The tool may also be able to suggest changes to the design to improve occupants' activity levels. With this tool an architect could explore whether a building design could meet the public health daily physical activity recommendations (U.S. Department of Health and Human Services 1996, 2000, Department of Public Health 2005) which suggest at least 30 minutes of increased bodily activity, such as brisk walking, at least 5 days a week.

3. Theoretical approach

In seeking to identify the relationship between human energy expenditure and the use of space, we have developed two theoretical models. The first takes into consideration both the horizontal and vertical axes of movement of an individual to estimate the energy consumption involved in moving between two locations. The second model is used to identify likely journeys between office destinations. These two models are now described in more detail.

3.1 Energy consumption model

We seek to identify whether it is possible to extract reliable data on energy expenditure based only on location information and derived velocity. Ralston (1958) showed that, during level walking, the energy expenditure is a linear function of the square of the speed and is calculated using the following empirically derived formula:

$$E_w = 29 + 0.0053v^2 \tag{1}$$

where E_w is energy expenditure in cal/min/kg, and v is velocity in m/min. Converting to SI units, we obtain:

$$P_w = \frac{\left(\left(29 + 0.0053 \cdot (60v)^2\right) \cdot 4.184\right)}{60} \cdot m \approx \left(2.02 + 1.33v^2\right) \cdot m \tag{2}$$

where P_w is power in W, v is velocity in m/s and m is mass in kg.

When a person stands up, they must gain gravitational potential energy. This can be expressed as:

$$E_g = m \cdot g \cdot \Delta h \tag{3}$$

where E_g is energy expenditure in J, m is mass in kg, g is the acceleration due to gravity (9.81 m/s^2) and Δh is change in height in m. Note that we assume the Bat is located at the centre of gravity of the wearer and do not take into account energy required to accelerate vertically and only consider positive changes in height.

When a person accelerates, they must gain kinetic energy. This can be expressed as:

$$E_k = \frac{1}{2} \cdot m \cdot (\Delta v)^2 \tag{4}$$

Where E_k is energy expenditure in J, m is mass in kg and Δv is the change in velocity in m/s.

Note that this model does not take into account the energy required to sit down, nor does it account for the gravitational energy gained or additional energy exerted when climbing or descending stairs, although it could be extended to incorporate such factors.

3.2 Behavioral Model

Based on our existing knowledge and previous research outcomes, it is apparent that broadly speaking all activities that take place within the office environmental layout are *voluntary*. Some are highly based on the personal initiative to move (e.g. visiting the coffee station or the print room) and other have more imperative characteristics (e.g. visiting the toilets or a manager's office). Voluntary movement can be influenced or impeded by many attributes, some architectural and others more variable and subject to factors such as the occupants' personality. By determining specific locations and destinations within the office setting it is possible to estimate the relationship between the stimuli to initiate a journey and the effort made.

In order to determine the likelihood of movements of individuals within the office workplace, data should be provided on the type of the organization, the age and gender of the occupant population, the layout type (e.g. 'open plan') and the nature of office relationships.

Thomas Allen (1984) showed that the likelihood of a predominantly voluntary trip decreases exponentially with distance, with the likelihood of a movement for informal communication asymptotically close to zero when the destination is further than 50m away from the initial location.

4. Results

4.1 Model evaluation

The Actigraph records *counts* which are a dimensionless unit, but Freedson et al. (1998) suggest a popular equation to derive energy expenditure estimates:

$$E = 0.00094c + 0.1346m - 7.37418 \tag{5}$$

where E is energy expenditure in kcal/min, c is counts/min and m is mass in kg. Converting to SI units, we obtain:

$$P = \frac{(0.00094(60c) + 0.1346m - 7.37418) \cdot 4184}{60} \tag{6}$$

where P is power in W, c is counts/s and m is mass in kg.

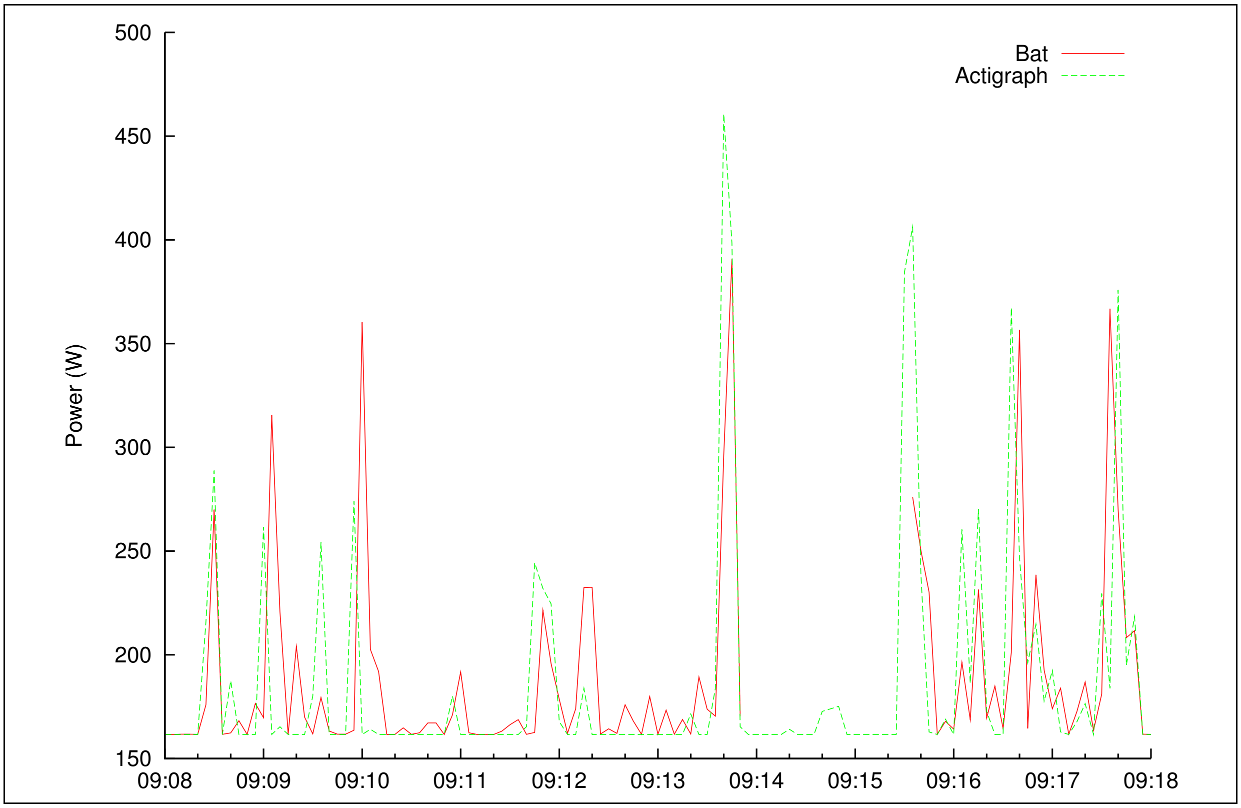

Figure 1 *Energy expenditure of an example individual as measured by both the Bat system and Actigraph between 09:08 and 09:18*

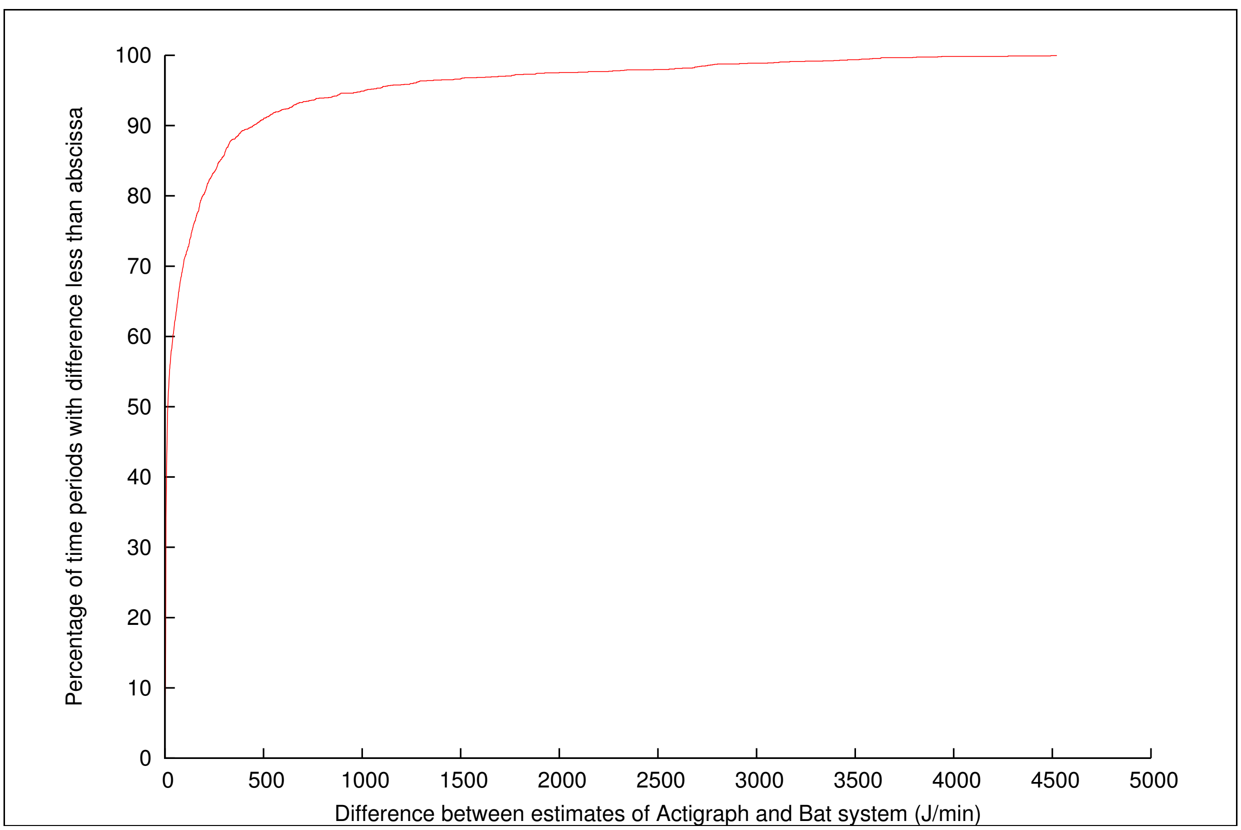

Figure 2 *Distribution of differences between energy expenditure estimates from the Actigraph and Active Bat System data over minute-long samples*

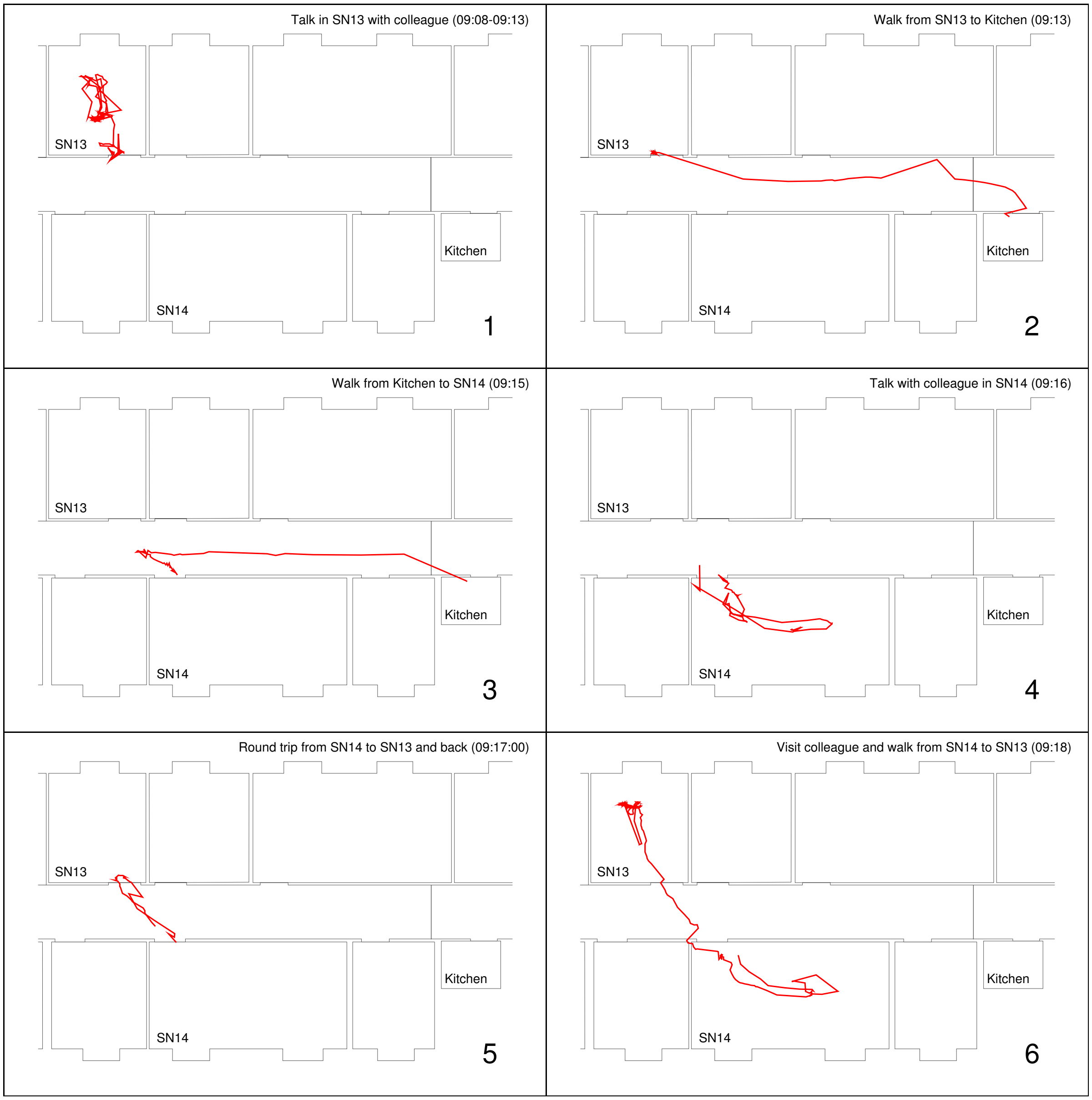

Figure 3 Trips made by an example individual between 09:08 and 09:18

The Actigraph manual recommends using the Freedson equation only when c > 1952 counts/min. In particular, the equation suggests energy expenditure is zero when no counts are recorded; this does not capture the Basal Metabolic Rate (BMR). The Ralston equation used to derive energy expenditure from movement gives a stationary power consumption of approximately 2.02m (where m is mass in kg). Accordingly, where c < 1952 counts/min we interpolate linearly between 2.02m and the value given by the Freedson equation for c = 1952 counts/min.

An example of one individual's energy expenditure over a ten minute period as measured using both an Actigraph and the Active Bat System is presented in Figure 1. Figure 3 shows the individual's location trace over the same period, separated into six sub-journeys. The first sub-journey, shown in the top left floor plan of the Figure, is depicted by a red line showing the movement of the Active Bat worn by the participant inside office SN13 over a five minute period. The next sub-journey records the movement of the study participant as he walked from SN13 to the Kitchen. The remaining four sub-journeys chart the movement of the user over the rest of the period covered by Figure 1.

Figure 1 shows that between approximately 09:14:00 and 09:15:30 no locations were recorded by the Active Bat system; Figure 3 shows that the subject was in the Kitchen, where no sensors are installed. Although the clocks in the Actigraphs were synchronised with those of the computers recording Active Bat System data at the start of the experiment, they were left to run freely thereafter and so will have drifted slightly; this may account for the slight time offsets seen in some of the peaks in Figure 1. On some occasions, the estimate based on the Active Bat data, as shown in Figure 1, is higher than that from the Actigraph: this is likely to occur if an individual stands up or changes direction very smoothly, so that the accelerometers inside the Actigraph do not correctly capture the energy expended. In other cases, the movement-based estimate derived that the Active Bat data is lower than that recorded by the Actigraph: this may be caused by forms of energy expenditure not accounted for in our movement model.

In general, there is little difference between the energy expenditure as estimated from the Actigraph and our movement model. This is demonstrated in Figure 2 which shows the difference between the energy expenditure recorded by the Actigraph and the estimate from our movement model using data from the Active Bat system. Figure 2 shows that over the course of one week, 90% of the energy expenditure estimates from the movement model differed from Actigraph data by less than 340 J per minute, and the mean error was found to be 198 J per minute. An error of 340 J per minute accumulated over 24 hours is equivalent to approximately 100 kcal (the energy found in an average-sized banana). The UK National Health Service recommended calorie intake per day is 2500 kcal for a man and 2000 kcal for a woman, therefore the error between our movement model and the Actigraph is less than 5% of the daily energy expenditure of a human being; we believe this is an acceptable error rate for estimating the health of office workers.

4.2 Indoor office environment movement patterns

The survey suggests that the most popular office activities are those which involve personal initiative and provide opportunities for informal interaction. Most preferred spaces for movement and interaction have been found (from Active Bat readings) to be individuals' desks along with the print station and the water cooler with a significant percentage of these trips involving stair use. Stair use is of great importance in increasing physical activity levels as medical studies have shown that the energy expended walking up and down stairs is approximately three times that required to walk slowly on a level plane (Rowett Institute 1992).

Of the interviewed population, 78% reported that walking up and down the stairs is necessary for time efficiency, as the lifts, also perceived to be operating in a relatively slow mode, were located further away. Additionally, 22% regarded stair use as positive, meaning that they would normally look forward to it during their daily office routine. None of the occupants reported stair use as a negative aspect of their day. Walking, in general, was regarded as positive by half the participants' population; 45% believed that walking around the workplace is a necessity and 5% perceived this activity neutrally.

In measuring the frequency and destination of occupants' movements, we identified that 18% of occupants' movement was towards settings allowing for informal communication – such as colleagues' desks. Another 18% was to the water cooler,12% to the floor kitchen and 17% to the printers. An overall 23% of the daily office activity involved stair use, including 6% to the ground floor cafeteria and 6% to the reception desk (see Figure 4).

Our investigations have shown that the occupants always tend to visit the rest room once or twice a day. The designed location of this space has been measured as on average 5 to 10 meters away from the participants' initial location. It has been suggested that because of the imperative nature of this trip the architectural practice could potentially prescribe the length of this trip and measure it from the design stage. Based on Thomas Allen's work suggesting that no voluntary trip is likely to take place of more than 50 meters we suggest that the rest room's location could potentially be located anywhere within this distance.

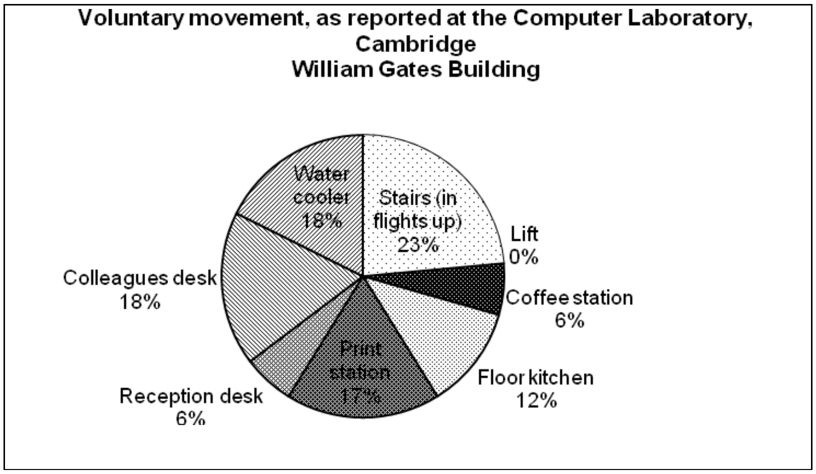

Figure 4 Results of interview on frequency and destination of movement

5. Discussion and Conclusion

In this paper we have established a model for estimating energy expenditure based on movement. Simultaneous analysis of the objectively measured results from the Actigraphs and the Active Bat System has shown that in order to gain comparable data sets we must take into account gravitational and acceleration effects.

Designing a software tool that may advise architectural practice on how to incorporate physical activity and health within the new strategies of sustainable and energy efficient design is not an easy task to accomplish. Further theoretical and practical analysis is required in order to build a design-time tool for architects. Such a tool requires static estimates of movement parameters, such as the change in height when standing up, since these are currently measured dynamically using the Active Bat System. The routes and frequencies of trips made by individuals inside the office space will need to be estimated too. These estimates will necessarily lead to a loss of accuracy, and an evaluation of the revised design-time model will be required.

We expect that ascending and descending stairs will comprise a significant proportion of total indoor energy expenditure, and is something we have not tackled in this paper. We suggest that new architectural design schemes are developed to incorporate the idea of ascending and descending stairs during the daily office routine, since energy expenditure when climbing stairs is significantly larger than walking on a flat surface.

Current research suggests that there are numerous interrelated attributes that may affect physical activity, space choice, indoor behavior, health and wellbeing. At the same time, design and management tendencies are towards making the workplace compact; sustainable design strategies ultimately aim to minimise movement by maximising layout density and energy efficiency, and to promote flexible working. The challenge is whether the trend for sustainability and working without anchor points may also increase human energy expenditure whilst still promoting the efficient use of space.

We believe that estimating energy expenditure is possible without the need for specialised medical equipment. If this can be achieved at the design stage, then architects should aim to increase levels of movement, occupant health and wellbeing in the indoor environment.

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