AUTHOR: **Jeremy Gabe**

Title of Paper: Design versus Performance: Lessons from Monitoring an Energy-Efficient Commercial Building in Operation

Researcher
Landcare Research
Private Bag 92170, Auckland, NEW ZEALAND
Telephone: +64 9 574 4138
E-mail: gabej@landcareresearch.co.nz

Abstract

Although they are commonly used to promote completed energy-efficient commercial buildings, building energy simulations poorly predict actual consumption. Empirical studies of buildings in operation routinely demonstrate high variability between design-stage energy modelling results and actual energy consumption. Furthermore, energy-efficient commercial buildings with high energy use (e.g., data centres and laboratories) more consistently perform poorly relative to their energy simulations than office-only buildings.

The Landcare Research building in Auckland, New Zealand, is one example of this trend. This high energy use building, completed in 2004 under a design philosophy of reduced resource consumption, has a complex mix of laboratories built to containment specifications, archival collections with stringent environmental requirements, and office space. It is consuming approximately double the amount of energy that design-stage models suggested, although it still outperforms benchmarks of energy intensity for conventional construction of its type and best-practice, energy-efficient laboratory/office buildings in the United States. The findings suggest that modelling assumptions in NZS 4232:1996 for office buildings underestimate continuous plug loads when used for high energy use buildings. They also highlight how building managers can have difficulty in controlling and managing complex building services (which are common in energy-efficient buildings), leading to further energy wastage. This study suggests great potential for increasing energy-efficiency of commercial buildings through better integration of building services design with typical building management behaviour in operation.

Key words: commercial building, energy, post-occupancy, assessment, automation, management

Introduction

Existing literature in empirical assessment of commercial buildings in operation shows that actual energy performance of commercial buildings is extremely variable when compared to design intentions (simulations). Diamond et al. (2006) found that the energy performance of 21 public LEED (Leadership in Energy and Environmental Design, a "green" building differentiation tool) buildings in the United States averaged out to be equal to the simulated total, but for each building, the standard deviation was 46% around this mean. Turner and Frankel (2008) corroborated this high variance with data from an additional 100 LEED buildings and also showed that there might be a systematic trend to the variance – buildings that predict relatively low energy consumption tend to use more energy in-use than anticipated, while buildings that simulate relatively high energy consumption tend to use less than anticipated. Finally, Probe, an extended study of 16 energy-efficient commercial office buildings in the United Kingdom, concluded that actual energy performance ranged "from excellent to below average", while the one building that had no design aspirations of energy efficiency outperformed those that did aspire (and win awards) for energy conservation (Bordass et al. 2001). The Probe study also addressed reasons why these commercial office buildings performed poorly, citing chronic problems related to unmanageable complexity created by clients and designers conspiring in “fantasies that solutions are ‘fit and forget’ while ‘fit and manage the consequences’…would be more like it” (Bordass and Leaman, 1997:151).

While most of the Probe research has focused on commercial buildings only containing office space and basic services (meeting rooms, toilets, kitchens, circulation spaces), Turner and Frankel (2008:28) found that alignment between simulated and measured energy consumption in “high energy use” buildings (namely laboratories and data centres) was “very poor…on average using two-and-a-half times as much energy as was predicted”. They speculate that the reason may be that the design community does not know these buildings very well. This paper looks in detail at the Landcare Research Building in Auckland, New Zealand, as an example of a “high energy use” laboratory and office building that was designed as an energy-efficient building with a very ambitious energy consumption target.

The Landcare Research Building

Landcare Research is a Crown Research Institute that studies New Zealand’s terrestrial environments, including sustainable urban development. In two years, between 2002 and 2004, Landcare Research procured a more sustainable office and laboratory building in the Auckland suburb of Glen Innes. It was first occupied in May 2004 by employees of Landcare Research and the Ministry of Agriculture and Forestry (MAF), which leases approximately one-third of the laboratory and office space. Occupancy has remained reasonably constant, with the building housing 65–70 Landcare Research staff and 30–33 MAF employees at any time.

There are three key functional programmes that occur in the Landcare Research building. Laboratories built to PC1 and PC2 containment specifications (AS/NZS 2243.3:2002) occupy 1,225 m^2 (29%) of the building. Archival collections of arthropods (nearly 6 million specimens), plant microorganisms, and fungi (nearly 1 million specimens) are housed on-site and these archival spaces occupy 668 m^2 (16%). Finally, office space for employees occupies 907 m^2 (22%). The remaining 1,391 m^2 of floor area is used for circulation spaces and communal servicing (including toilets, mechanical plant, cafeteria, kitchen, etc.).

The demonstration of more ecologically sustainable principles relative to conventional building practice was a key objective in the design of the Landcare Research building (Vale et al. 2006). Energy conservation was a primary goal, along with more sustainable attempts at integrated urban water management, materials selection, and a healthy indoor environment. The key constraints during the design and procurement process were financial and temporal: the building had to be built within a financial target of no more than NZ$2,000 per square metre (roughly equivalent to the average cost of contemporary commercial office construction in Auckland) and had to be occupied before the end of the 2003/2004 financial year (June 2004). As a result of exemplar design within these constraints, the Landcare Research building and its design team (led by architects Chow:Hill and engineers Connell Mott MacDonald) have won many awards, including the EECA Energywise Commercial Building Award of Excellence (which recognises national excellence in energy-efficient design).

Monitoring the Landcare Research building's environmental and social performance in-use has been a priority since construction. Vale et al. (2006) provided an initial overview of the operational energy and water consumption, including appropriate benchmarks. Trowsdale et al. (2007) discussed the highly successful natural water management results in detail. Gabe et al. (2007) reported on 3 years of employee satisfaction surveys, as well as a qualitative video voice project, to conclude that employees were more satisfied with the building's passive and unique features relative to its more conventional spaces. This study aims to provide a detailed investigation of the building's operational energy consumption.

Energy Modelling

The Landcare Research building has won its awards for energy efficiency based on initial design simulations. The simulation used E-20 modelling software and the assumptions prescribed for office buildings in NZS 4243:1996 – the building code for energy-efficient large buildings. Simulation results indicated that, including internal plug loads (defined in NZS 4243:1996), the building would operate at an energy intensity of 99 kWh/m^2/year. This represents approximately 60% less operational energy consumption than conventional construction (Vale et al. 2006).

The modelled building was based on preliminary concept plans, not the final design. This occurred because of the procurement process used to lower capital costs and construct the building quickly. As part of that process, construction contractors began working on-site before detailed design drawings were complete and worked with the design team to complete the detailed design based on the client's key constraints as construction progressed. Noteworthy changes in the transition between preliminary and detailed design that may have affected energy simulation outputs included the removal of an atrium roof that was meant to assist passive ventilation; downgrading double-glazed windows to less expensive models without low emissivity glazing and thermal breaks; and modifications to the automated Building Management System (BMS) as a result of the controls contractor going into receivership during construction. The energy simulation was never run on the as-built design.

Energy Conservation Strategy

The building design used two principal strategies to achieve 99 kWh/m^2/year. First, it attempted to maximise passive climate control via northern orientation and best-practice building envelope construction: superinsulation (R4 batts in external wall construction and R5 in the ceilings), exposed thermal mass (concrete structural elements and uncarpeted concrete floor construction), and operable double-glazing in occupied spaces (where allowed). Second, a complex suite of four separate mechanical space-conditioning and ventilation strategies that target only the spaces that require particular levels of servicing were designed to meet the diverse space conditioning needs. These incorporated:

- Two "Eco-air" package units that supply tempered air (which aims to keep serviced areas between 18 and 25°C) and negative pressure to laboratories that must meet standards to avoid contaminant egress (AS/NZS 2243.3:2002). All extracted air (mostly through fume cupboards, to avoid excess withdrawal) exchanges heat with incoming air.
- One air handling unit that maintains all archival collection spaces at a very strict temperature of 17°C with 50% or lower relative humidity (dehumidification is obtained

via an electrical chilled water system that cools incoming air to approximately 6°C and reheats the air using waste heat from the chiller).

- One reverse-cycle heat pump servicing eight separate rooms that must be kept to strict temperature requirements.
- A heat-recovery (with supplementary gas) system that supplies waste heat from refrigeration compressors to passively ventilated offices via hot water in radiating coils.

In general, waste heat recovery and heat exchange are the key features that make the installed mechanical ventilation plant more efficient than conventional plant. Control of these mechanical features is remotely automated through BMS software.

Other energy conserving strategies included maximising passive daylighting with shallow-plan depths and an open atrium that ensures all offices have access to daylight and natural ventilation. All artificial lighting is provided by 28-W fluorescent tubes (2 per ballast) controlled by manual switches located adjacent to the area being serviced. Hot water used in laboratory, restroom, and kitchen fixtures is supplied using two flat-plate solar collectors with natural gas backup.

Energy Monitoring Programme

Monitoring the energy performance of the Landcare Research building in operation involves a low-cost system of metering energy consumption. The building is mostly all-electric, with a reticulated natural gas supply that is used both in the laboratories and as a supplementary backup for the solar water heating panels. Electric sub-meters were installed on each switchboard, which divides the three-story building's electricity consumption into seven geographical areas: two for lighting and plug loads on the ground floor; two for lighting and plug loads on the first floor; one for lighting and plug loads on the second floor; one for the roof mechanical plant; and (by subtraction from the building's main meter) the building's lift/elevator. Readings for all submeters and the building's main meter are recorded remotely every hour via magnetic pulse. Readings began on 26 October 2006. Gas consumption is read manually off the site meter each week.

Energy Performance Benchmarks

Because of the relatively unusual mix of laboratories, archives, and offices in the Landcare Research building, Vale et al. (2006) researched benchmarks that could meaningfully put its performance into the appropriate context. Compiling data from Australian Commonwealth building averages for offices (256 kWh/m^2/year), archives (194 kWh/m^2/year), and laboratories (291 kWh/m^2/year), Vale et al. (2006) calculated that average performance of a "conventional" Landcare Research building would be 1,077,300 kWh/year, or 257 kWh/m^2/year.

Landcare Research operates a number of other buildings throughout New Zealand and two of these, its Palmerston North building and the Fleming building in Lincoln, contain both laboratory and office spaces. These buildings were designed without any specific brief for energy efficiency. The 2,845 m^2 Palmerston North building uses 170 kWh/m^2/year (as of May 2007), and the 2,570 m^2 Fleming building, built during the mid-1990s, consumes 171 kWh/m^2/year (as of June 2007). Many mixed office-laboratories striving for energy efficiency in the United States have also reported on their measured energy performance (US Dept. of Energy, 2008). The 16,400-m^2 Pharmacia Corporation's LEED-Gold Building Q in Skokie, Illinois, consumed 417 kWh/m^2/year in 2001. The 6,130-m^2 Georgia Public Health Laboratory in Decatur, Georgia, consumed 1,130 kWh/m^2/year in 2004. Finally, the 6,680-m^2 LEED-Gold US Environmental Protection Agency Region 7 Science and Technology Centre in Kansas City, Kansas, consumed 855 kWh/m^2/year between 2003 and 2005.

Monitoring Results

Energy consumption monitoring reveals that the Landcare Research building, as a whole, is using approximately double the amount of energy that design simulations initially predicted, though it continues to outperform the benchmark calculated by Vale et al. (2006) as well as similar buildings in the United States. With nearly two years of consumption data, Figure 1 presents a running daily calculation of its annual energy consumption intensity since 26 October 2007 – the first day that annual energy data is available. Annual energy consumption continues to climb as each day's energy consumption is typically higher than one year previously (regular "dips" in Figure 1 are weekend days replacing weekdays). On 26 October 2007, the building had an annual energy consumption intensity of 197 kWh/m^2/year. This has increased 20 kWh/m^2/year, to 217 kWh/m^2/year, by 1 July 2008, the most recent date for which data are available. Table 1 lists these performance figures and the benchmarks discussed earlier.

Table 1. Energy Consumption of the Landcare Research Building and appropriate benchmarks

Building	**Location**	**Energy Use Intensity kWh/m^2/yr**	**% Labs**	**% Archives**	**% Offices**	**% Other**
Landcare Research Building (design simulation)	Auckland, NZ	99	29	16	22	33
Palmerston North Building	Palmerston North, NZ	170	n/a	n/a	n/a	n/a
Fleming Building	Lincoln, NZ	171	28	n/a	32	40
Landcare Research Building (Year ending 26 October 2007)	Auckland, NZ	197	29	16	22	33
Landcare Research Building (Year ending 1 July 2008)	Auckland, NZ	217	29	16	22	33
Conventional Landcare Research Building (hypothetical) [a]		**257**	**29**	**16**	**22**	**33**
Pharmacia Building Q (2001) [b]	Skokie, Illinois, USA	417	31	n/a	14	55
US EPA Region 7 Science/Technology Center [b]	Kansas City, Kansas, USA	855	40	n/a	60	
Georgia Public Health Laboratory [b]	Decatur, Georgia, USA	1130	53	n/a	21	27

Sources: [a] Vale et al. (2006) [b] US Dept. of Energy (2008)

The increase in Figure 1 is entirely electricity consumption. Annual gas consumption has steadily declined, from 20.26 kWh/m^2/year for the year ending 26 October 2007 to 18.65 kWh/m^2/year for the year ending 1 July 2008 – 10.2% and 8.6% of total energy consumption respectively.

To investigate the electricity increase, the building's electricity consumption was divided into two uses: baseload and operational. Baseload is the electricity consumed by sources that operate 24 hours per day, calculated as the average electric load between the hours of 22:00 the previous night and 05:00 in the morning. Operational electricity is the excess consumed during the day, and is calculated as the difference between the daily metered electricity consumption and electricity consumption from 24 hours of the calculated baseload. The breakdown between gas, operational electricity and baseload electricity consumption is provided in Table 2. Clearly, the rise is from increasing baseload electricity consumption.

Table 2. Energy Consumption Breakdown of the Landcare Research Building (all units in kWh/m^2/yr)

Year Ending	Total Energy Use Intensity	Gas	Baseload Electricity	Operational Electricity
26 October 2007	197	20	114	63
1 July 2008	217	19	135	63

Figure 2 shows a bar graph of daily baseload power in units of kilowatts (kW). Three key dates show sudden events that are likely explanations for the increasing baseload electricity consumption. An investigation of the seven electrical submeters was carried out to determine where this baseload increase occurred. Baseload increases in two geographical areas – the ground floor space occupied by MAF tenants (Figure 3) and the roof plant (Figure 4) – can account for almost all of the 20 kWh/m^2/year increase seen in Figure 1. Discussions with the building manager were able to ascertain what caused these increases.

On 15 May 2007, an electron microscope used by MAF was not responding well to being powered off and on, and its managers decided to default the machine to "on". This caused the approximate 5-kW increase in baseload evident in Figure 3. This event accounted for approximately 25% (5 kWh/m^2/year) of the entire building's increasing energy unit intensity.

The increase in baseload seen in the mechanical plant submeter (Figure 4) explains another 13 kWh/m^2/year (65%) of the increase during this period. On 18 January 2008, following complaints of overheating, a management decision was made to run the Eco-air package units constantly between midnight on Monday mornings to 18:00 on Friday afternoons as a way of increasing cooling loads. This began the obvious increase in weekday baseload seen in Figure 4. BMS control settings for the Eco-air units were scaled back to run only 16 hours per weekday (06:00 to 22:00) on 27 February 2008 and then reset to their pre-18 January state (running 06:00 to 18:00) on 6 March 2008. Weekend settings remained constant throughout (running 06:00 to 18:00).

Despite returning to identical BMS settings, the weekday baseload of the roof plant after 27 February remains 10–20 kW above the weekday baseload before 18 January. The reason for this remains unclear, but there is some evidence that either a sensor or unit that was reset in the process is now operating differently than from before.

Discussion

The Landcare Research building is an example of a "high process energy" building consuming double the amount of energy initially simulated (Turner and Frankel 2008). In this case, most of the difference can be explained by an increase in baseload approximately 4 times as large as simulated values. Increased operating hours do not appear to contribute. Since monitoring began, there remains an observed gradual increase in annual energy consumption as a result of two sudden baseload increases; both from management decisions to run services continuously.

An out-of-control baseload

Modelling results suggested the building would only consume 2 kWh/m^2/month (24 kWh/m^2/year) at night and on weekends. As a baseload, this equates to 11.7 kW. The observed

Figure 1. Trend of annual energy consumption intensity for the entire Landcare Research building

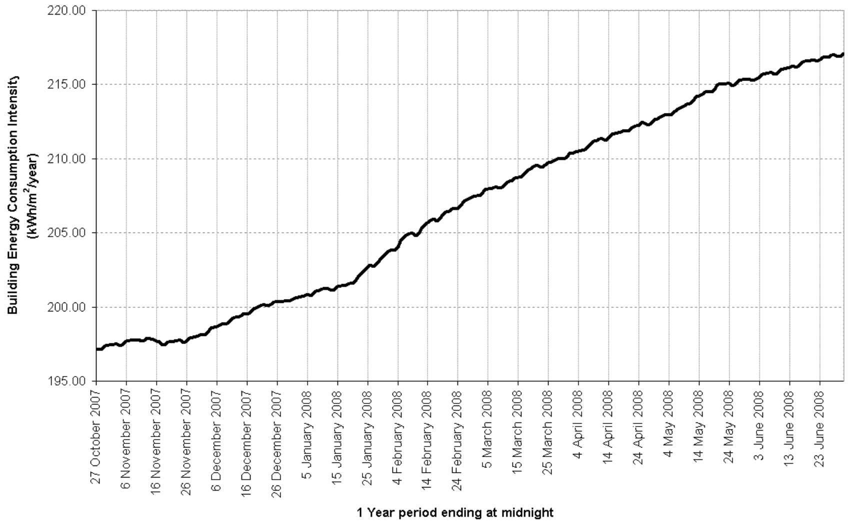


Figure 2. Daily baseload power for the entire Landcare Research building

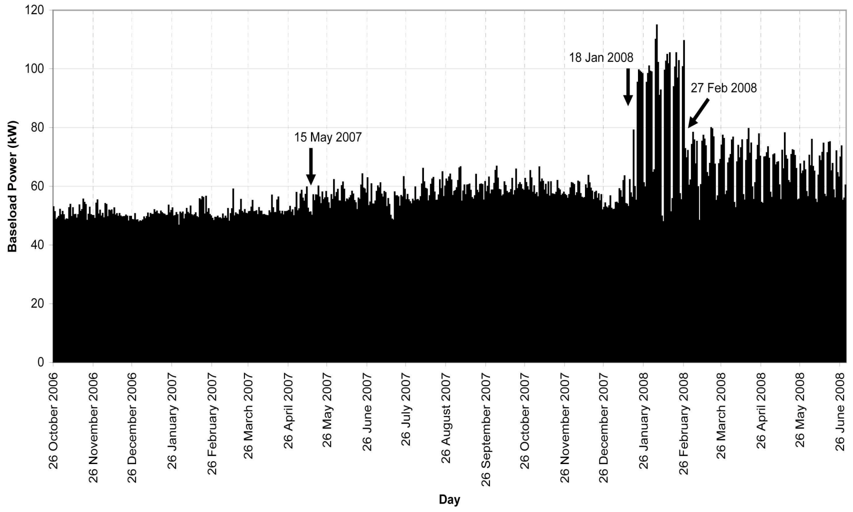


Figure 3. Daily baseload power for plug loads and lighting in MAF tenant offices and laboratories

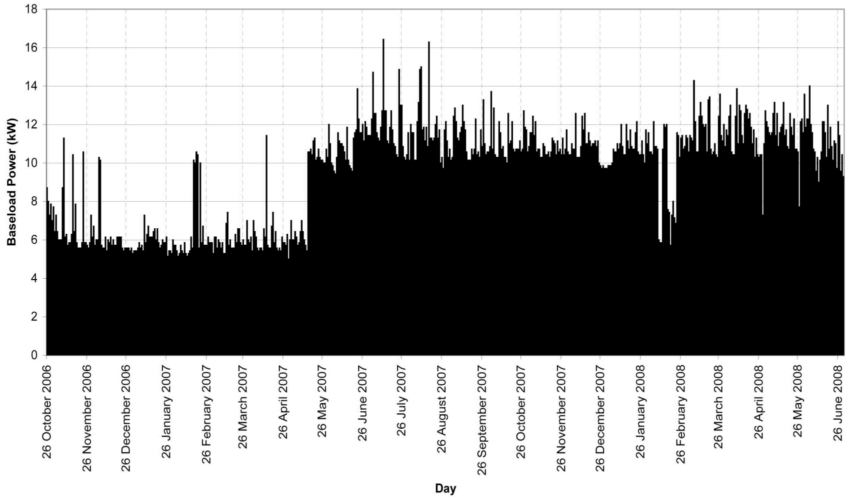
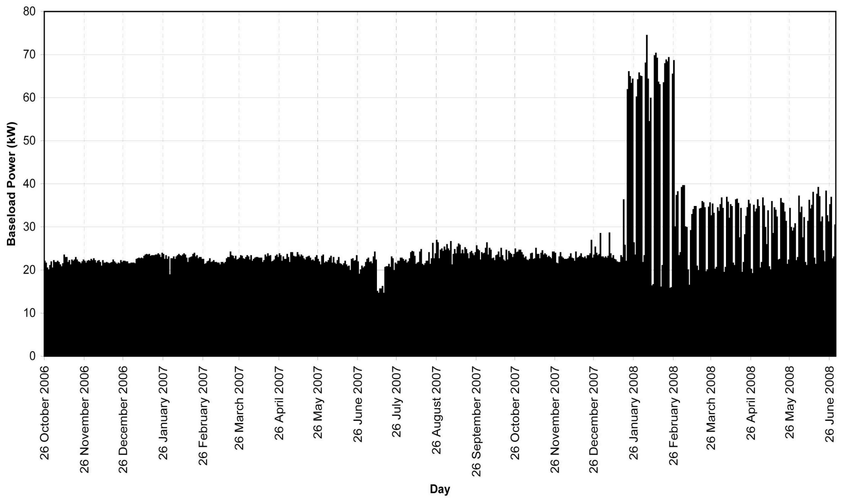


Figure 4. Daily baseload power for the roof mechanical plant in the Landcare Research building



baseload (before 17 May 2007[1]) was approximately 50 kW (Figure 2). This inflated baseload is responsible for much of the gap between the energy simulation and the building's actual operational consumption. In the Landcare Research building, a baseload increase of 40 kW would lead to an approximately 80 kWh/m^2/year increase in energy consumption intensity, or most of the approximately 100 kWh/m^2/year gap. The actual contribution to the gap would be slightly less under the assumption that some of the observed baseload consists of operational loads that run continuously.

One key cause is a modelling underestimation of continuous plug loads. Unlike office buildings, the Landcare Research building features intensive continuous loads such as large freezers that cool to minus 80°C. While the lack of distinct seasonal variations may suggest that these types of large continuous plug loads are indeed the main contributor, the electricity submeters show that plug loads are, at most, only 50–60% (25–30 kW) of the observed baseload.

The mechanical plant makes up the remainder of the baseload, with a pre-17 May 2007 baseload around 21–25 kW (Figure 4). This is approximately double the modelling prediction of 11.7 kW for the whole building. With a lack of submetering on each system, it is not known exactly what is causing this increase and a detailed audit of the building's mechanical plant baseload is needed to determine exactly why the roof plant baseload is much higher than anticipated. The signs of an uncontrollable building, such as the inability to control weekday baseload after 27 February 2008, may hint that automated controls are not functioning as designed.

The impact of working on weekends

Another potential explanation for a portion of the gap between simulated and actual energy consumption is that the model underestimated the hours of building operation. Without explicit guidance from the client, the building's energy consumption was modelled according to standard operating hours specified in NZS 4243:1996, which assumes operation 11 hours per day, 5 days per week. Following occupation, the tenant required weekend laboratory operation (meaning all laboratories had to be turned "on" as they cannot be separated) and flexible work schedules led to 12-hour daily operation, thus the actual hours of full operation increased by 29 hours per week, or 52% greater than the model assumption. While it is tempting to blame this extension in operating hours for approximately half the observed increase, monitoring shows that operating energy consumption is reasonably in-line with the model, even with the extended operating hours. If all gas consumption is considered operational, the building's operational energy use intensity (which includes weekends), has remained constant at approximately 83 kWh/m^2/year (Table 2). Modelling simulations predicted that operating intensity would seasonally vary between 4 and 8 kWh/m^2/month (with baseload removed), or 48 and 96 kWh/m^2/year, reasonably in-line with observed results. Thus, the baseload increase contributes much more to the overall energy consumption gap than an increase in operating hours. However, this balance would shift if it is shown that the baseload increase is due to operating loads being left running continuously.

Designing buildings to be managed by humans, not computers

Examination as to why the building is systematically increasing its energy use intensity revealed the direct cause to be two management decisions that set equipment to run continuously when

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[1] As specific management decisions were shown to be responsible for increases after 17 May 2007, this analysis will focus on the data before this date.

faced with occupant complaints or equipment failure. This phenomenon is not unique to the Landcare Research building. Bordass et al. (2001) argue that defaulting systems to “on” (whether intentional or not) is one of the “most common characteristics” of Probe buildings that used more energy than intended. It is tempting for designers to use this as a clear example of poor building management. However, it is more instructive to look deeper at the two incidents, which may suggest methods that could help design more manageable energy-efficient buildings.

First, “poor” management decisions that default equipment to continuous operation can be justified as “economically rational” decisionmaking within complex systems. The decision to leave a 5-kW electron microscope continuously running may represent how managers knowingly trade energy efficiency for a low-cost “solution” to a complex problem. Diagnosing faults and fixing (or replacing) a specialist electron microscope may be especially expensive or disruptive. As a result, the cost of addressing the problem could cost more than the approximately NZ$12,000 per year (at current electricity rates) spent on the “solution” to leave it permanently on, so the manager makes an economically rational decision to avoid the complex problem.

Second, the complexity added by BMS systems that aim to optimise building services operations through a network of environmental sensors may produce energy wastage when building mangers make seemingly logical decisions to address complaints. In continuously running the Eco-air unit to increase cooling loads, the building manager understandably addressed a problem within the context in which it was presented: overheating rooms during one of the hottest periods of the year. Logically, it was decided that the solution was to increase cooling loads.

However, upon extensive review of data logs from the BMS, the overheating problem is likely to have begun 5 days earlier, as a result of a brief 10-minute power cut at midnight on 14 January. Only weekday operating schedules had been altered on the afternoon of Friday 18 January, but temperature data show that the laboratories cooled back to their normal state over that first weekend. Therefore, it seems most likely that the act of adjusting the schedule reset a sensor or unit that had not functioned properly following the brief power cut. Occupants were satisfied with cooler laboratory temperatures that following week, so the building manager received immediate feedback that her solution of 24-hour cooling on weekdays was likely responsible for the improvement. It was not until data from the building’s temperature monitoring system was analysed a month later that the waste of electricity became apparent and the BMS was reset back to its previous state. Restarting the computer may have been the low-cost solution to this problem, but, unless the BMS was programmed to recognise this specific malfunction (the system reported normal operation at the time), the manager is not likely to see a computer restart as a logical solution when faced with complaints of overheating in high summer

These two incidents build on the observation of Bordass and Leaman (1997) that the designer-client conspiracy striving to maximise “fit and forget” has shifted tasks once handled by human managers to computers. The complexity that results inevitably continues to be managed by humans, hence Bordass and Leaman describe the reality as “fit and manage the consequences”. In the Landcare Research building, construction alterations to meet financial or temporal constraints have shown how the initial design conspiracy fell apart in practice, leaving building managers to manage the consequences. These two examples suggest managers are looking for quick, low-cost, and logical solutions to problems with building services. Recognising this may assist designers of energy-efficient building services to design systems that better integrate with the way operational building management decisions are made. As Table 1 showed, older and much less complex buildings, such as the Fleming Building in Lincoln and the Palmerston North building, can be more energy-efficient than highly-automated and complex buildings such as the Landcare Research building. Staff satisfaction surveys have shown that building occupants in the Landcare Research building prefer simple, passively designed, areas where ventilation is controlled by opening windows and lighting is controlled using window blinds and a light switch (Gabe et al. 2007). As these parts of the building use almost no energy (some use between zero and $3.5W/m^2$ at peak hours), there is great potential for improving energy efficiency through optimising occupant-friendly passive design as opposed to optimising soon-to-be-unmanageable complexity.

Conclusion

Empirical monitoring of the award-winning energy efficient Landcare Research building in Auckland, New Zealand, showed that, although it is still outperforming benchmarks for average buildings of its type, it is using twice as much energy than was predicted in design simulations. Although energy modelling underestimated the continuous plug loads that were needed in this specialist building, the rest of the increase is likely to be due to an inability to control and manage a complex suite of building services that is then reflected in a further increase in baseload over design expectations. This suggests there is great potential to deliver energy-efficient commercial buildings by better integrating design and simple, human-focused, operational building management, as opposed to the "fantasy" of fit-and-forget automation.

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