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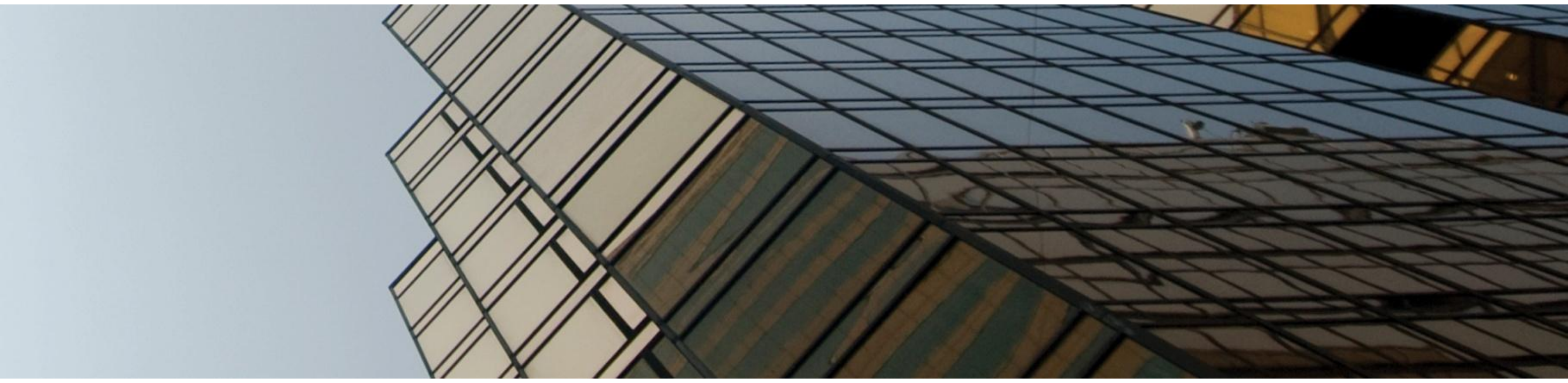

STUDY REPORT SR 260/3 [2011]

BEES INTERIM REPORT

Building energy end-use study - Year 4

DELIVERED DAYLIGHTING

Rob Bishop, Michael Camilleri & Nigel Isaacs

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BEES (BUILDING END-USE STUDY) YEAR 4: DELIVERED DAYLIGHTING

BRANZ Study Report SR 260/3

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Reference

Bishop, R., Camilleri, M & Isaacs, N. (2011). BEES (Building energy end-use study) Year 4: Delivered daylighting, BRANZ study report 260/3, Judgeford.

BEES publications can be downloaded from the BEES website - http://www.branz.co.nz/bees

Following is a list of other reports in the BEES Year 4 series:

- Saville-Smith, K. (2011). BEES (Building energy end-use study) Year 4: Insight into barriers, BRANZ study report 260/1, Judgeford.
- Camilleri, M., & Babylon, W.M (2011). BEES (Building energy end-use study) Year 4: Detailed monitoring, BRANZ study report 260/2, Judgeford.
- Bishop, R., Camilleri, M & Isaacs, N. (2011). BEES (Building energy end-use study) Year 4: Achieved conditions, BRANZ study report 260/4, Judgeford.
- Bishop, R., Camilleri, M. & Burrough, L. (2011). BEES (Building energy end-use study) Year 4: Temperature Control, BRANZ study report 260/5, Judgeford.
- Bishop, R. (2011). BEES (Building energy end-use study) Year 4: Electrical loads, BRANZ study report 260/6, Judgeford.
- Isaacs, N. (2011). BEES (Building energy end-use study) Year 4: From Warehouses to Shops - Changing Uses in the Non-residential Buildings Sector, BRANZ study report 260/7, Judgeford.

PREFACE

Understanding how energy and water resources are used in non-residential buildings is key to improving the energy and water efficiency of New Zealand's building stock. More efficient buildings will help reduce greenhouse gas emissions and enhance business competitiveness. The Building Energy End-use Study (BEES) is taking the first step towards this by establishing where and how energy and water resources are used in non-residential buildings and what factors drive the use of these resources.

The BEES study started in 2007 and will run for six years, gathering information on energy and water use through carrying out surveys and monitoring non-residential buildings. By analysing the information gathered, BEES aims to answer eight key research questions about resource use in buildings:

1. What is the aggregate energy and water use of non-residential buildings in New Zealand?
2. What is the average energy and water use per unit area per year?
3. What characterises the buildings that use the most energy and water?
4. What is the average energy use per unit area for different categories of building use?
5. What are the distributions of energy and water use?
6. What are the determinants of water and energy-use patterns e.g. structure, form, function, occupancy, building management etc?
7. Where are the critical intervention points to improve resource use efficiency?
8. What are the likely future changes as the building stock type and distribution change?

Understanding the importance and interaction of users, owners and those who service non-residential buildings is also an important component of the study.

For the BEES study, non-residential buildings have been defined using categories in the New Zealand Building Code, but in general terms the study is mainly looking at commercial office and retail buildings. These vary from small corner store dairies to large multi-storey office buildings. For more information on the building types included in the study please refer to BRANZ report SR224 Building Energy End-use Study (BEES) Years 1 & 2 (2009) available on the BEES website (www.branz.co.nz/BEES).

The study has two main methods of data collection – a high level survey of buildings and businesses, and intensive detailed monitoring of individual premises.

The high level survey initially involved collecting data about a large number of buildings. From this large sample, a smaller survey of businesses within buildings was carried out which included a phone survey, and collecting records of energy and water use and data on floor areas. The information will enable a picture to be built up of the total and average energy and water use in non-residential buildings, the intensity of this use and resources used by different categories of building use, answering research questions one to four.

The detailed monitoring of individual premises involves energy and indoor condition monitoring, occupant questionnaires and a number of audits, including: appliances, lighting, building, hot water, water, and equipment.

This report presents data and analysis drawn from the detailed monitoring carried out during the fourth year of this six year study. This report looks at measured data of lighting levels in non-residential spaces. This is of value as it shows there a large potential for energy savings through controlling the timing and amount of lighting in these spaces. The data and analysis in this report contributes to answering research questions three and six. This is one of seven interim reports giving a snapshot of analysis completed to date. When all data collection has been completed further analysis will be reported on with the full sample including relationships between end-uses, building types and services.

At this stage of the project, not all the data we need to fully answer the research questions is available. This report only provides analysis and results on buildings less than 9,000 m^2 (size strata 1-4 of the BEES sample). It does not cover the full range of buildings sizes, so these results are not representative of the non-residential building stock. In the remaining two years of the BEES study, further analysis will be carried out using the full sample which will include buildings greater than 9,000 m^2. Further work that is planned on lighting includes looking at daylighting potential varying by building size and use and developing methods to automatically generate data showing daylighting potential so then building owners can easily see the savings available.

SUMMARY

- The BEES study has so far has found about 10% of spaces within non-residential buildings have sufficient access to daylighting to meet daytime lighting needs for that space. A further 25% have a level of daylighting that meets the daytime lighting needs at least half of the time.
- For these spaces, the use of lighting controls that turned lights on and off when needed according to the amount of daylight would be an effective energy efficiency measure.
- At this stage of the project the daylighting profiles analysed so far have been for buildings with a total floor area less than 9,000 m^2.

This research, undertaken as part of the Building Energy End-Use Study (BEES) has analysed the daylighting potential of the first 200 spaces within buildings measured from 2009-2011.

The results of the individual analysis of each space have been combined to produce the graph below that indicates the estimated average amount of daylight (as a fraction of the typically supplied electric luminance) for each of the spaces during weekday core occupancy hours of 10am – 4pm.

The vertical axis shows the estimated average amount of daylight supplied during these hours, as a ratio of the estimated electric illuminance in the space, i.e. the amount of illuminance needed. The horizontal axis shows the fraction of the spaces with this much or less daylight. (That is, the spaces are ordered in terms of increasing daylight fraction).

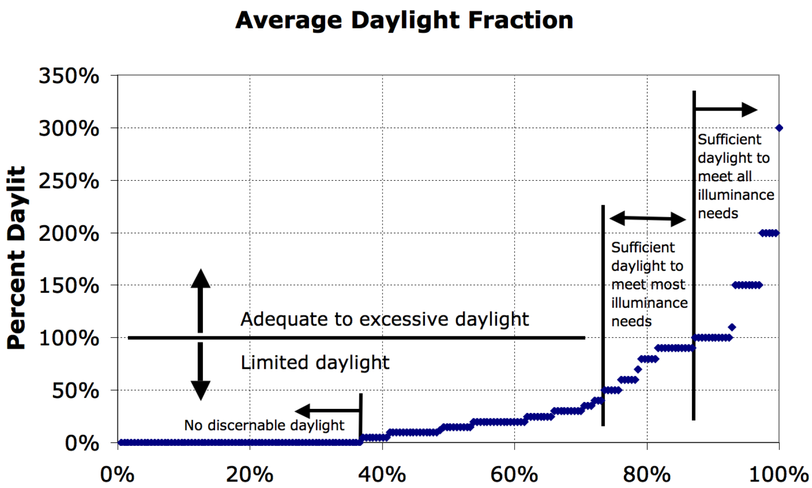

Figure 1. Average Daylight Fractions

This shows that about one-tenth of spaces received daylight illuminance greater than or equal to their delivered electrical illuminance, or sufficient daylight to meet all illuminance needs, on average. About a quarter received daylight illuminance on average equal to half or greater of their electrical illuminance level. These are the types of spaces that could practically deploy electrical lighting controls to substitute daylight for electrical lighting.

About one-third of the spaces received no discernable daylight, and the balance of spaces received some, but less than half the daylight as they had electrical illuminance.

Further analysis showed the top one-third of spaces recording maximum daylight illuminance of at least the intensity of their electric lighting. Again, these are the types of spaces where daylighting controls would be effective in supplanting electrical lighting for a significant fraction of the time.

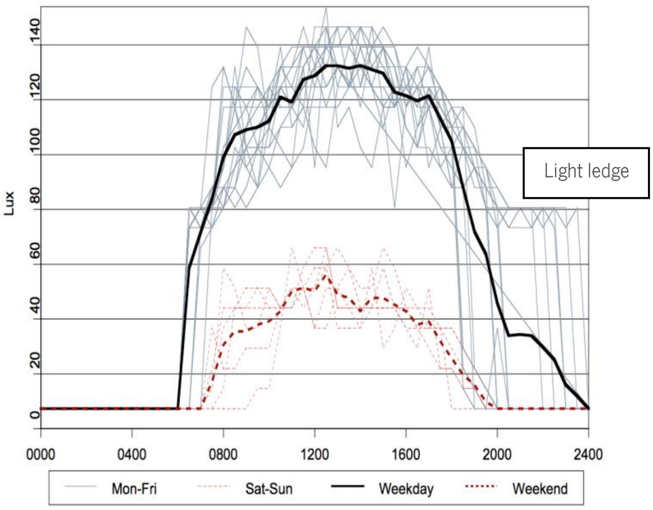

Figure 2. Load shape showing a distinctive ledge

The data used for this analysis was collected within the detailed monitoring component of BEES. The data loggers used to record illuminance levels recorded the lux incident on the logger's surface usually every fifteen minutes during the time that the loggers were in place. For ease of analysis, each resulting time series was converted to a recurring 24-hour load profile which was presented graphically for visual inspection and analysis.

Each load profile graph was visually examined to determine how much of the recorded illuminance appeared to be from natural daylight, and how much from electric lighting. The percentage of daylight (as a function of electric illuminance in the space) was estimated, both on average for weekdays over the period 10am and 4pm, and at the peak. Also, the reliability of each daylight estimate was itself estimated, on a scale of 1 to 10.

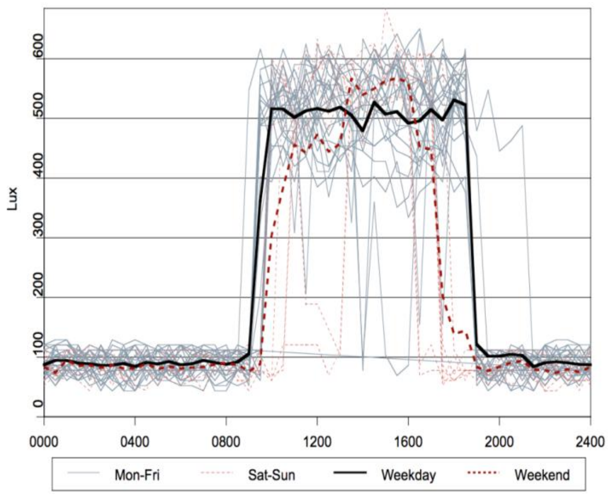

Figure 3. Square-wave load shape – showing lack of daylight

In the highest reliability illuminance profiles, there was a visible "ledge" of illuminance, where the observed illuminance stayed at a relatively constant value. When the ledge occurred during hours when daylight was not available, it was taken as a good measure of the illuminance available in the space from electric lighting only, and gave a reference illuminance to compare to daylight, e.g. Figure 1.

Spaces that receive most or all of their illuminance from electric lighting will have a relatively "flat" or "square wave" load profile, for the hours that the lights are operating. An example of this is shown in Figure 2. As can be seen, this graph shows illuminance values in the range of 450 – 600 lux between about 9am and 7pm each day, with 60-110 lux recorded at all other times. The observed variation in recorded illuminance over the course of the day could be caused by (1) variations in the output of electric lights as voltage varies, (2) the effects of nearby lights that are being switched on and off, and (3) a small amount of daylight.

The other extreme of load-shape is a space with significant daylight, which usually has a rounded, humped shape, with higher illuminance in the middle of the day (when most daylight is usually available) than at either end. An example of this load shape is shown in Figure 4.

This specific space was estimated to have a weekday daytime average lux of 375, with an evening ledge of 250 lux, so the average daylight contribution was 50% (300% at peak), with a reliability of 8.

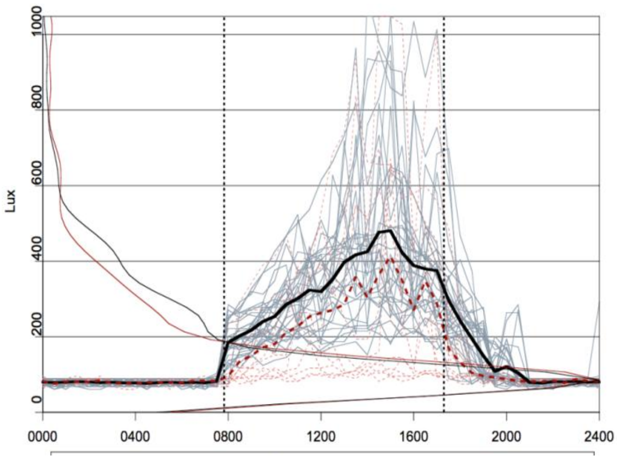

Figure 4. Rounded load shape – showing abundant daylight

Analysis of the reliability of the data showed three-quarters of the data sets were rated "5" or higher and one-third were rated "8" or higher. This indicates that most of the analysis in this report is considered to be reliable.

It must be noted that the illuminance data analysed covered the first two hundred illuminance data sets generated by BEES. Because the initial monitoring concentrated on smaller buildings, these results cannot necessarily be extrapolated to all New Zealand buildings. In the coming years, the data will be updated to include buildings greater than 9,000 m^2 and further analyses will be carried out to determine how the daylighting potential of spaces varied with building size, design and use.

CONTENTS

FIGURES

1. INTRODUCTION

This report shows the results of the analysis of the daylighting potential of the first 200 spaces within buildings measured as part of the Building Energy End-use Study (BEES) from 2009-2011. This report has been developed to present these data so that they are useful to the stakeholders in this study. The results show that:

- About one-quarter of the spaces measured had sufficient daylight so that automatic lighting controls could be cost-effective in reducing electrical energy use
- About one-tenth of the spaces had sufficient daylight illuminance so that electric lighting could generally be turned off during the peak hours of most weekdays.

The illuminance (lux) in each space was recorded by the data loggers. The loggers also recorded temperature and relative humidity.

BEES is an study of overall energy use and delivered energy services in non-residential buildings, so sensors were not specifically placed to measure daylight. The sensors were usually placed to measure the illuminance on typical work surfaces. Because daylighting is only one of many topics explored in the BEES, these sensors were not necessarily close to windows, nor were ambient [outdoor] illuminance sensors used.

This report does not attempt to quantify the overall lighting measured in the buildings; that is covered in another topic report, on the conditions measured in buildings.

One of the main intentions of this report was to analyse the first set of data to allow the development of an automated procedure for determining the amount of daylight received in spaces, as daylighting is such an effective technique to reduce the energy used for lighting non-residential buildings. Future work may include comparisons of actual measured to predicted (modelled) daylight in spaces.

The individual days' data (instead of data averaged over the monitoring period) were required to determine the illuminance variability during the logging period, which gives an indication of the daylighting potential.

For analysis, each space's data were plotted as a daily "illuminance profile", with the individual days shown (as lighter grey lines) separated into weekday and weekend days, the average illuminance for weekdays shown as a black line, and the average weekend illuminance shown as a dashed red line. Several examples are shown in this report (e.g. Figure 5).

2. ANALYSIS OF ILLUMINANCE DATA TO DETERMINE DAYLIGHTING

The data loggers used to record illuminance levels recorded the lux incident on the logger's surface usually every fifteen minutes during the time that the loggers were in place. For ease of analysis, each resulting time series was converted to a recurring 24-hour load profile.

This load profile was presented graphically, with the illuminance for each weekday shown as a thin solid black line, for each weekend day as a thin dashed red line, the mean value for all weekdays as a thick solid black line, and the mean value for all weekend days as a thick dashed red line.

In some of the graphs, the frequency of occurrences of each lux reading was shown as contour lines adjacent to the vertical axis. Again, black was used to show the contour for weekdays, and red for weekend days.

Then, each load profile graph was visually examined to determine how much of the recorded illuminance appeared to be from natural daylight, and how much from electric lighting. The percent of daylight (as a function of electric illuminance in the space) was estimated, both on average for weekdays over the period 10am and 4pm, and at the peak. Also, the reliability of each daylight estimate was itself estimated, on a scale of 1 to 10.

In the most reliably analysed illuminance profiles, there was a visible "ledge" of illuminance, where the observed illuminance stayed at a relatively constant value. When the ledge occurred during hours when daylight was not available, it was taken as a good measure of the illuminance available in the space from electric lighting only, and gave a reference illuminance to compare the daylight to.

This pattern is shown in Figure 5, where illuminance of about 80 lux is measured after 8pm for several evenings. The vertical lines dropping down from the 80 lux "ledge" are indications of the electrical lights being switched off at different times between about 6pm and 11:30pm, after which the illuminance drops to the overnight minimum of about 10 lux.

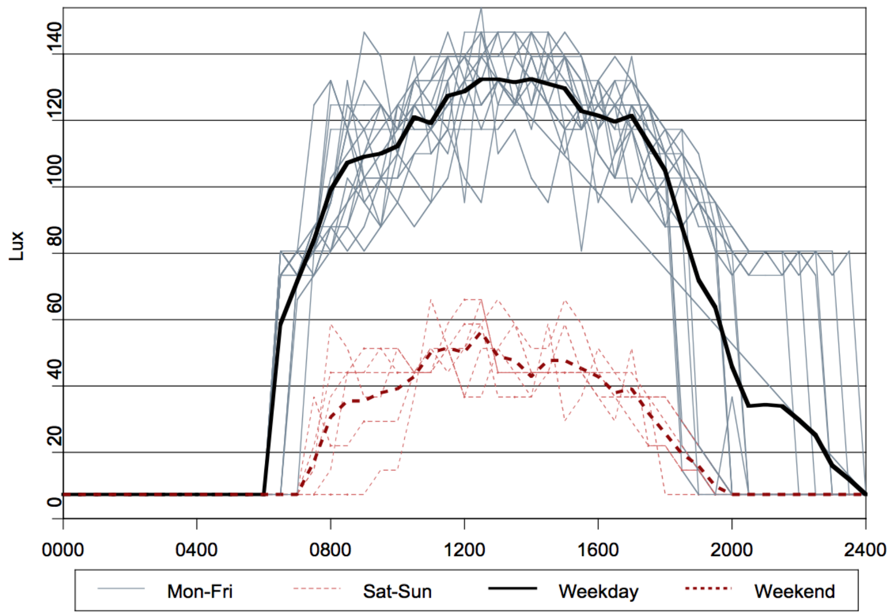

Figure 5. Load shape showing a distinctive ledge[1]

During weekdays, the average illuminance was about 120 lux, 50% higher than the ledge, so the average weekday daylight contribution was estimated as 50%. Similarly, on weekends, the illuminance was always below 75 lux, indicating that the electric lights were off. The average weekend daytime illuminance was about 40 lux, supporting the 50% (of 80 lux) daylight estimate. The highest recorded illuminance was about 145 lux, or 80% higher than the "ledge", so the peak daylight contribution was taken as 80%.

Because of the distinct "ledge" and the repeatability of the amounts of apparent daylight on weekdays and weekend days, the reliability of this load profile was taken as "9", or very high.

A more typical load profile is shown in Figure 6, which is slightly more difficult to interpret.

[1] Figure 1 shows the load profile for R0054AA1 Office 2a

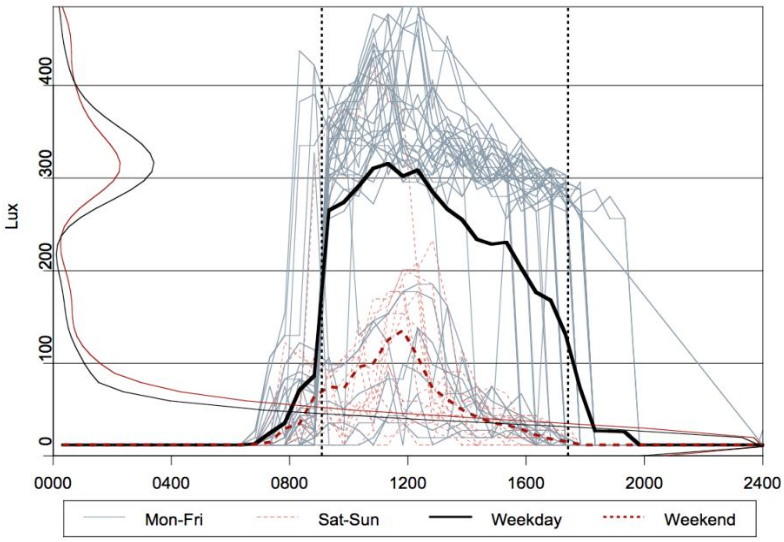

Figure 6. Morning – daylit load shape[2]

The profile in Figure 6 shows that the most common illuminance is at about 310 lux, shown by the contours on the vertical axis. Also, there is an evening illuminance "ledge" observed at about 270 lux, at a time when daylight would not be expected (8pm in September).

The largest variation in weekday illuminance is between 8am and 2pm, indicating that daylight is most available at that time. Individual weekdays show an illuminance profile close to a square wave in the afternoon, showing no daylight at that time, except for the variability in the time the electric light was switched off (shown by the near-vertical grey lines). This causes the downward-sloping average weekday load profile.

Also, on several weekdays the daytime illumination is under 200 lux, less than the electric lighting seems to provide. This causes the average illuminance to be lower than most individual days.

Because most weekdays there was regular illuminance of about 100 lux above the level of the 270 lux "ledge", and on weekends about 100 lux in total. In this case, the average daylight was taken as 35% of the electric lighting level, with the maximum as 120% (one weekend day showed an illuminance of 350 lux).

These features combined to make the perceived reliability of this analysis to be "8".

Spaces that receive most or all of their illuminance from electric lighting will have a relatively "flat" or "square wave" load profile, for the hours that the lights are operating. An example of this is shown in Figure 7.

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[2] Figure 2 shows the load profile for R0433AB1 Office 3a

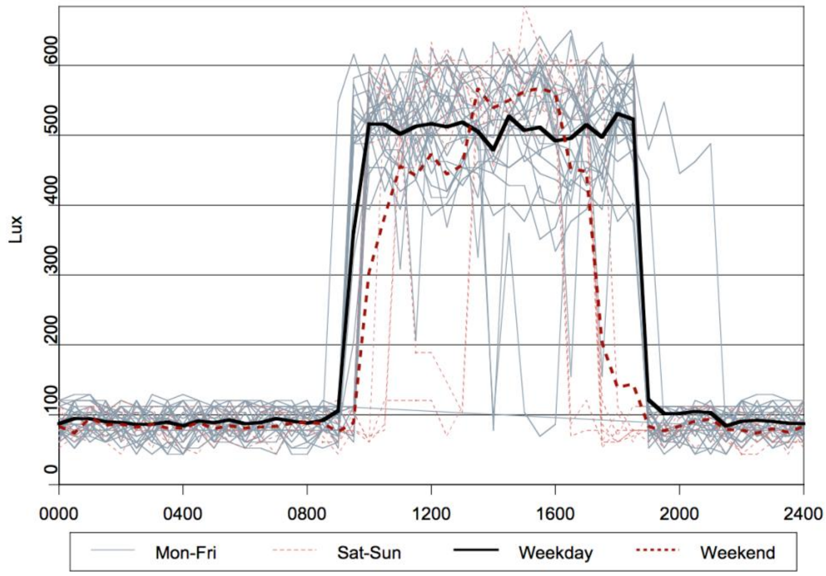

Figure 7. Square-wave load shape – showing lack of daylight

As can be seen, this graph shows illuminance values in the range of 450 – 600 lux between about 9am and 7pm each day, with 60-110 lux recorded at all other times. The observed variation in recorded illuminance over the course of the day could be caused by:

- variations in the output of electric lights as voltage varies,
- the effects of nearby lights that are being switched on and off, and
- a small amount of daylight.

The space in Figure 7 was estimated to have a daylight contribution of zero, with a reliability of 5. The reliability of this data set was lower due to the uncertainty of the cause of the mid day illuminance variation. The daylight contribution was taken as zero because of the flatness of the average weekday illuminance – from 9am until 6pm, the average illuminance varied by only ±5%.

The other extreme of load-shape is a space with significant daylight, which usually has a rounded, humped shape, with higher illuminance in the middle of the day (when most daylight is usually available) than at either end. An example of this load shape is shown in Figure 8. (The vertical dashed lines show the approximate start and stop times of the lighting.)

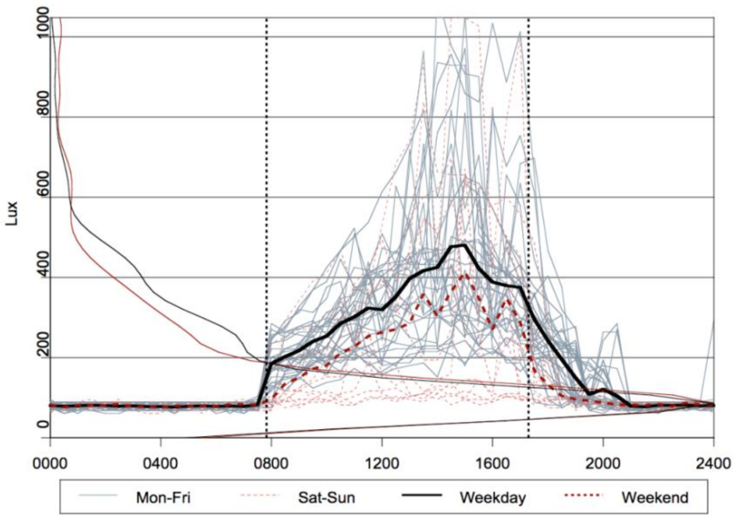

Figure 8. Rounded load shape – showing abundant daylight[3]

We can infer that this space is largely daylight lit by the huge reading-to-reading variation in lux levels (200 – 1000 lux). This is due to the natural variability of daylight availability as the weather varies, and usually results in a peak illuminance in the middle of the day, though the position of windows can alter this. (This space had its peak in the afternoon, probably due to west-facing windows.)

This space was estimated to have a weekday daytime average illuminance of 375 lux, with an evening ledge of 250 lux, so the average daylight contribution was 50% (300% at peak), with a reliability of 8.

All of the first two hundred illuminance data sets generated by BEES were analysed like this. The results were tabulated, and are summarised in the following sections.

[3] Figure 4 shows the load profile for R0471AA1 Reception 1a.

3. SUMMARY OF DAYLIGHTING POTENTIAL

This section generalises and summarises the results of the analysis of daylighting.

Figure 9 indicates the estimated average amount of daylight (as a fraction of the typically supplied electrical illuminance) for each of the spaces surveyed in the initial BEES space conditions monitoring.

The vertical axis shows the estimated average amount of daylight supplied on weekdays, as a ratio of the estimated electrical illuminance in the space. The horizontal axis shows the fraction of the spaces with this much or less daylight. (That is, the spaces are ordered in terms of increasing daylight fraction)

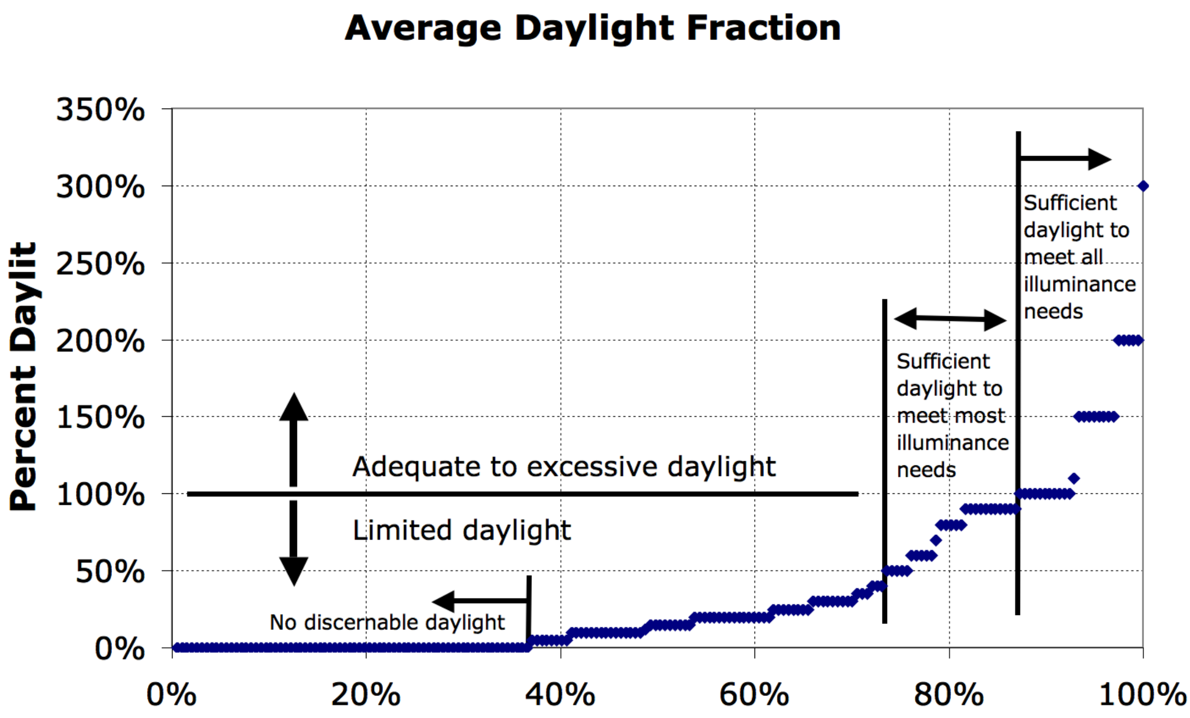

Figure 9. Average Daylight Fraction

This shows that about one-tenth of spaces received daylight illuminance greater than or equal to their delivered electrical illuminance, or sufficient daylight to meet all illuminance needs, on average.

About a quarter received daylight illuminance on average equal to half or greater of their electrical illuminance level. These are the types of spaces that could practically deploy electrical lighting controls to utilise daylight in place of electrical lighting.

About one-third of the spaces received no discernable daylight, and the balance of spaces received some, but less than half the daylight as they had electrical illuminance.

Figure 10 indicates the estimated maximum amount of daylight (as a fraction of the typically supplied electrical illuminance) for the same spaces.

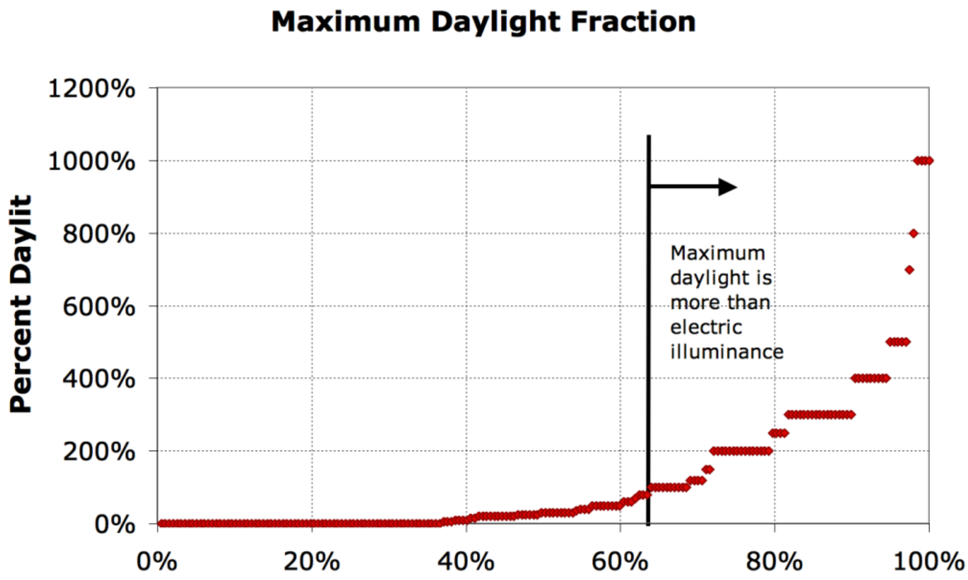

Figure 10. Maximum Daylight Fractions

As can be seen, the results are similar, with the top one-third of spaces recording maximum daylight illuminance of at least the intensity of their electric lighting. Again, these are the types of spaces where daylighting controls would be effective in supplementing electrical lighting for a significant fraction of the time.

Note that the order of the spaces in Figure 10 has altered somewhat from Figure 9, as the average and peak daylight fractions are not necessarily related.

Finally, the distribution of Reliabilities across the data set is shown in Figure 11.

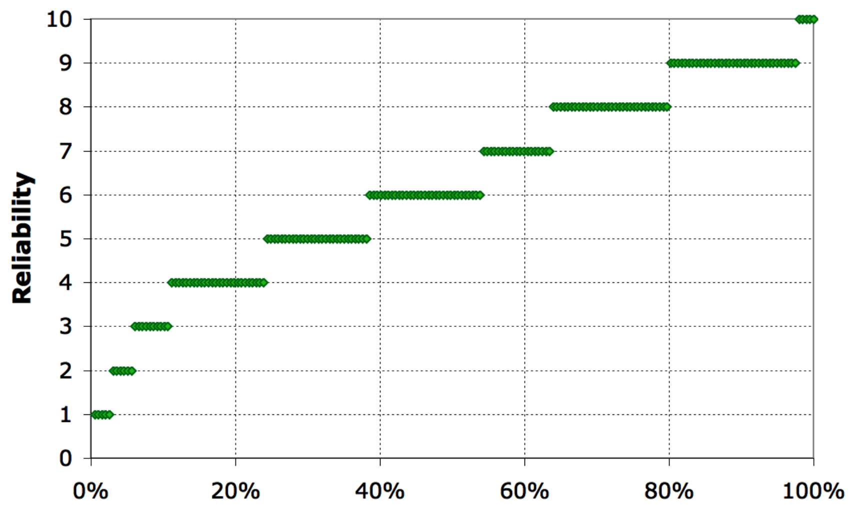

Figure 11. Distribution of Assessed Reliability of these data series

As can be seen, three-quarters of the data sets were rated “5” or higher. One-third were rated “8” or higher. This indicates that most of the analysis in this report is considered to be reliable.

It must be noted that the illuminance data analysed in this Topic Report covered the first two hundred illuminance data sets generated by BEES. Because the initial monitoring concentrated on smaller buildings, these results cannot necessarily be extrapolated to all New Zealand buildings.

In future years, it would be useful to determine how the daylighting potential of spaces varied with building size and use.

4. NEXT STEPS AND DISCUSSION

In future years, it would be useful to automatically perform this type of analysis on illuminance data, to determine the daylighting potential of spaces as a matter of course. Then the daylighting potential of each space could be quantified as part of the delivered energy services, in addition to the temperatures, humidity, etc.

Thus one purpose of this topic report was to understand the patterns that determine the daylighting potential of spaces, and to develop quantitative methods for automatically analysing illuminance data.

There are two (sometimes three) general indications that a space has a significant quantity of its illuminance supplied by natural daylight.

One is the shape of the space's average illuminance graph, over a 24-hour period. Those with significant daylight have a rounded, humped shape, with higher illuminance in the middle of the day (when most daylight is usually available) than at either end. An example of this load shape is shown in Figure 5 and Figure 6.

The other extreme load shape pattern is characteristic of spaces with only electric lighting, which tend to have "square wave" illuminance patterns over 24 hours, as the output from electric lights is generally constant. This was shown in Figure 7, earlier.

However, the wave shape is not a reliable indicator of daylight, as spaces that are intermittently occupied or have frequent manual switching of electric lights, may have the electric lights on in the middle of the day more often than at either end, giving an illuminance profile similar to one which incorporates daylight.

The second main indication of daylighting is that spaces which have significant daylighting have a variability in the day-to-day illuminance over the sample period. This is due to the natural variability of daylight availability from one day to the next, as the weather varies. For example, Figure 8 shows dramatic (up to 500%) hour-to-hour variability of illuminance readings.

A third, occasional indication of daylighting is specific to spaces that are occupied only five days a week, and do not have blinds in place on weekends and holidays. In this case, there is usually lower and variable illuminance on weekends, from day to day (supplied almost exclusively by daylight). This is usually about equal to the variable daylight supplied on weekdays. This effect is shown in Figure 5 and Figure 6.

One difficulty in automated analysis is for spaces which have adjacent sources of light, which can provide intermittent additional illuminance in spaces. This is most prevalent where there are multiple sets of manually-switched electrical lights that are switched separately from each other. Figure 12 shows this pattern, with regular illuminance at each of 180, 240 and 320 lux.

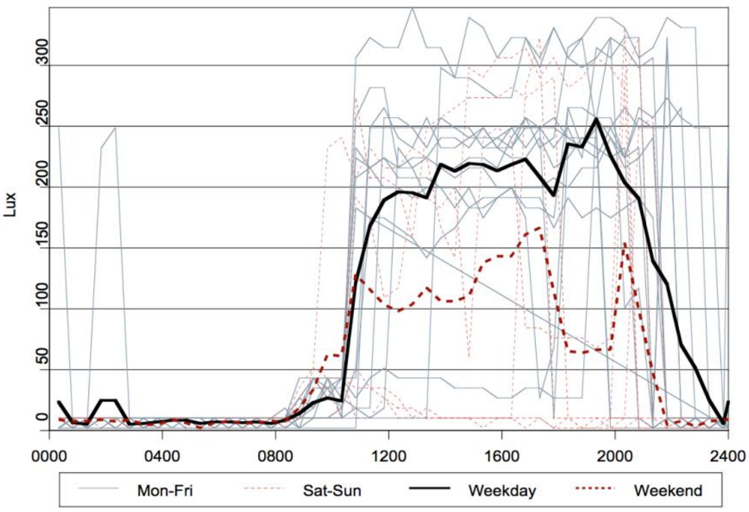

Figure 12. Load shape showing contamination from adjacent illuminance[4]

This load profile was judged to have a daylight contribution of zero, with a reliability of 4.

[4] Figure 8 shows the load profile for R0020AE1 Kitchen 1a.