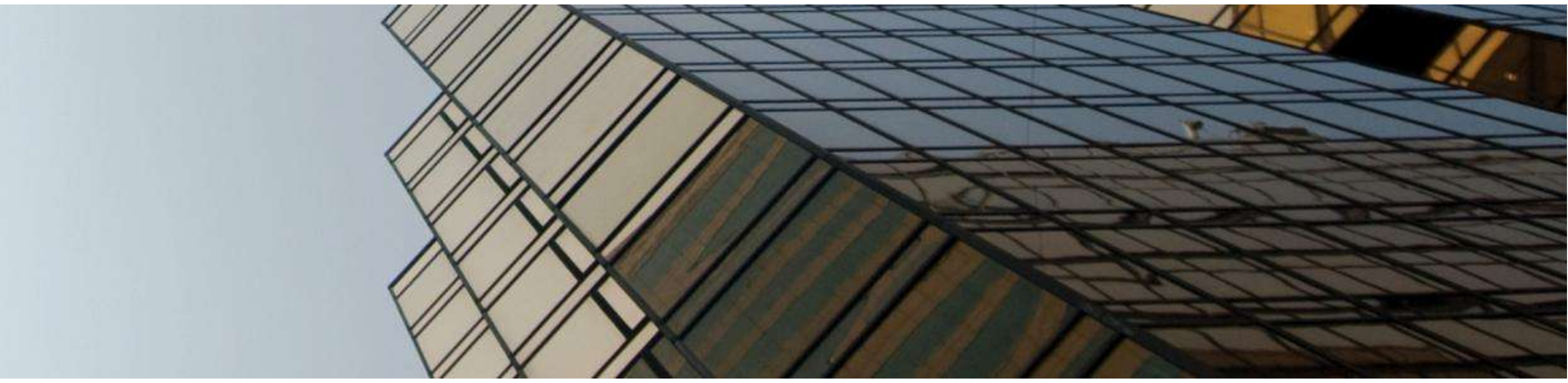

STUDY REPORT SR 277/7 [2012]

BEES INTERIM REPORT

Building Energy End-Use Study - Year 5

CHRISTCHURCH URBAN FORM AND ENERGY

Tavis Creswell-Wells, Michael Donn and Shaan Cory

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BUILDING ENERGY END-USE STUDY (BEES) YEAR 5: CHRISTCHURCH URBAN FORM AND ENERGY

BRANZ Study Report SR 277/7

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Reference

Creswell-Wells, T., Donn, M., and Cory, S. (2012). Building Energy End-use Study (BEES) Year 5 Interim Report: Christchurch Urban Form and Energy, BRANZ Study Report 277/7, Judgeford.

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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, we aim 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 is a study of the BEES modelling conducted by the Centre for Building Performance Research. The studies are distributed between three reports. The first report (Gates, Creswell-Wells and Cory) documents the outcomes of a study identifying which aspects of energy simulation models that must be carefully quantified to ensure accurate energy performance modelling.

The second report (Cory, Munn and Gates) explores the means by which computer modelling might be used to determine optimum building energy performance. This third report applies the results from the first and second reports to examine the likely energy and environmental effects of the proposed urban form in the Christchurch central city draft plan.

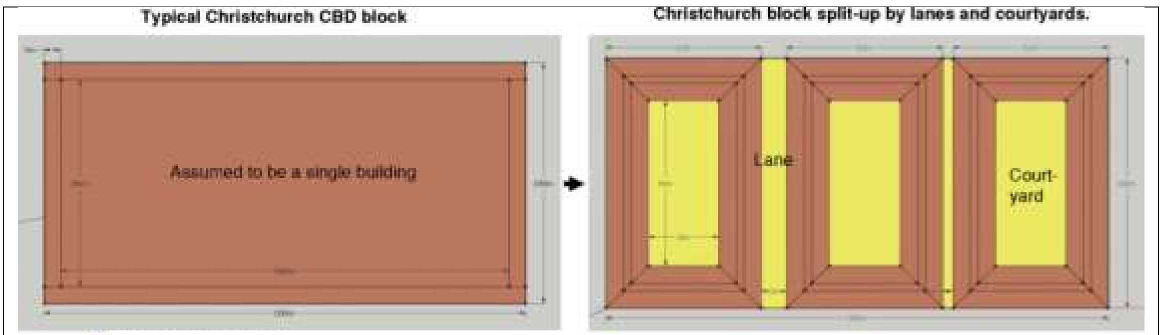
SUMMARY

- Improved indoor environment is possible through natural (passive) measures provided buildings are no wider than 17m.
- Courtyards in conjunction with lanes (of 10m width) could deliver a significant reduction in energy (up to 47.4% per m^2 less than the 'deep-plan' baseline model) as they facilitate passive cooling and daylighting.
- Opening up the city centre with courtyards and lanes also creates useful outdoor spaces.
- Planned façade step-backs are not effective in saving energy or making sunnier streets during the winter period.

This report presents the results of a systematic investigation of energy performance design options for the Christchurch central city. It is part of the BEES study in which modelling templates were previously developed, and have been applied to this study.

In response to the Christchurch earthquakes, the Christchurch City Council (CCC) produced the 'draft Central City Plan' (CCP). Included in this plan was an outline of urban form features (i.e. building height limits, façade step-backs, lanes and courtyards) which were envisaged to increase daylight into the city; and create porosity for movement and pockets of community. Beyond these benefits, however, was the potential these urban forms offered for improvement of environmental and energy performance in buildings.

The goal of the urban form ideas was that buildings and city streets would gain greater solar and fresh air access (refer Figure A) through breaking up city blocks with lanes and courtyards. This had the potential benefit of creating buildings that could effectively use natural lighting/heating/cooling and ventilation and therefore a passively comfortable environment.



Largely internal building space; in reality may be comprised of many individual buildings; shows total net lettable area if all the city block was developed intensely

Open outdoor space: sun, fresh air: public/ private; lost net lettable area

Indoor spaces adjacent to light, sun and fresh air; remaining net lettable area in individual buildings grouped around the courtyards

Figure A: Plan View of City Block with the CCP Urban Form Changes Implemented

The level of improvements likely to result from the CCP's urban form features was estimated using OpenStudio software and simulated in EnergyPlus. Model and simulation parameters were based on relevant New Zealand Standards and BEES data. The performance was compared to a conventional 'deep-plan' model. Simulations drew on the work reported in the BRANZ BEES Modelling Optimisation analysis (Cory, Gates and Munn). Each urban form feature (step back, lane and courtyard) was tested in terms of daylight, heating, cooling and ventilation. This determined the amount of energy each building form required. Energy consumption was the over-arching performance indicator.

Results found that step-backs had minimal effect on total building energy consumption; and lanes on their own were marginally better (refer Figure B). However, courtyards (three per block) in conjunction with lanes (two 10m wide) could deliver a significant reduction in energy (up to 47.4% per m^2 less than the 'deep-plan' baseline model) as they allowed passive cooling through natural ventilation and reduction in electric light use through daylight.

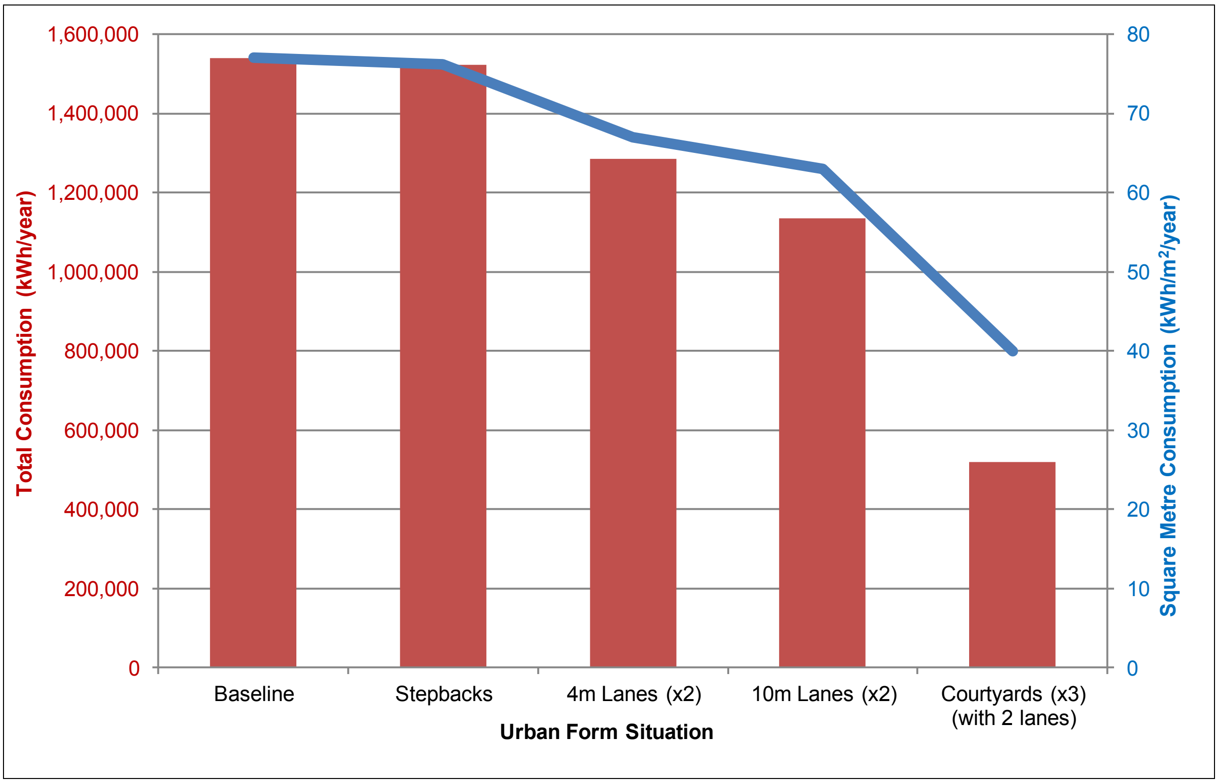


Figure B: Overall Energy Consumption for each Urban Form Change against Baseline Model

The courtyard plan form shown in Figure A is not intended to be understood as a set of three courtyard shaped enormous buildings. Rather it shows how the many building sites in the large city blocks might be developed. The key feature is that, however these buildings are actually placed on the city block, they are all 17m deep at most – from window wall to window wall, to optimise daylight access and use passive cooling. The courtyard form is a traditional European and Middle Eastern approach to this placement along city streets. It is by no means the only way buildings open to air and light might be arrayed in a city grid. The critical dimension (~17m depth) brings major energy savings and more productive and comfortable building occupants who not only have improved access to light and air but also value the views over those from deeper plan buildings.

Where the city height limit is 29m (7 storeys), the CCP proposes to have the upper two storeys step back at a 45^o angle, only a marginal effect on the energy performance of buildings facing the street has been demonstrated, (Figure B). It has also been identified that this measure has a negligible effect on the sun experienced by pedestrians in the streets. The only observable change was experienced during summer, with no increase in solar access to street level during the winter months.

If the height limit was only 17m (4 storeys) then stepping back the upper two storeys at 45^o would increase street level solar access in winter as well as summer.

CONTENTS

FIGURES

TABLES

GLOSSARY

Baseline Model	Computer model representing urban and building parameters identified throughout the study
CCC	Christchurch City Council
CCP	Draft Central City Plan
CCP Model	Baseline Model + CCP proposed changes
Central City Grid	The orthoganal street and block layout/configuration in central city Christchurch
CERA	Christchurch Earthquake Recovery Authority
Daylight Autonomy	Percentage of time per year that a building is occupied when target illuminance can be maintained by daylight alone
Daysim	Computer program specialising in daylight calculations in buildings
DF	Daylight Factor (the ratio – on cloudy days only - of indoor illuminance (using only daylight as a source) to outdoor illuminance
Ecotect	Autodesk computer program used for building environmental calculations
EnergyPlus	Computer program used for simulation of comfort and energy factors
Facade Step-back	Where a façade is stepped back away from the vertical boundary of the building to reduce its mass and allow more sunlight into the adjacent street.
GenOpt	Computer program which optimises building components within a defined set of parameters
NIWA	National Institute of Water and Atmospheric research
NLA	Net Lettable floor Area - floor area within a building that can be leased. NLA extends from the inner face of external walls and does not include communal building facilities such as bathrooms, plant rooms stairwells, lifts, etc.
OpenStudio	Energy Plus 'plug-in' into SketchUp
Passive	Relating to, or being of a heating, cooling, ventilating or lighting system that uses no external mechanical power.
SketchUp	Computer modelling program used for creating building geometry
Thermal Comfort Band	Temperature range in which humans have been found to be most comfortable
Urban Canyon	Physical gap in an urban environment created by a street cutting through dense blocks of structures (between buildings)
VSA	Visible Sky Angle - Degree of unobstructed sky visible from the middle of the window in the subject space. Angle is from bottom of eave/overhand at window, to top of building opposite the window.

W/H	Width-to-Height ratio
Working Plane	Typical office desk height (700mm above finished floor level)
WWR	Window area to Wall area Ratio

1. INTRODUCTION

This report summarises the results of a systematic investigation of energy performance design options for the urban form of the Christchurch central city. The aim is to examine the significance for energy performance and quality of the central city built environment using the principal features of the Central City Plan (CCP) – as were available in May 2012. Ultimately it is anticipated that this material will be of assistance to all Christchurch citizens, whether professionally qualified or generally interested, on the relationship between urban form and energy consumption in central city Christchurch.

There were two motivations for this project. The first motivation arose from the BEES project team's desire to examine how the BEES project might contribute knowledge of commercial building energy performance to the Christchurch rebuild. The Christchurch earthquakes of December 2010 and February 2011 have resulted in 80-90% of the CBD being demolished (OPUS). As the focus of BEES draws statistically relevant energy performance data about New Zealand commercial buildings through studying existing buildings, Christchurch had to be left out of the survey portion of the study. The BEES modelling team undertook this study based on models drawn up for the statistical analysis of the BEES survey data. It therefore became a first application of the potential of the BEES modelling approach to explore how simulation based design studies might be performed on the whole BEES dataset.

The second motivation arose from a desire to examine how modelling might examine new-build design options in general and in particular for Christchurch. Through the 'Share an Idea' scheme set up to address the rebuild, the Christchurch people indicated a strong sentiment for a highly sustainable exemplar city – *"Aim high. Develop a world-class, sustainable, modern green city. The next Malmo, Vancouver or Reykjavik. Establish a new benchmark!"* (Christchurch City Council) The Christchurch City Council (CCC) and contributors developed the draft CCP to direct the rebuild of the city centre. On the 18th of April 2012, the Canterbury Earthquake Recovery Authority (CERA) Minister Gerry Brownlee gave the CCC approval to proceed with the CCP (Christchurch City Council).

1.1 Significance and Aim of Study

The basis of this analysis is the presumption that an opportunity exists for Christchurch to recreate itself as a world leading sustainable city. The CCC's draft CCP reflects the general desire of the Christchurch people to move in the 'green' direction. Features such as height limits and courtyards are proposed (in the CCP) to increase accessibility to natural commodities within an otherwise energy-intensive urban environment. However, opposition exists to the concept of surrendering profitable privately owned land area to public courtyards and lanes. Some remain unconvinced that the benefit these urban restrictions will provide justifies the loss in productive space (Christchurch City Council).

This study applies simple analytical tests with independently validated software to question the energy and environmental benefit of the CCP's proposed urban design features. The significance of these analyses is not identification of 'best' or 'optimum' urban forms, but to demonstrate the energy and environmental impact of urban form policy planning in the central city rebuild.

1.2 Overview and Scope

The study intends to quantify the effects of design features of the CCP for the Christchurch rebuild. Specifically, urban building form features of the CCP are investigated for their effect on passive performance – the intrinsic performance of the buildings themselves, reducing their reliance on installation of energy efficient equipment such as boilers and chillers or energy supply services such as photovoltaic electricity generation. This 'passive' performance is evaluated by calculating the energy required to meet thermal and lighting comfort standards in a range of standard offices.

This study draws on another BEES Year 5 report: Building Design Optimisation (Cory, Munn and Gates, Building Energy End-use Study (BEES) Year 5 Interim Report: Building Design Optimisation). That report establishes parameters and methods for testing the buildings in Christchurch and indicated that passive building features could achieve energy consumption reductions.

1.3 Research Question

What affect will the urban form features proposed by the CCP have on the new buildings' energy consumption?

1.4 Scope of Study

1.4.1 The Draft Central City Plan (CCP)

All elements investigated and tested in this study are found in and based on the CCP documents which are available to the public on the CCC website (Christchurch City Council).

1.4.2 The Passive Urban Form Focus

Passive design is a response to a site's conditions which form the basis of a building's performance. Because they are fundamental to the form and the design appearance of a building, passive design measures can only be implemented at the beginning of a project. This is because changes in building design form and appearance are expensive and time consuming to make late in the design process. A passive urban form study for Christchurch is therefore only useful now during the planning stages while significant design changes affecting the form of buildings and the form of the city itself can still be made. For this reason, this study focuses on the passive elements of a proposed sustainable urban Christchurch.

1.4.3 'Central Core' Zone in Christchurch CBD

This study is specific to the Christchurch central city. Focus is placed on central city area due to the BEES focus on commercial buildings. This is planned as an area of higher population and building density; the city see development of this area as *"…protecting the role of the central city as the region's primary commercial area"* (Christchurch City Council).

Figure 1 shows the 'Central Core Zone' (in red) as defined by the CCP. It is bound within the confines of the Avon River on the northern and western fronts, by Lichfield Street to the south and by Manchester Street to the east.

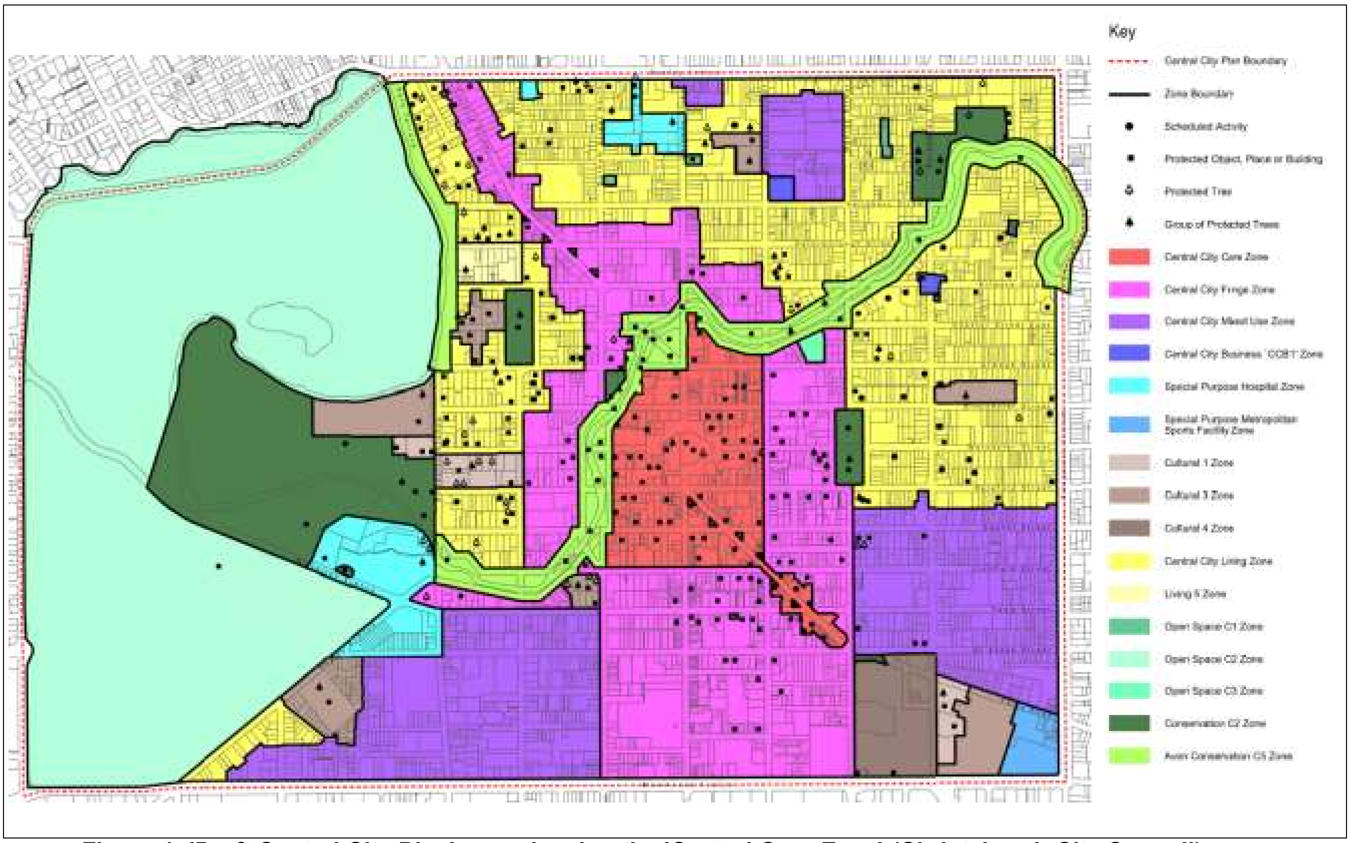


Figure 1: 'Draft Central City Plan' map showing the 'Central Core Zone' (Christchurch City Council)

2. CCP TESTING PARAMETERS

2.1 CCP Proposed Passive Urban Form Features

This section introduces the proposed CCP urban form features to be tested in the study. The urban form features manifest the CCC's urban planning intentions - mainly permeability for pedestrian access to the large city blocks and sunlight to the street. These urban form features also enable more building spaces to access daylight and fresh air with the by-product being a likely improved energy performance in buildings.

Sunlight is beneficial in providing natural heat both to buildings and the street, and can be utilised to create thermally comfortable environments passively. Daylight enhances visual capacity and comfort naturally, at the same time reducing the need for expensive artificial lighting. Finally, building occupants require high-quality fresh air to function properly ('old' or 'used' air in buildings typically has higher levels of CO_2 than outdoor air which can cause drowsiness). This passive approach to bringing fresh outdoor air through windows into buildings is often described as 'natural' ventilation to distinguish it from the delivery of the same fresh air by mechanical means to people in commercial buildings.

Increasing permeability through the city (lanes and courtyards), brings more building surface area into contact with outdoor air and thus makes natural ventilation more likely to be employed. As fan energy is often a large component of any heating, ventilation and air conditioning (HVAC), using simple openings like windows and passive ventilation openings has the potential to save energy, while still delivering better indoor air quality.

2.1.1 Building Height Limits

As a result of the earthquakes, people in Christchurch have become concerned about the safety of tall buildings. For this reason, and to create a more open 'sunny' atmosphere, residents of Christchurch requested smaller buildings through the 'Share an Idea' initiative, *"keep the buildings low rise – it lets more natural light into the city"* (Christchurch City Council). Figure 2 illustrates the CCP's proposed maximum building height limitations for different zones. The focus central core zone, seen in red, is subject to a 29m (seven storey) maximum limit, with a minimum of three storeys. This proposed seven storey building height restriction will be used as a modelling 'constant' throughout this study. The seven storey model will not be tested against taller city models because of the CCP limit.

The study does look at the implication of maximising profit by maximising the floor area of buildings under this height limit. One possible result of placing a height restriction like this seven storey limit is that land owners see the only possible means of maximising returns on their site is to develop all the floor area of each site up to the height limit. The eventual result could be covering all the land area of the city blocks with buildings up to a limit of 29m.

NOTE: In all situations presented in this study the ground floor height is 5.0 m; and the floors-above have 4.0 m inter-floor heights, in accordance with the CCP.

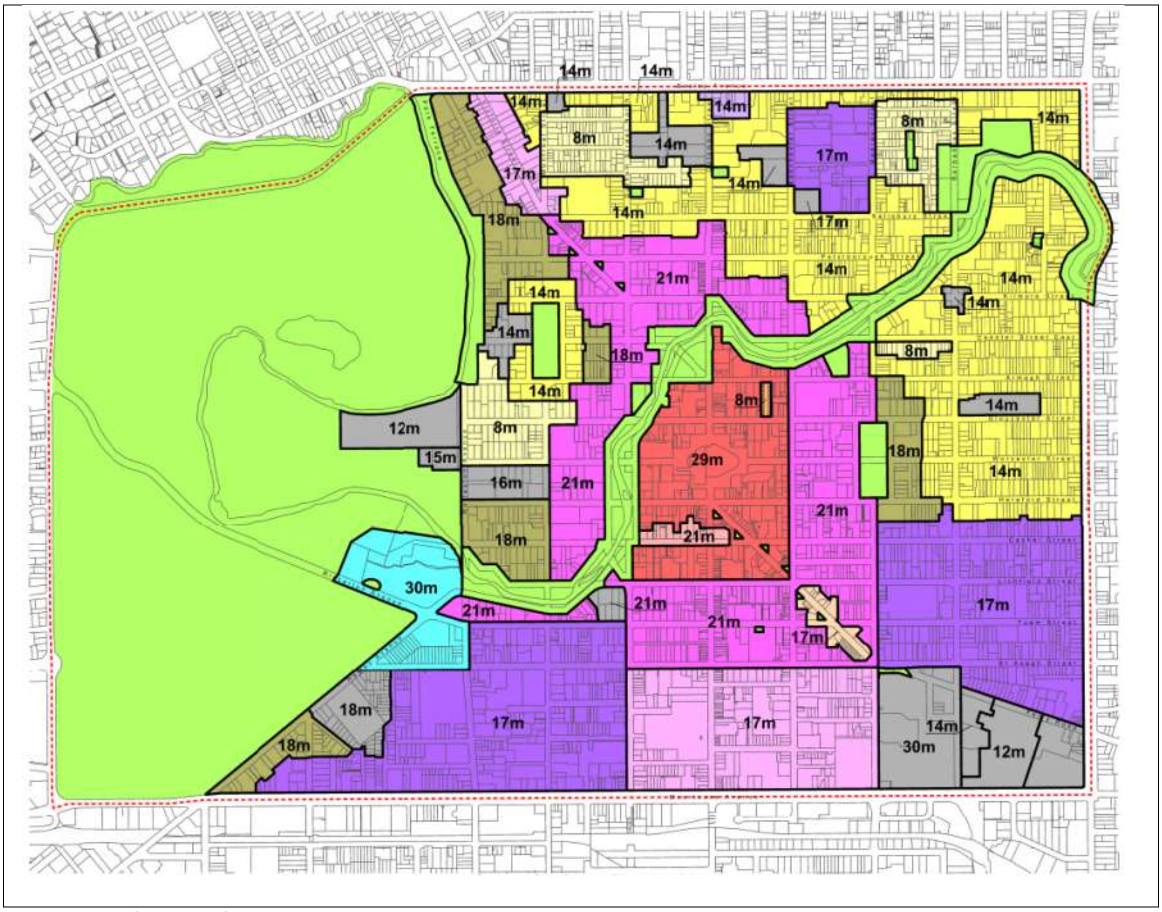


Figure 2: Central City Planning Map 3: Regulatory Framework- illustrating intended building height restrictions (Christchurch City Council)

2.1.2 Façade Step-backs

The first 'passive urban form feature' studied is the façade step-back, shown in Figure 3. This is a method proposed by the CCP to increase solar penetration to the urban canyon ('urban canyon' describes the result of a road cutting through dense buildings). Applied on the southern side of buildings at a 45^{o} angle, the step-back intends to allow more sunlight (direct solar beam) and daylight (diffused light) deeper into the city. Figure 4 demonstrates how cutting the top two (sixth and seventh) floors back to a 45^{o} angle will result in sunlight reaching two floors lower on the opposite side of the road (at equinox). The desired result is more daylight to buildings and more sunlight to the street for greater pedestrian comfort.

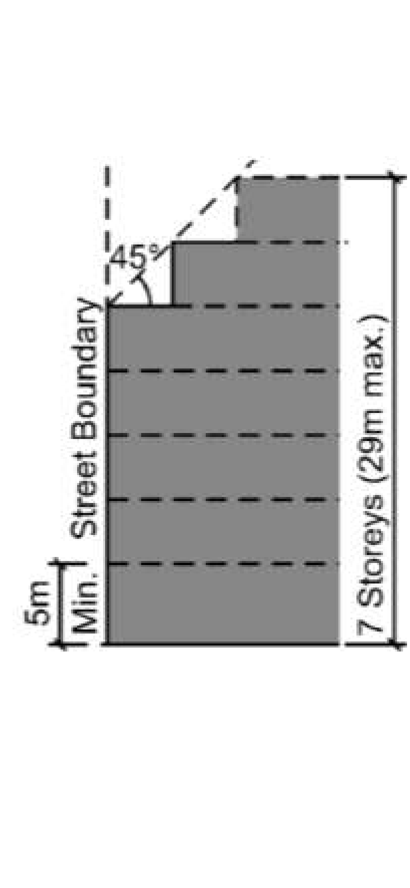


Figure 3: CCP Proposed Step-backs (Christchurch City Council)

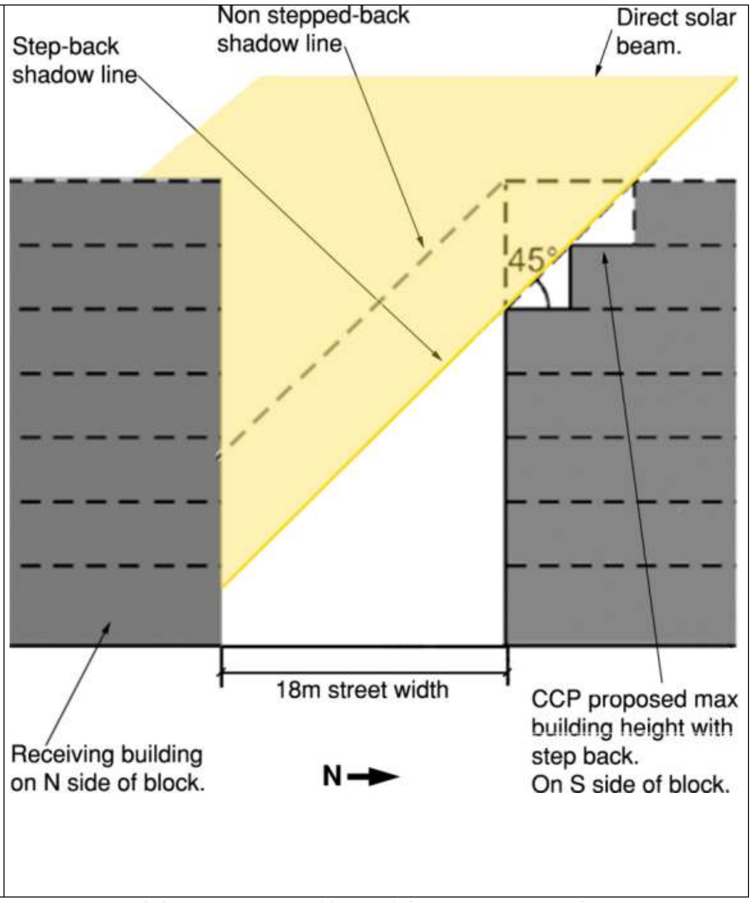


Figure 4: CCP Intended Effect of Step-backs on Solar Access to the Urban Canyon

2.1.3 Lanes/Alleyways

The existing/retained CBD grid consists of rectangular blocks approximately 100m long in the north-south direction by 200m long in the east-west direction. These are substantial distances which create difficulty in pedestrian movement and accessibility. The CCP's 'Strengthening the Grid' project (increasing permeability through the large 200x100m city block system) proposes to add seven 'lanes' to the 13 existing lanes in the central core zone (Christchurch City Council). The Crown (via CERA) is prepared to, and intends to, secure the land targeted for transformation into public access routes by purchasing obstructing land parcels. Lanes (refer Figure 5 which shows in black the lanes that existed pre-earthquake but also large blocks with no lanes) are expected to increase urban canyon area and allow more natural light and air to buildings (Christchurch City Council).

There are three types of lanes proposed in the CCP – 'wide lanes' (4-10m wide), 'narrow lanes' (2-4m) and 'service lanes' (3-5m). This study tested two variations of lane. The first is 4m wide as this width represents the distinction between narrow and wide lane types and is also the mid-range size for a service lane. The second is 10m wide as it demonstrates the effects the largest possible lane size will have on surrounding buildings. The goal was to bracket the range of small to large, and thus establish what effect lane width might have on building performance rather than test a myriad of combinations of lane width, none of which would be precisely right.

Despite the suggestion in the CCP of having lanes covered to provide shelter from rain, all lanes were modelled as open to the sky to best determine their influence on daylight to those spaces.

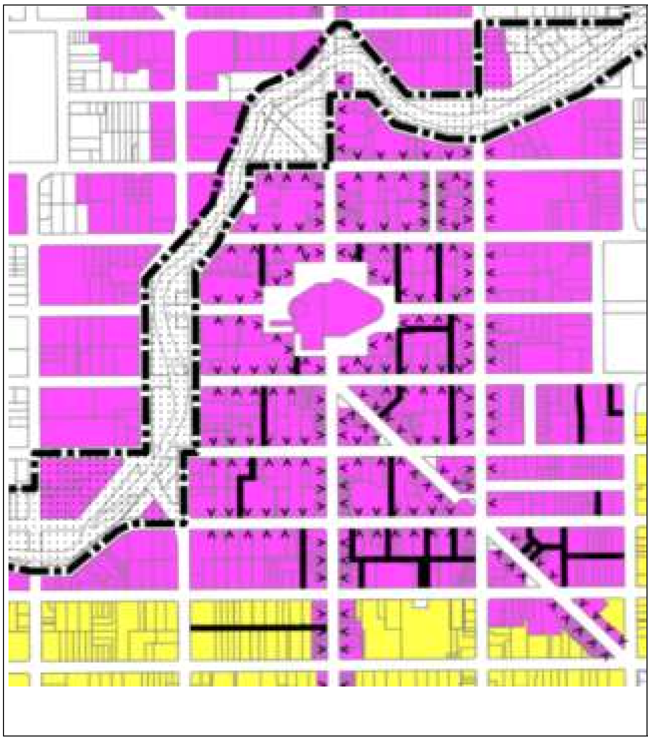


Figure 5: CCP Map of Existing (black) and Proposed Central City Lanes (Christchurch City Council)

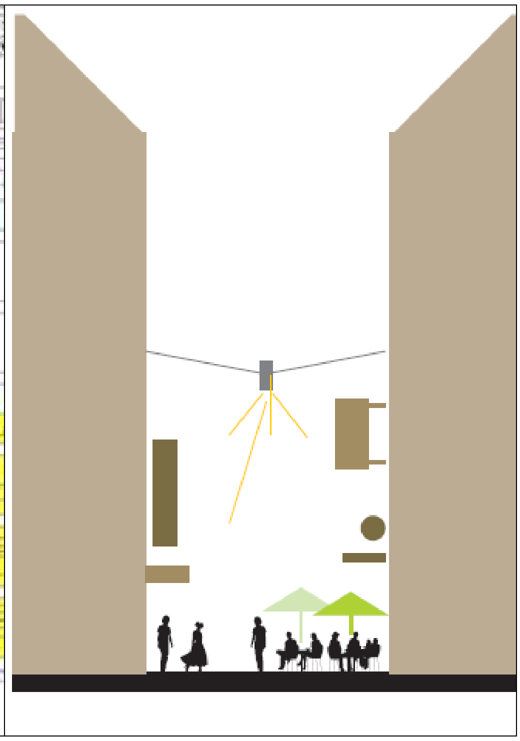


Figure 6: CCP Impression of a Lane Environment (Christchurch City Council)

2.1.4 Internal Courtyards

The intention of introducing internal courtyards is to increase proximity of internal spaces to the ambient environmental amenity of light, sun and fresh air. Courtyards work on the theory that elimination of central ‘core’ zones of deep-plan buildings, which rely entirely on artificial heating/cooling, lighting and ventilation, will be of benefit to a building’s performance through greater access to these natural ‘amenities’.

The BEES Year 5: Building Design Optimisation report (Cory, Munn and Gates, Building Energy End-use Study (BEES) Year 5 Interim Report: Building Design Optimisation) demonstrated perimeter zones possess not only better access to natural amenities in terms of energy, but also provide more desirable working conditions due to their proximity to the outdoors (views, natural light, etc). Replacing part of the energy-intensive core zone of the building with a courtyard, converts more of the total floor area to ‘perimeter’ zones. Because of their access to views, these lower energy use and higher environmental quality spaces are also of greater prestige and thus potentially higher rents. Section 2.3 explains how desirable working conditions contribute to higher productivity and better returns for businesses.

An additional benefit of courtyards is the outdoor public space they provide (refer Figure 7). Courtyards can also be used as entertainment precincts as they provide effective shelter from all winds but still receive useful sunlight and daylight.

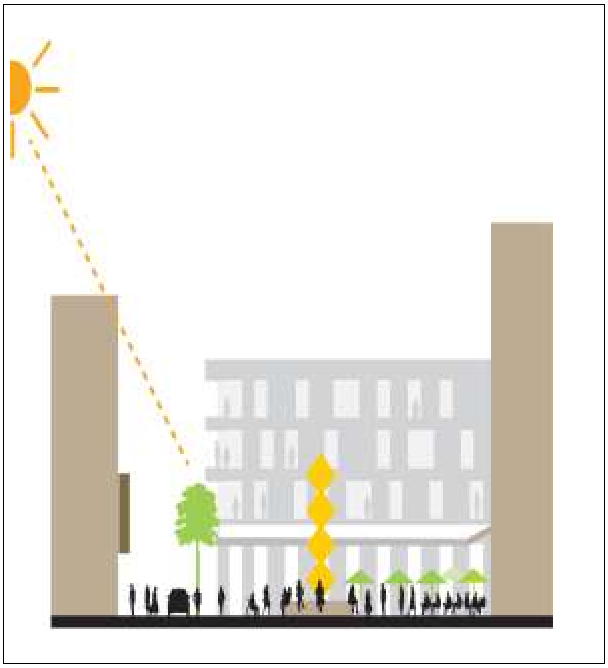


Figure 7: CCP Impression of the Public Environment from Courtyards (Christchurch City Council)

2.2 Restrictive Parameters Set by the CCC

2.2.1 Retaining the Central City Grid

The existing central city grid has been retained in the CCP because:

- There is a potentially enormous cost involved in changing grid layout and the associated legal infrastructure.
- There is little difference in passive solar performance between the existing layout and other layouts such as the 'Spanish Grid' (same orthogonal form but on a diagonal orientation) (van Esch, M. et al.).
- The Christchurch people have expressed a desire to retain the heart of their city through the 'Share an Idea' scheme (Christchurch City Council).
- And, it is feasible because geotechnical data indicates it is safe to rebuild (Tonkin & Taylor Ltd.).

2.2.2 Road Widths

The measurement tool in Google Earth was used to determine street widths within the central core zone existing in 2010. Lichfield, Cashel, Hereford, Colombo, Manchester and High Streets were measured for width, with an average of 18m calculated. If an inaccuracy of ±1m was allowed for in the measurement (Google Earth is not a precise tool), then over a distance of 18m, this is a possible inaccuracy of only 5.6% in the final measurement. In street widths up to 20m the overall conclusions of the study would not change.

2.3 Major Issues Regarding the CCP's Passive Urban Form Features

2.3.1 Net Lettable Area (NLA) and Productivity

Opposition to the concept of sacrificing net lettable area (NLA) to make way for urban form features (Christchurch City Council) is likely to stem from property owners who see themselves as losing NLA that could otherwise be rented. However, the flipside of that concept is the level of quality of those remaining spaces will be much higher.

A study by Leaman and Bordass (1999) suggests that factors of staff comfort, health and satisfaction can contribute financial gains or losses of up to 15% of turnover in a typical office organisation. They also state that productivity increases when staff have opportunity for personal control of their environment with rapid changes to comfort. This is best achieved with shallow-plan building forms as they allow for simple adjustments (like opening a window) which deliver quick results. Added benefits of shallow-plans include views and interaction with outdoors. Productivity is increased when staff are situated in desirable locations such as near windows. Such situations are increased with the inclusion of lanes and courtyards.

Although, some undesirable windowless space is indeed being 'sacrificed', this building form is contributing to developing highly-productive, desirable spaces. These desirable 'perimeter' spaces offer greater potential for productivity (and reduced energy costs) than lower quality 'core' spaces, and are therefore more likely to be attractive and return higher per square metre rentals.

2.3.2 Density and Urbanisation

Density is a key issue within the urban form topic. The CCP 'Technical Appendices' (Christchurch City Council) document describes how there are polarised views on the matter across the Christchurch population. Most people agree that medium-to-high population density is required to maintain life, energy and economic viability in the city centre. However, there is debate as to the level of building density required to sustain the population required for socio-economic fertility in the central city. While this study does not look at such factors, it may aid in discerning an appropriate built form density. Section 12.2.3 Policy: 'Building Density' of the CCP Regulatory Changes document states:

> *"The scale and concentration of built development will be greater in the central city than elsewhere in the city. Development is encouraged to take full advantage of the potential provided, having regard to an appropriate urban shape and form, within the central city to ensure maximum environmental benefit, and value in terms of city identity."*
>
> (Christchurch City Council).

By determining which urban form features provide benefit in terms of energy and comfort, these findings could inform a level of building density that is environmentally sustainable.

3. BENCHMARKS OF PASSIVE PERFORMANCE

In building performance simulation there is a need to be able to compare results. The means by which performance is measured often goes well beyond the legal minima of codes and standards. This section describes the indexes used in this study to measure building performance.

3.1 Daylight to Buildings

Daylight autonomy (DA) measures illuminance levels across a space, over the full occupied year. It shows where in the space daylight is plentiful, and where it may be lacking. DA can be set to a required minimum illuminance level (320 Lux in this case, according to 'New Zealand Standard 1680: 2006 Interior Lighting') (Standards New Zealand) and will demonstrate which areas of that space are sufficiently lit and for what percentage of the year. In essence, DA illustrates what percentage of the year artificial lighting can be turned off in that space and the energy savings realised.

3.2 Passive Thermal Performance in Buildings

Thermal conditions are measured in degrees Celsius (^{o}C) across the occupied year (weekdays 8am-5pm). A comfort band of 18-25^{o}C is used in these analyses to determine 'comfort' in test cells. Time spent below 18^{o}C is considered 'too cold' and time spent above 25^{o}C is considered 'too hot'. The more time spent within the prescribed comfort zone, without active heating or cooling, the better the passive thermal performance. This narrow range of comfort has been seriously questioned during the CBPR BEES modelling team collaboration with a group of researchers in the International Energy Agency (IEA) Research Task focused on Net Zero Energy Buildings (Net ZEBs). It is argued by several researchers and practitioners in this Task that this 18-25^{o}C range is biased towards air conditioning of fully sealed spaces often with no contact with the outdoors. It is especially focused on cooling the building, not keeping the occupants comfortable. The increasing use of the 'Adaptive Comfort' model of human comfort – rather than the Fanger model of human comfort has been brought about by a desire to avoid energy-intensive environmental control strategies. Which often preclude thermally variable solutions, such as many climate-responsive and energy-conserving designs, or innovative mechanical strategies that allow for personal control.

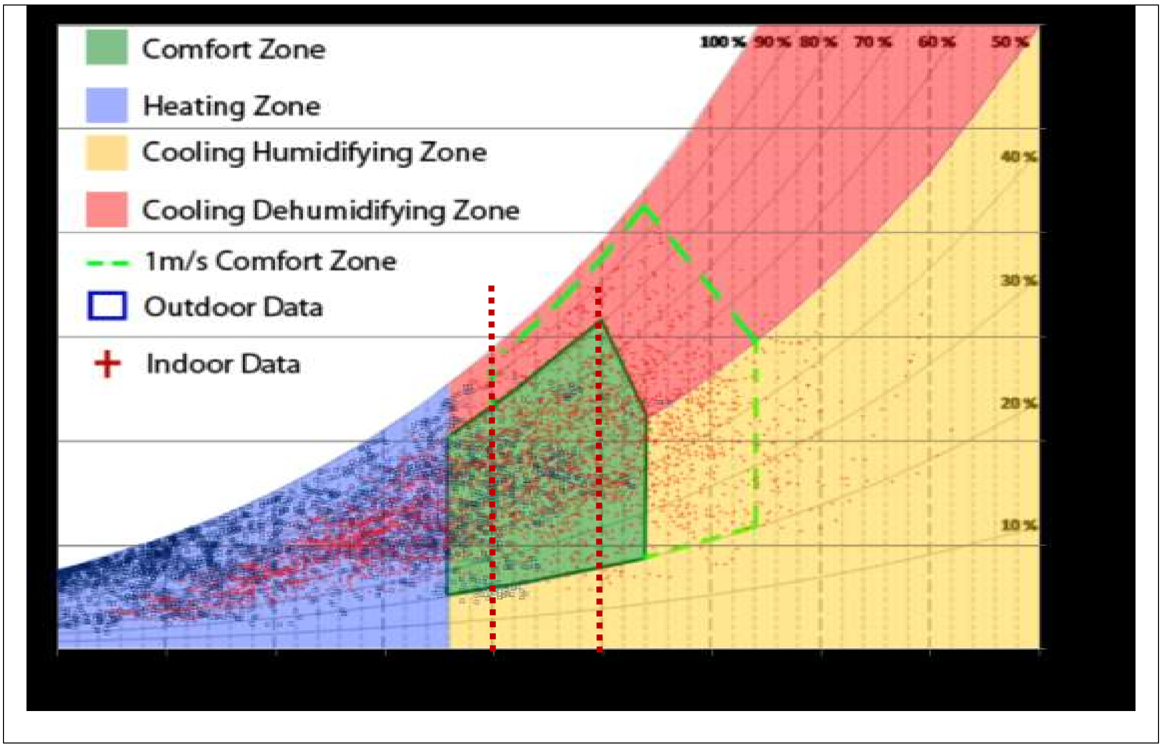


Figure 8: Plot of Temperatures vs Humidities: Shading shows Cool (Blue), Hot Humid (Red) and Hot Dry (Yellow) Climates; Human Comfort (green) & Human Comfort with Air Movement (Dotted Green)

3.3 Natural Ventilation to Buildings

Natural ventilation is not simulated in detail in this study. The modeling of the wind, its effects on the surrounding buildings and thus its effects on an individual window or set of windows in a building is not attempted. Instead, a rule of thumb is used which is derived from the BEES Year 5: Building Design Optimisation report (Cory, Munn and Gates, Building Energy End-use Study (BEES) Year 5 Interim Report: Building Design Optimisation) that 90% of artificial cooling requirements in Christchurch can be subtracted from the simulated figure due to the use of natural ventilation. This 90% reduction was applied to any space that was part of the 'core' zone in the baseline model but which was converted into a 'perimeter' zone by any of the CCP form changes being tested in this study. In such a case, 90% of the cooling load energy calculated for that perimeter zone will be deducted from the total energy consumption.

3.4 Total Energy Consumption in Buildings

Energy consumption is measured in annual kilowatt hours (kWh) for each zone within the subject building and/or for the whole building (kWh/year); and energy intensity is measured as total annual kWh for each square metre (kWh/m^2/year). Total building energy is useful for knowing the urban form changes' overall effect on the full building. Square metre energy rates are useful for comparison against the loss of NLA associated with implementing these urban form changes. This is where a debate central to this study lies (environmental and energy performance of the building vs. floor area and profitability of that building) and so the relationship between NLA and energy requirements of that floor area is significant.

3.5 Sunlight to the Street

Christchurch people were reported as requesting more sunlight to the outdoor public areas (Christchurch City Council). The Autodesk software Ecotect has a function called **'Total Sunlight Hours'** which measures exactly that. Total sunlight hours counts the time each point of an analysis grid spends in direct sunlight over a full year. It focuses on direct solar beam referred to as 'sunlight' and does not take into consideration diffuse (reflected) light referred to as 'daylight'. Total sunlight hours are measured between 7am and 7pm (Christchurch City Council). The resulting values are between 0 hours (no time spent in sun) and 4,380 hours (maximum possible sunlight hours). The closer the figure is to 4,380 hours, the sunnier that point (or grid average) is.

4. IMPORTANT MODELLING FACTORS

Prior to modelling, certain modelling factors need to be established. The following issues are significant (in terms of modelling accuracy and reliability) and complex enough to warrant particular investigation. Final values to be carried forward to the modelling/simulation stages are **highlighted in bold** for easy reference.

4.1 Testing Locations

Testing every possible location in an urban study of this scale is an impossibly long and time consuming exercise. In order to portray the range of scenarios encountered around the city, this study selected a systematically representative set of locations for testing.

4.1.1 Heights

Simple, office scale 'test cells' were located on ground (G), fourth and seventh levels of seven-storey building models. These levels are selected because:

- This provides good coverage of all possible situations, with any level not tested being only one level away from a situation that is tested (comparative information)

4.1.2 Horizontal Locations

The horizontal positioning within city blocks of these typical office test cells depends on which of the two types of analysis is being undertaken.

For daylight analysis, test cells are located at the mid-point of the block in the horizontal dimension. This is because daylight and sunlight are identical on a façade regardless of location within that façade. Placing small test cells in the centre generates quicker simulation results which can then be applied and averaged over the full length of the façade.

For thermal/energy analysis, the 'test cells' encompass the full length of the façade. This is because it is facilitated applying the validated and tested BEES energy simulation template models (refer Section 4.3) as full floor levels.

4.2 Daylight Modelling Factors

In order to determine useful daylight within a building space, that space needs to be designed appropriately to gain maximum benefit from available daylight.

4.2.1 External Window Size

Window-to-wall ratio (WWR) is a pivotal component to successful daylighting. Too high a glazing ratio and glare becomes an issue (as well as the obvious solar gains and heat losses); whereas too low a ratio will result in insufficient daylight to the space. The following WWR's were determined using a calculation devised by Reinhart and LoVerso, refer Appendix A. **Ground floor WWR = 0.8 (80% glazed); fourth level WWR = 0.5 (50%); and seventh level WWR = 0.5 (50%).**

4.2.2 Test Cell Dimensions

Ecotect software user resources suggest a rule of thumb for useful daylight design. It is generally accepted that daylight will penetrate a space horizontally by a factor 2.5 times the height of the aperture it is emitting from (Ecotect). With the CCP-proposed floor heights of 4m, it can be assumed glazed areas will be 3.5m above floor level (allowing 0.5m for structural and mechanical services in the ceiling). This equates to useful daylight penetration of 7m into the space.

Test Cell dimensions will therefore be set at 7m deep and 7m wide, to maintain a square form.

4.3 The BEES Template

A product of this study is the BEES modelling templates. These templates embody current best practise building industry and practise data (such as material properties/schedules/building form etc). They are accurate to within 5% of a detailed model (Cory, S., Gates, A., Donn, M.). This study will employ the large open plan (OP5) template which represents the common four perimeter zones and one core zone office building.

4.4 Working Plane Height

The ‘Metric Handbook Planning and Design Data’ reference guide defines the **working plane height to be 0.7m above the floor level** for office situations (Adler).

4.5 Thermal Comfort Band

The earlier discussion in Section 3 on definitions of thermal comfort describes the definition of a thermal comfort zone from **18-25^{o}C with humidity ranging from 20-70%**.

5. MODELLING METHODOLOGY

5.1 Modelling and Simulation Computer Software Used

A range of computer packages were required to undertake the desired testing for this study. A particular point of note is the different geometry methods required for different environmental analysis programs. Specifically, Ecotect and Daysim (daylight analysis software) use standard SketchUp geometry; whereas EnergyPlus (thermal/energy analysis) must use OpenStudio (SketchUp plug-in) geometry. The two methods are very similar but do possess variations. These are outlined in Appendix C. The software packages (and their functions) used are:

- Trimble (formerly Google) SketchUp – basic universal modelling tool that will be used to create geometries.
- Ecotect in conjunction with Daysim – powerful environmental analysis tools which will be used for examination of solar-related elements (i.e. daylight autonomy to buildings and total sunlight hours to the street). The combination is used here because Ecotect is apt in handling external daylighting factors and geometry but Daysim generates more accurate calculations for internal situations. In essence, Ecotect is an interface to the more reliable calculation engine Daysim.
- EnergyPlus – a complex, widely-employed simulation tool used for accurate analysis of thermal comfort and energy consumption elements (plugs into SketchUp through OpenStudio plug-in).
- OpenStudio – EnergyPlus interface to SketchUp. Geometry built for EnergyPlus needs to be made in OpenStudio in order to translate through.

5.2 The 'Baseline Model' and the 'CCP Model'

In essence, two models are tested in this study. The main intent is to measure effectiveness of the CCP passive urban form features. To do that a baseline must be established for comparison – the first of the two models is therefore a 'Baseline Model'. The second model is the 'CCP Model' and it encompasses the passive urban form features proposed in the CCP as identified in Section 2.1. Both models consist of identical foundation parameters (i.e. block and street dimensions, materiality, testing methods, measurables and outputs). The differences are the passive urban form features. When one of these CCP features (set-backs/lanes/courtyards) is inserted into the model, it becomes a CCP model and is so named.

5.3 Modelling the Baseline

The 'Baseline Model' is illustrated in Figure 9. This model embodies the CCP 29m building height limit defined in Section 2.1 and the restrictive parameters (200m x 100m grid form and 18m street width) set out in Section 2.2. All identified passive urban form features will be applied to this Baseline Model in turn, and tested using the measures established in Section 3. These baseline tests will provide a datum against which the passive urban form features can be compared. A step-by-step process description can be found in Appendix C.

5.3.1 Baseline Core Area Zone

The baseline 'core' zone is important to this study as it lays the foundation for which lanes, courtyards and overall energy effects are compared. The model simplifies the block to a single building. It is recognised that city blocks are typically many individually owned building sites. What is explored here is the extreme if every site owner built to the full extent of their site. Then there would only be a small 7m deep perimeter around the edge of the city block where access to daylight and fresh air could be guaranteed. There is a large central core area which is unaffected by the CCP's proposed façade step-back change, but will be altered by the lane and courtyard changes. As the core is bound within the four perimeter zones it possesses no access to daylight or fresh air. As a result, all heating and lighting to that space are artificial.

The effect of the step-backs, lanes and courtyards is essentially measured by the improvement they generate over the core zone. The perimeter zones retain the same access to fresh air and daylight. Results from lane and courtyard changes will be compared to the 100% artificial environments of the Baseline Model core zone.

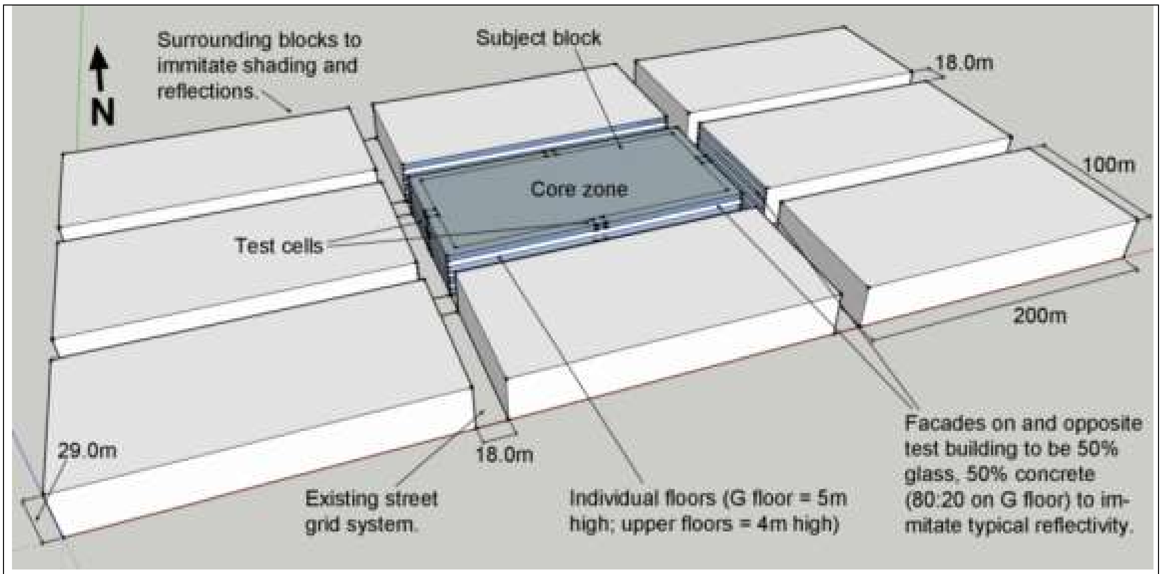


Figure 9: Daylighting 'Baseline Model' with Foundation Parameters Identified

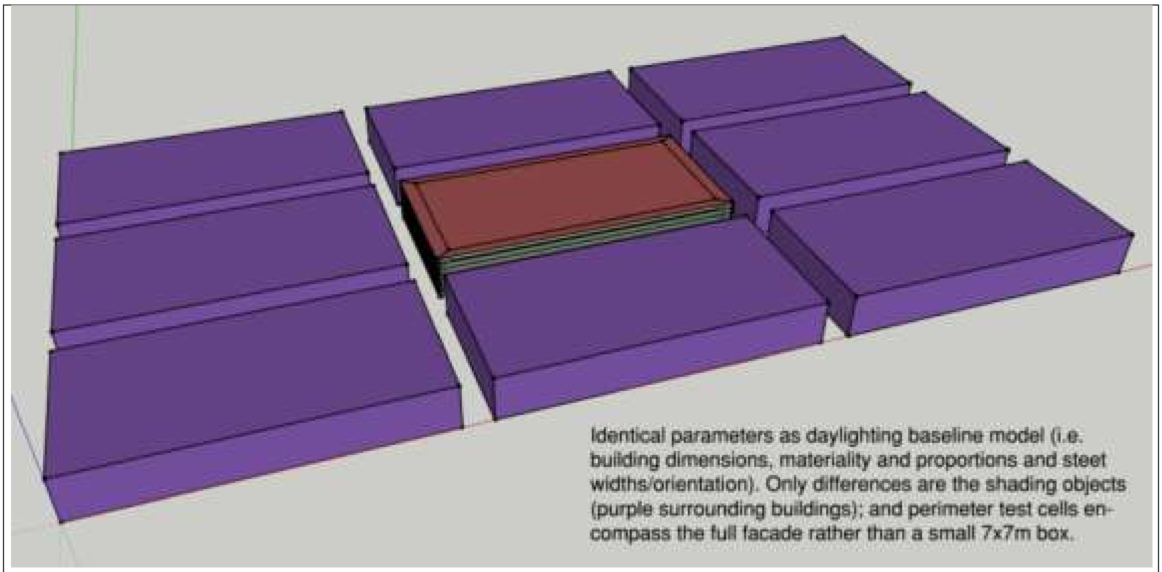


Figure 10: Thermal and Energy 'Baseline Model'

5.4 Modelling the CCP Step-backs

5.4.1 CCP Step-backs Geometry

The only alteration here from the geometry methodology established in Appendix C, is adding the step-backs. The step-backs, explained in Section 2.1, can be seen applied to the model in Figure 11.

NOTE: This alteration is identical for both the daylight and thermal/energy model geometries in their respective ways.

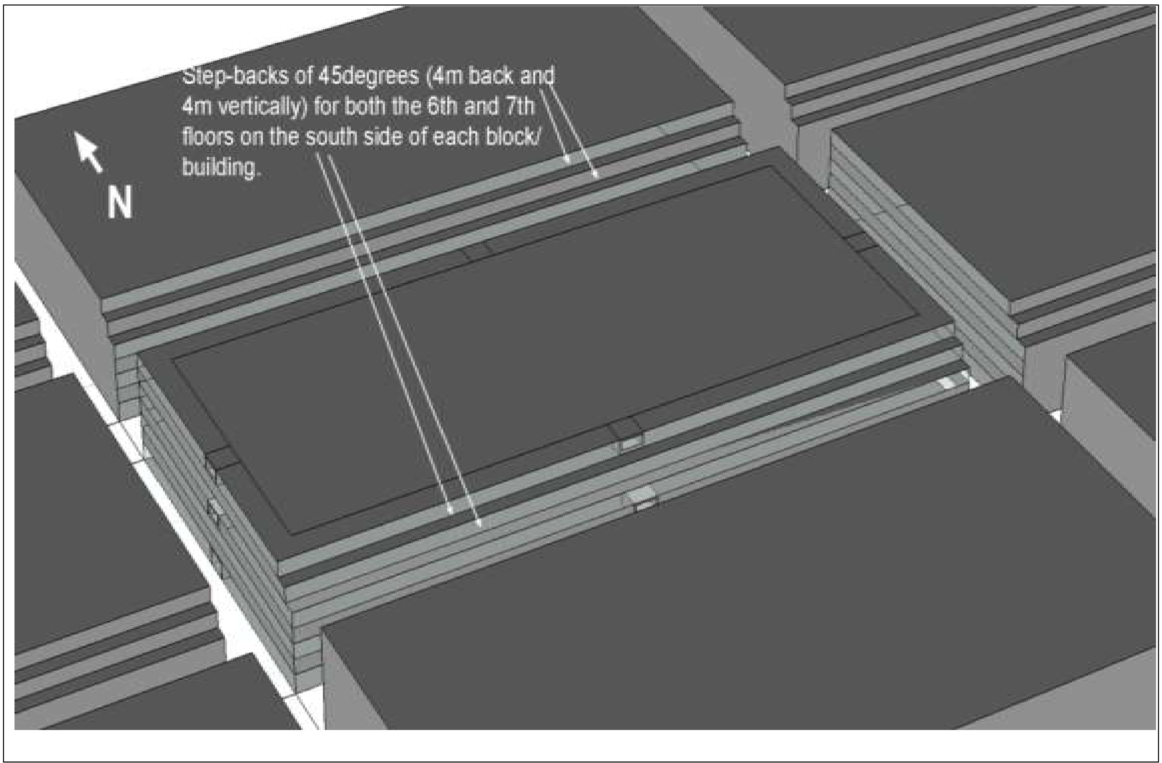


Figure 11: Perspective of CCP Step-backs – Ecotect Model Geometry

5.4.2 CCP Step-backs Daylight Analysis

The methodology here is exactly the same as for the Baseline Model (refer Appendix C), but for one difference. As the step-backs are only applied to the southern side of the blocks, differences will only be noticed on the opposite north-facing façades (although minor effects may also be experienced on the south-facing façade). East and west-facing façades will not be affected. Therefore, daylight testing will only be done for north and south-facing façades.

5.4.3 CCP Step-backs Thermal and Energy Analysis

For the same reasons as with the daylight analysis, thermal and energy tests were only done for the north-facing façade. It was too difficult to model south-facing cells with a step-back included (due to geometric complexities within the OpenStudio software) and difficulties were not justified for such minor effects (<6%) as seen in daylight analysis on the south façade (refer Fig 17). Differences seen in the north-facing perimeter zones can then be directly compared to the Baseline Model north-facing perimeter zones results. Additionally, those localised improvements can be added to the baseline results to determine an overall square metre improvement. These two approaches will provide insight into how much effect improvements in north-facing zones have across the entire block.

5.5 Modelling CCP Lanes

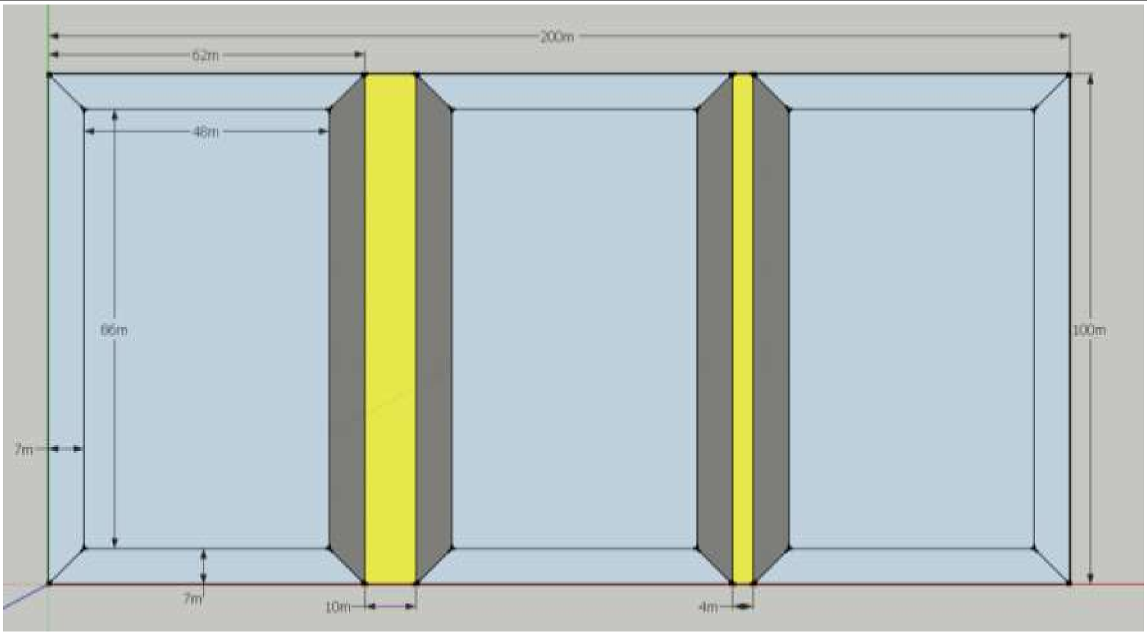


Figure 12: Diagram of CCP Lanes in Context of City Block

As described in Section 2.1, a 4m wide lane and a 10m wide lane, each cutting through a city block from north to south, will be tested. Lanes will create new perimeter zones (refer grey areas of Figure 12) that will benefit from daylight and natural ventilation, and therefore create more area with a lower energy consumption and higher desirability over the baseline core zone.

5.5.1 CCP Lanes Geometry

Lanes are inserted into the original model, rather than into the step-backs model, to ensure all changes are standalone and comparable to the baseline. Figure 13 displays the 4m wide lane situation. The 10m wide model is executed in exactly the same manner but with the lane (to the right in Figure 13) now set to 10m instead of 4m.

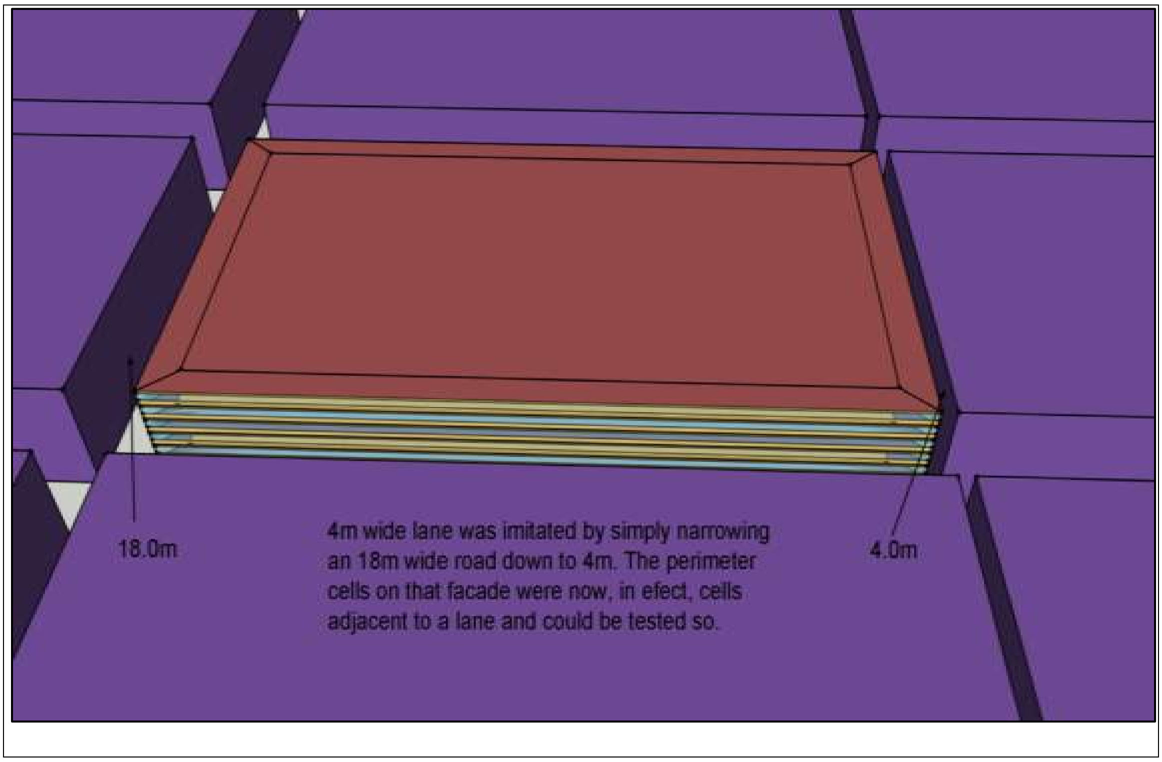


Figure 13: Perspective of CCP Lanes – OpenStudio 4m Model Geometry

5.5.2 CCP Lanes Daylight Analysis

As the city blocks in Christchurch's CBD are oriented due north, it was assumed cells facing east and west would perform identically. Therefore, daylight analysis could be carried out in only a single cell for lanes. This cell was situated, in both the 4m and 10m lane width models, at the fourth level to represent an average of daylight performances across the full seven levels.

5.5.3 CCP Lanes Thermal and Energy Analysis

Zones for thermal and energy analysis encompassed the entire length of the perimeter zone adjoining the lanes. As with the daylight analysis, this was also applied to the fourth level.

5.6 Modelling CCP Courtyards

5.6.1 CCP Courtyards Geometry

The CCP does not define sizes for their proposed courtyards. A recent study on the most effective courtyard width-to-height (W/H) ratio for natural ventilation found that a W/H ratio of 1:1 provides the best shelter from wind in the courtyard space while retaining sufficient air movement for natural ventilation in internal spaces (Tablada). This would indicate a 29m wide courtyard (equal to the 29m building heights) should be used to realise best natural ventilation.

Building spaces adjacent to the courtyard now become perimeter zones and can thus be naturally lit and naturally ventilated (refer dark grey sections in Figure 15). Now the original perimeter zones (7m wide) PLUS the new 'internal' perimeter zones (also 7m wide), PLUS a 3m wide movement route between them, can all be naturally lit and cross-ventilated. Using this model (refer Figure 14), a full courtyard plus building totals 63m width.

NOTE: The courtyard is reduced to 28m in width in order to split the full block into three courtyards, each separated by a 4m or 10m wide lane.

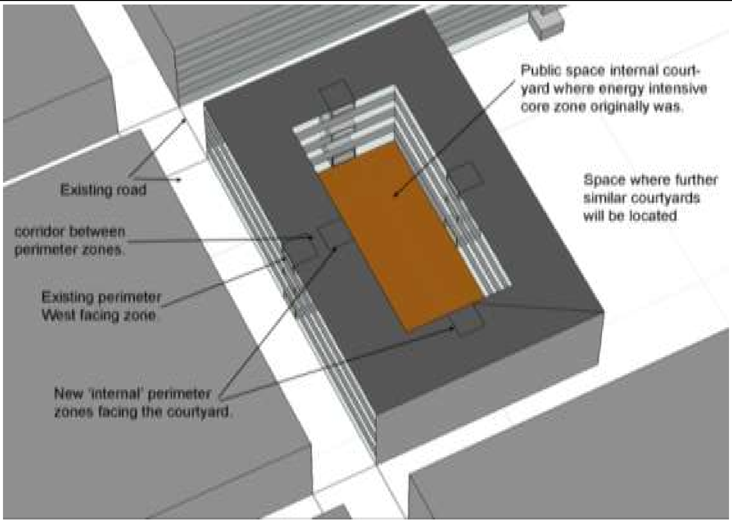


Figure 14: CCP Courtyard – Ecotect Model Geometry

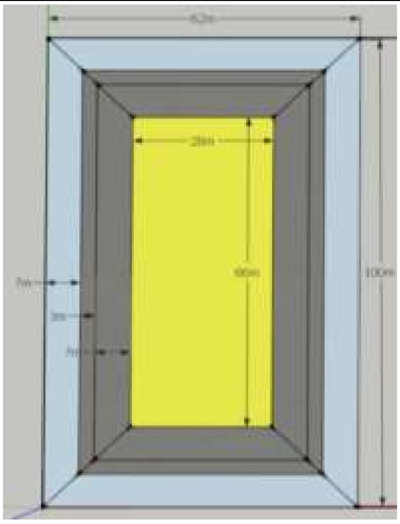


Figure 15: CCP Courtyard Dimensions

5.6.2 CCP Courtyard Daylight Analysis

Analysis of daylight availability was done for all of the new 'internal' perimeter zones opening out onto the courtyard to determine the overall effectiveness of this urban form feature. East and west-facing zones were again considered to perform identically. As was done for the lanes, daylight was only assessed at the fourth level. This was to represent an average situation of the full height.

A 'total sunlight hour' analysis was also done for the outdoor public courtyard space at ground level. This was done using the same method and scale as was used for the assessment of sunlight to the street in the step-backs model.

5.6.3 CCP Courtyard Thermal and Energy Analysis

Geometry was manipulated so shading objects represented the building sections that enclose the courtyard. All other modelling and simulation factors were identical to the technique employed for the analysis of lanes.

6. TESTING AND DISCUSSION OF RESULTS

6.1 Baseline Model

The baseline was intended as a point of reference for results of urban form changes to be compared against. Therefore, baseline model results will be presented against changes where required.

6.2 CCP Model: Façade Step-backs

6.2.1 Daylight Autonomy in Buildings

Daylight can only access 'perimeter' zones and does not affect 'core' zones (refer Figure 16). The step-back urban form change influences daylight in only the north and south-facing perimeter zones (east and west perimeter zones are not affected due to orientation).

Figure 17 displays DA for test cells on levels G, four and seven on both north and south perimeter zones. It compares DA of each cell between step-back and baseline models to illustrate improvements relative to each cell. DA is given in terms of range, which covers lowest point of daylighting performance in the cell to the highest; and average DA, which indicates percentage of the year that artificial lighting can be turned off in that cell.

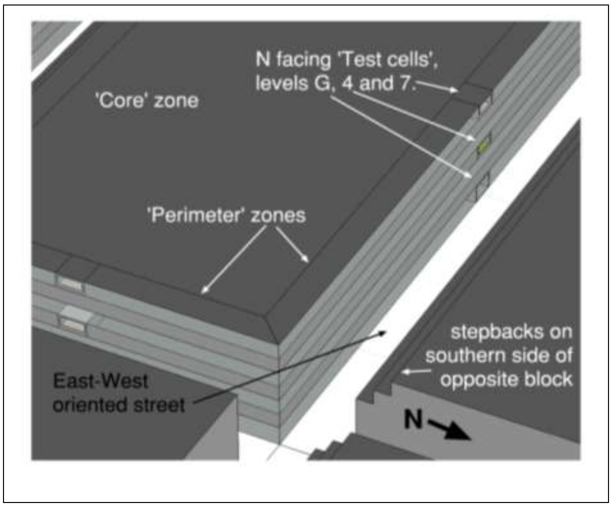


Figure 16: 'Perimeter' and 'Core' zones in Southern Facade Step-back

This graph demonstrates a clear improvement in DA across most cells. This was expected on the north-facing perimeter but not to such an extent on the south. The area of greatest importance is cell N4 the mid-level zone on the northern façade (cell codes are first letter of orientation, e.g. 'N' for north; and number of level, e.g. '4' for fourth floor; equals cell N4). This cell is located in the region of that façade that was expected to be most influenced by the step-backs. Additionally, it best represents likely circumstances of commercial offices.

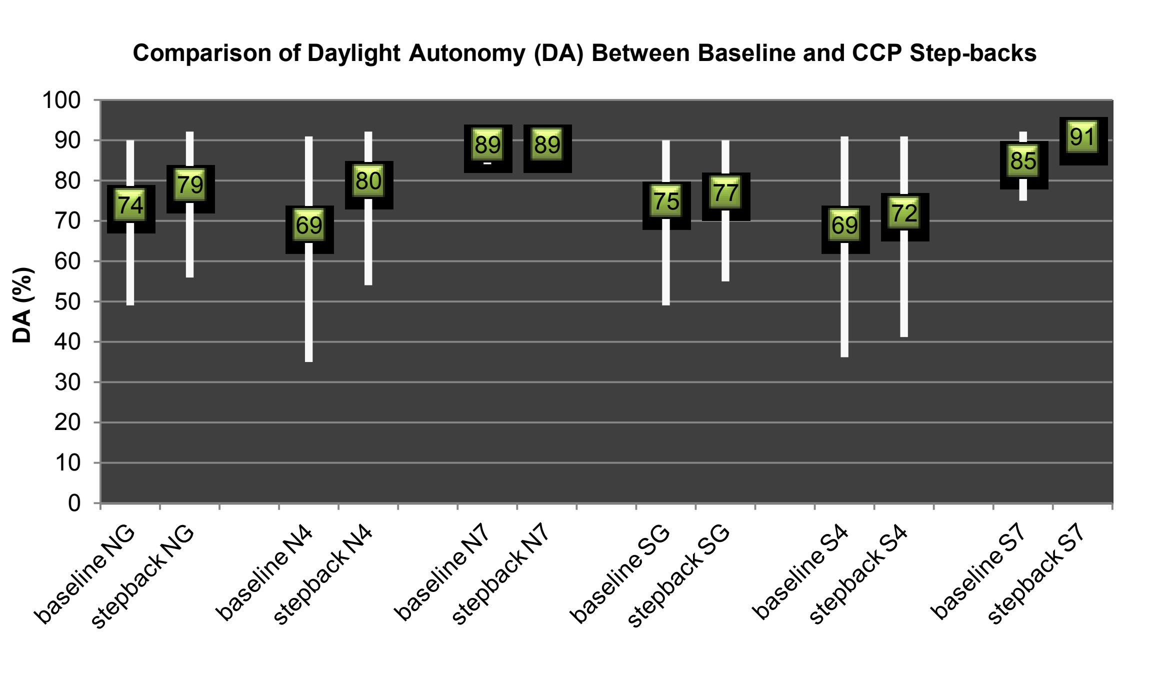


Figure 17: Daylight Autonomy in Level G, 4, 7 cells on north and douth facades

Figure 18 and Figure 19 offer a visual representation of DA in cell N4. Here, DA patterns can be seen at each specific point in the test cell. Yellow squares represent areas of high DA (80-100% of year sufficiently lit), whereas red represents less effective daylighting (40-60% of year sufficiently lit). By comparing DA of the Baseline Model with DA of the step-backs model, an evident improvement can be seen by the increase of yellow squares in the step-backs map (Figure 19). This improvement can be measured as an 11% (average DA of 69% up to 80%) increase in DA in this space. Basically, this means artificial lighting can be completely turned off for an extra 11% (around 5 weeks) of the working year.

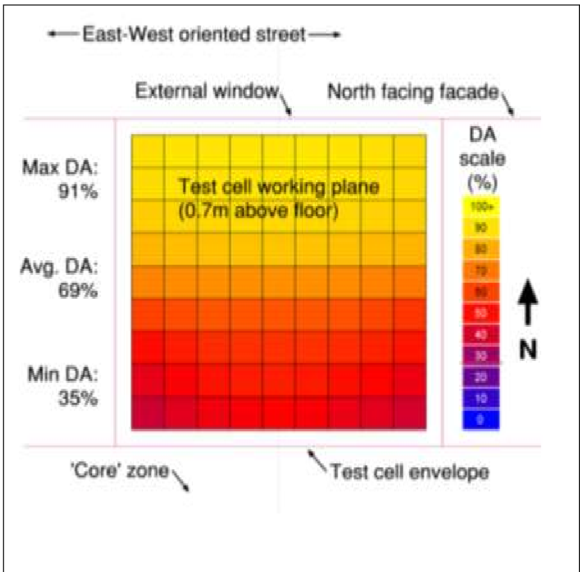


Figure 18: Baseline Daylight Autonomy of Cell N4

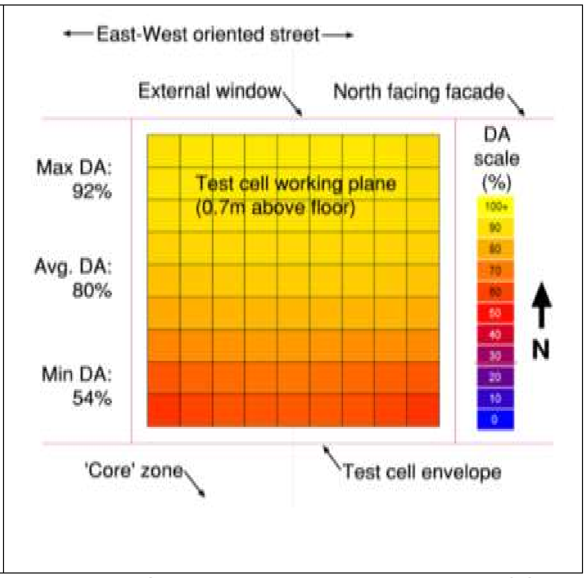


Figure 19: Step-back Daylight Autonomy of Cell N4

6.2.2 Thermal Comfort

As expected, increasing daylight to building spaces also contributes to increased temperatures. Figure 20 demonstrates how the extra solar penetration into the urban canyon improves thermal conditions (for most levels), making northern perimeter zones passively warmer than they were in the baseline model. As was the case with the daylighting analysis, the seventh floor was entirely unaffected by the step-backs.

NOTE: the below graph represents passive temperatures without the influence of natural ventilation. Natural ventilation is not considered for the step-back alteration, as there has been no change in access to fresh air, so no difference would be encountered.

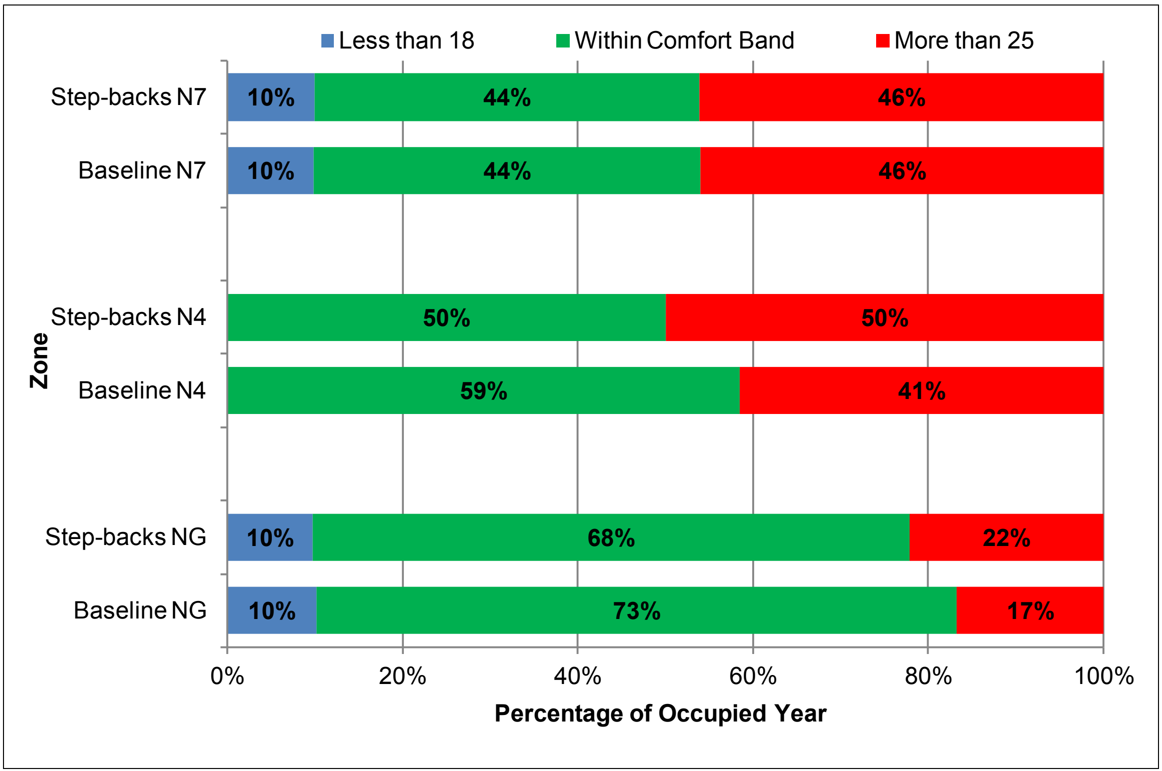


Figure 20: Baseline and Step-back Temperature Tendencies in North Facing Perimeter Zones

6.2.3 Total Energy Consumption

DA results indicated an improvement in daylighting for test cell N4. With a 6% reduction in energy requirements for that zone, Figure 20 supports the daylighting influence seen in Figures 18 and 19. However, both other north-facing perimeter zones react differently to cell N4.

Test cell NG (north-facing at ground level) experienced an increase in required space conditioning energy despite improved daylight. This is likely to be a result of the large WWR of 80% which, as Figure 20: Baseline and Step-back Temperature Tendencies in North Facing Perimeter Zones showed, would allow substantial heat gains (and losses) through the low insulation glazed area.

The artificial lighting energy saved would be offset by the amount of artificial cooling and heating required to maintain thermal comfort. Test cell N7, not surprisingly, has not been influenced in terms of daylight or energy consumption as it is already exposed to maximum visible sky angle and therefore maximum solar access.

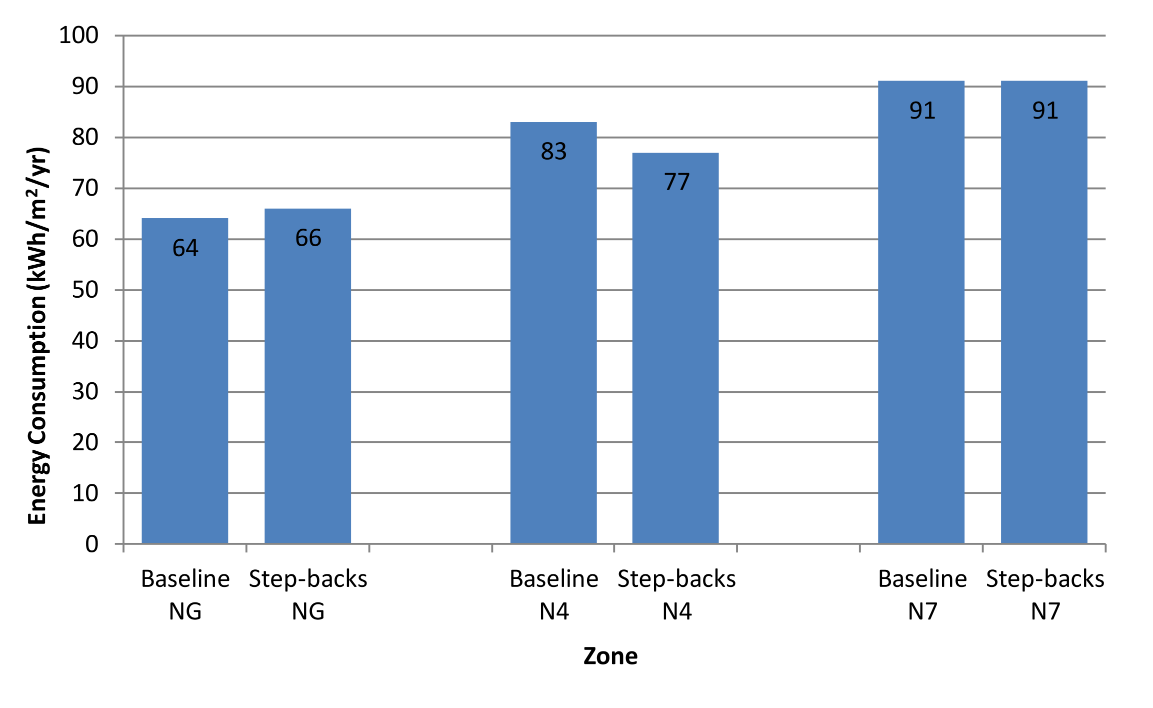


Figure 21: Baseline and Step-back Energy Consumption Comparison

An important consideration in determining the overall influence of the step-backs on energy consumption over the entire building is the relationship between core and perimeter zones. As this urban form change only affects the northern perimeter zones, core zone energy consumption will remain the same. Figure 22 demonstrates how little effect the step-backs make when applied to the entire block/building. Calculations can be found in Appendix D.

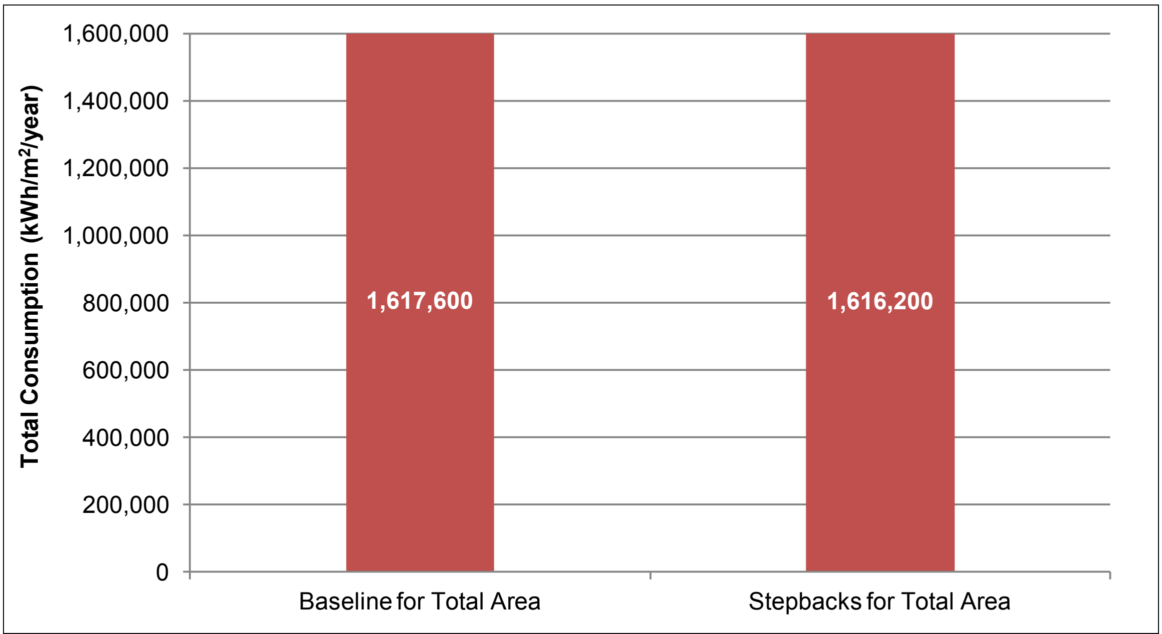


Figure 22: Baseline and Step-back Total Energy Consumption Comparison

This reduction of 1,400 kWh/year (<0.001%) over the entire building is negligible. The step-backs change illustrates well the purpose of this study. Despite being conceived based on logical theory, testing of the step-backs demonstrates that they in fact do not deliver any significant improvement to the city's performance, at least not in terms of energy consumption.

6.2.4 Total Sunlight Hours

Another factor that the step-backs influence is sunlight to the street.

Figure 23 and Figure 24 demonstrate how stepping back the façade on just the top sixth and seventh floors can make a considerable difference to the amount of sunlight that reaches the street. This factor is important for pedestrian comfort and has been requested by the Christchurch people. The 'total sunlight hour' maps below for east-to-west oriented streets show that an additional 236 hours (30%) of direct sunlight can be realised through step-backs over the year (out of a possible 4,380 total sunlight hours). Most of this improvement would be during summer months (as the angle of the winter sun would not reach the ground level over a seven storey building in winter).

North-to-south oriented streets experienced an improvement of 6% (738 up to 778 hours) all of which occurred at the northern most edge of the analysis grid, meaning changes were very localised and largely unhelpful.

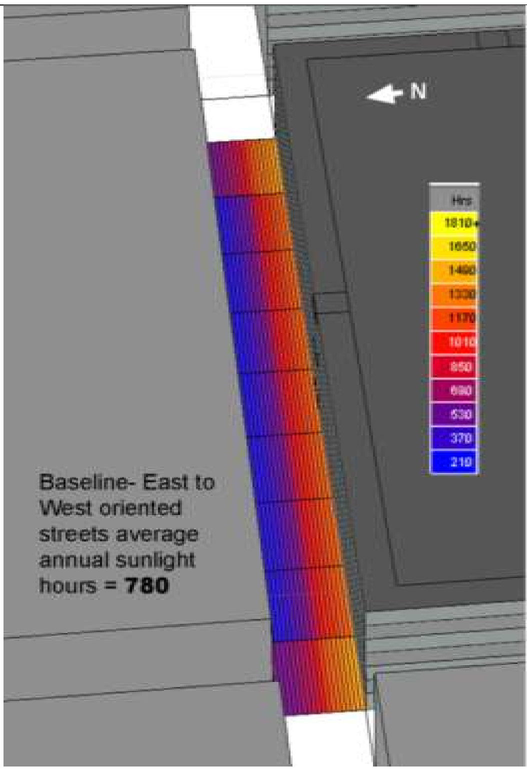


Figure 23: Total Baseline Sunlight Hours

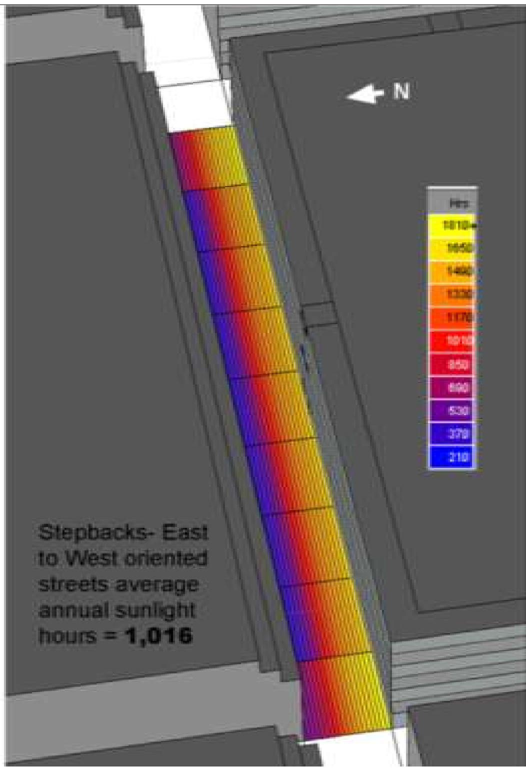
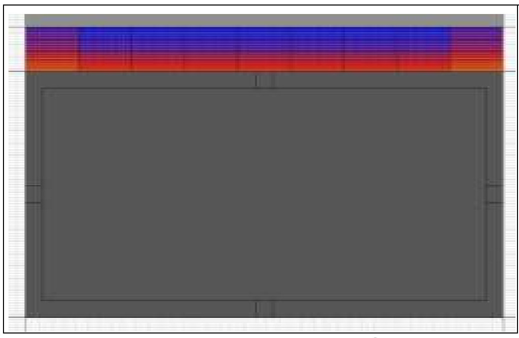


Figure 24: Total Sunlight Hours with Step-backs

In the following set of diagrams (Figure 25 to Figure 34) the images on the left show a plan view of the grid used for the baseline buildings with no step-back of the upper floors. The images on the right are with the step-backs in place.

Comparing Figure 25 and Figure 26, the average annual hours of sunshine does change – there are more red grid squares, or sunshine hours, in Figure 26 where step-backs are modelled, than in Figure 25 – the baseline seven storey building. However, if only the winter sunshine hours are analysed, there is no difference between the baseline model (Figure 27) and step-backs (Figure 28). Finally, if only summer sunshine hours are analysed (Figure 29 and Figure 30) it is immediately obvious that the 45° upper level step-backs do allow more summer sunshine hours. The major benefit in east-west streets of the step-backs shown in Figure 30 is experienced in summer. There is no apparent improvement in street level sunshine in winter as a result of the proposed step-backs.

It seems that most of the improvement is as a result of the marked improvement in summer sun availability, not a year-round improvement.



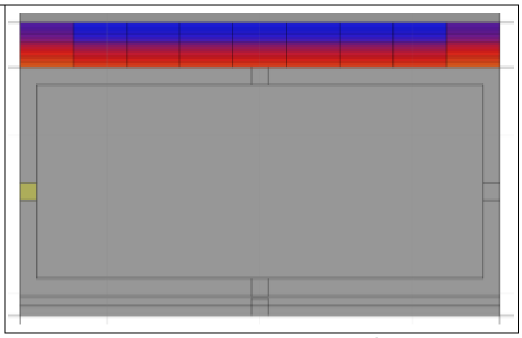
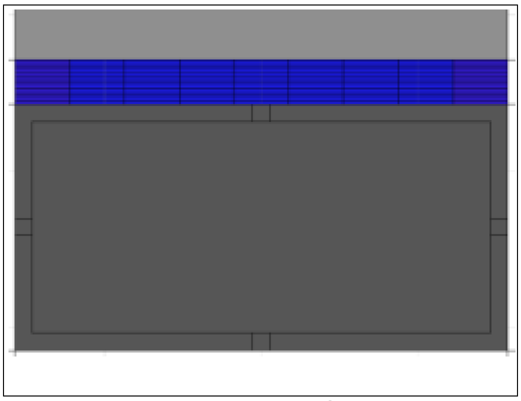


Figure 25: Average Annual Sunlight Hours, Seven Storey Baseline Model

Figure 26: Average Annual Sunlight Hours, Seven Storey WITH Step-backs



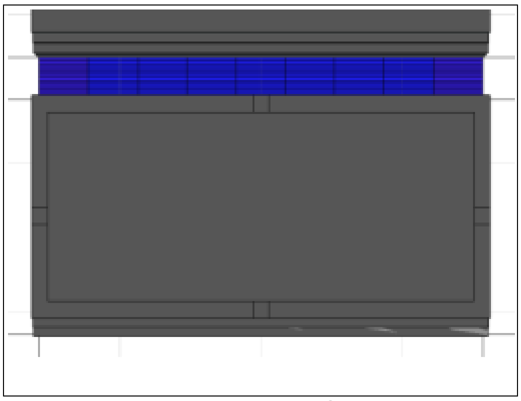
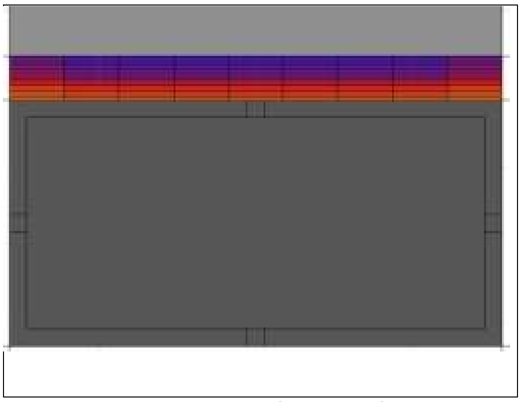


Figure 27: Average Winter Sunlight Hours, Seven Storey Baseline Model

Figure 28: Average Winter Sunlight Hours, Seven Storey WITH Step-backs



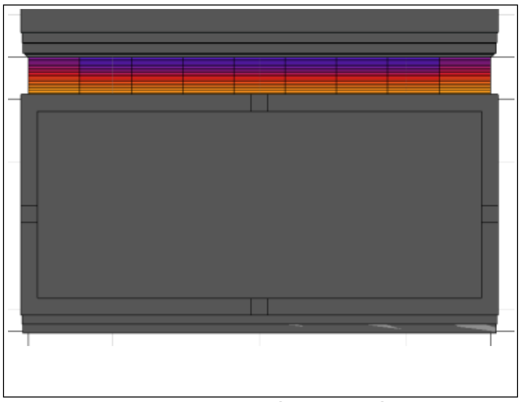
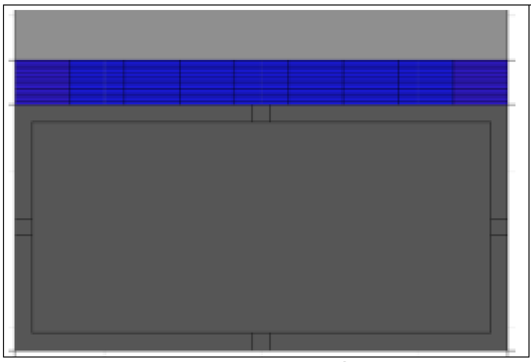


Figure 29: Average Summer Sunlight Hours, Seven Storey Baseline Model

Figure 30: Average Summer Sunlight Hours, Seven Storey WITH Step-backs

The analysis looked at buildings that were four storeys as well as the proposed maximum seven storey limit. As shown in Figure 31 to Figure 34 the step-backs of levels three and four do have an effect across the whole year, though this change is still more obvious during the summer months. Comparing the fourth storey and the seventh storey results, the common sense notion that the lower city would have sunnier streets in winter is obvious.



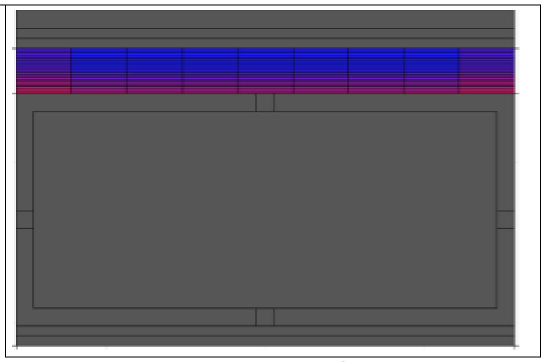
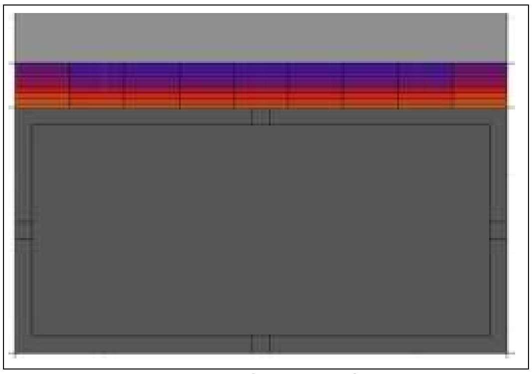


Figure 31: Average Winter Sunlight Hours, Four Storey Baseline Model

Figure 32: Average Winter Sunlight Hours, Four Storey WITH Step-backs



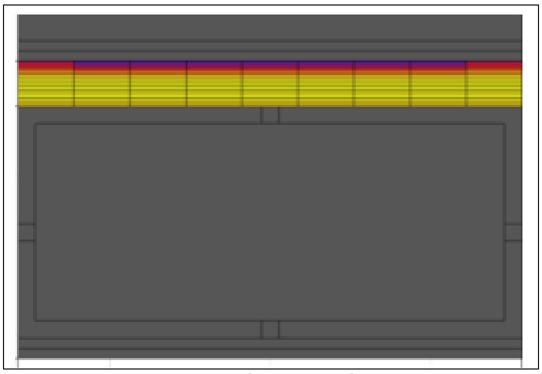


Figure 33: Average Summer Sunlight Hours, Four Storey Baseline Model

Figure 34: Average Summer Sunlight Hours, Four Storey WITH Step-backs

6.3 CCP Model: Lanes and Alleyways

6.3.1 Daylight Autonomy

Daylight analyses were carried out at mid-height on the east-facing perimeter zone (cell E4). This location was selected as it gave an average situation overview of the daylight down each of the 4m wide and 10m wide north/south lanes. East and west oriented cells perform equally. Figure 35 display the level of DA that could be expected in each of the lanes.

At 4m wide, the first lane model delivers very poor daylight to adjacent internal spaces, averaging only 9%, with the majority of the space not reaching adequate illuminance levels at all during the year. Therefore the 4m wide lane proved ineffective for daylighting. The 10m wide lane, however, provides considerably more daylight and deeper into the space. Here almost half of the space (44%) is sufficiently lit to 320 Lux throughout the year. Although still low, this test cell demonstrates that a 10m wide lane can provide useful daylight to adjacent spaces.

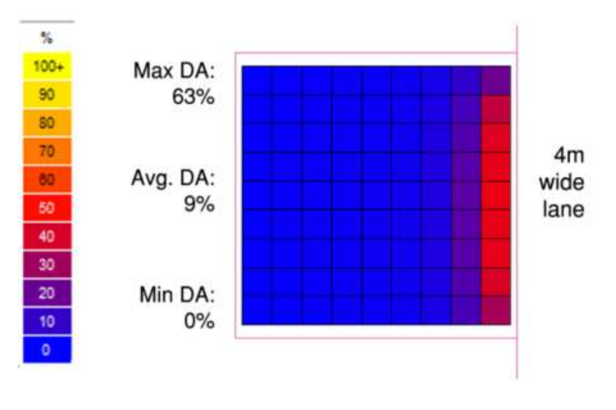


Figure 35: Daylight Autonomy Model of Cell E4 with 4m Lane Adjacent

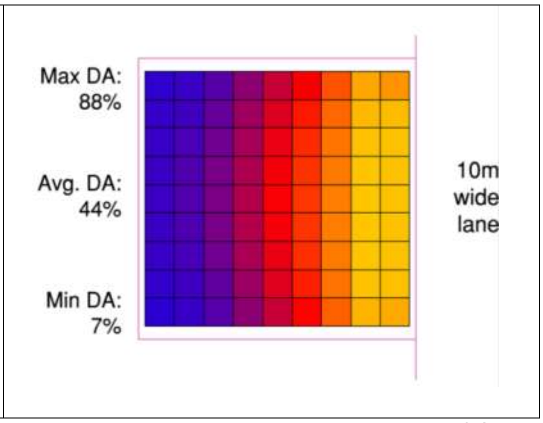


Figure 36: Daylight Autonomy Model of Cell E4 with 10m Lane Adjacent

6.3.2 Total Daylight Hours

Aligned with daylighting within buildings, is sunlight to ground level in the lanes. The 4m lane is expectedly very dark with an average of only 93 hours of direct sunlight per year over the lane. The 10m wide lane, as in the test cells, is subject to better sunlight with an average of 348 sunlight hours per year (out of 4,380 possible sunlight hours).

6.3.3 Thermal Comfort

At the fourth level this zone benefits from thermal 'buffer zones' above and below, stabilising temperatures and minimising heat loss. Additionally, as the narrow urban canyons created by the lanes provide little avenue for direct sunlight onto these façades, solar gains are limited. Figure 37 demonstrates how both 4m and 10m wide lanes would result in passively comfortable spaces in adjoining perimeter zones for around 80% and 93% of the year respectively.

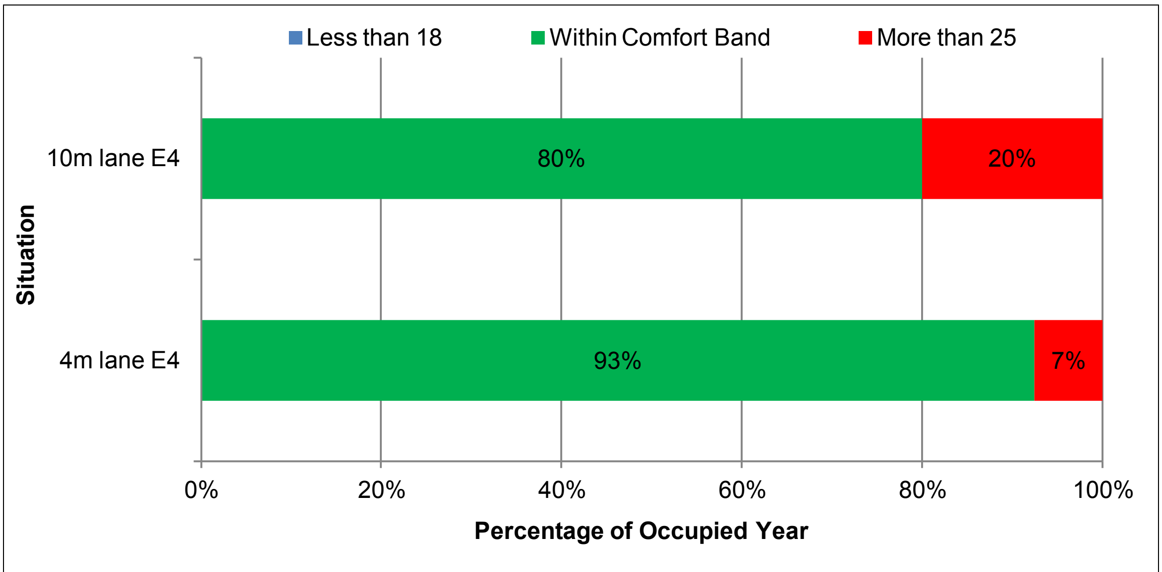


Figure 37: Annual Passive Temperatures (^{o}C) in Adjacent Zones for 4m and 10m Wide Lanes

6.3.4 Total Energy Consumption

Figure 38 shows how natural temperatures in a zone adjacent to a 4m wide lane would be comfortable more often than in a 10m wide lane scenario. This, however, does not include the effects of natural ventilation. Figure 39 illustrates how implementing natural ventilation in perimeter zones can drastically reduce overall energy consumption. The BRANZ BEES Interim Report 'Building Design Optimisation' (Cory, Munn and Gates) states that natural ventilation can reduce artificial cooling requirements by up to 90%. When this 90% reduction value is applied to the two lanes scenarios, the 10m lane perimeter zones actually decrease further than the 4m wide zones, due to the higher frequency of overheating in the 10m lane. This natural ventilation (Nat. Vent.) effect can be seen as the red 'cooling' component of Figure 38, for each of the lane scenarios.

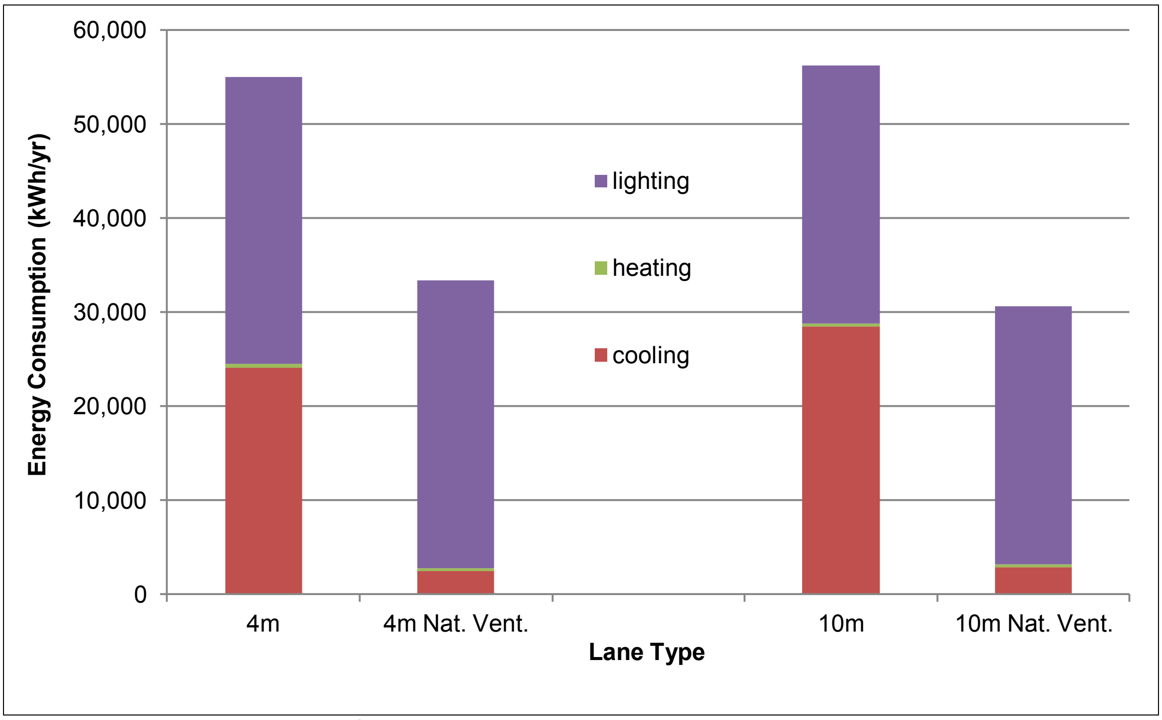


Figure 38: Energy End-Use Component Breakdown in Perimeter Zones Adjacent to 4m and 10m wide Lanes

Figure 39 illustrates how with natural ventilation and intelligent artificial lighting (providing only enough light to supplement natural daylight to the required illuminance level) energy consumption can be drastically reduced. Here zones adjoining 4m wide lanes benefit mainly from natural ventilation, but the 10m wide lane model benefits from daylighting as well. Compared to the baseline square metre energy rate of **76 kWh/m^2/year**, the 4m wide lane reduces energy to **67 kWh/m^2/year** (12% reduction) and the 10m wide model down even further to **63 kWh/m^2/year** (17% reduction).

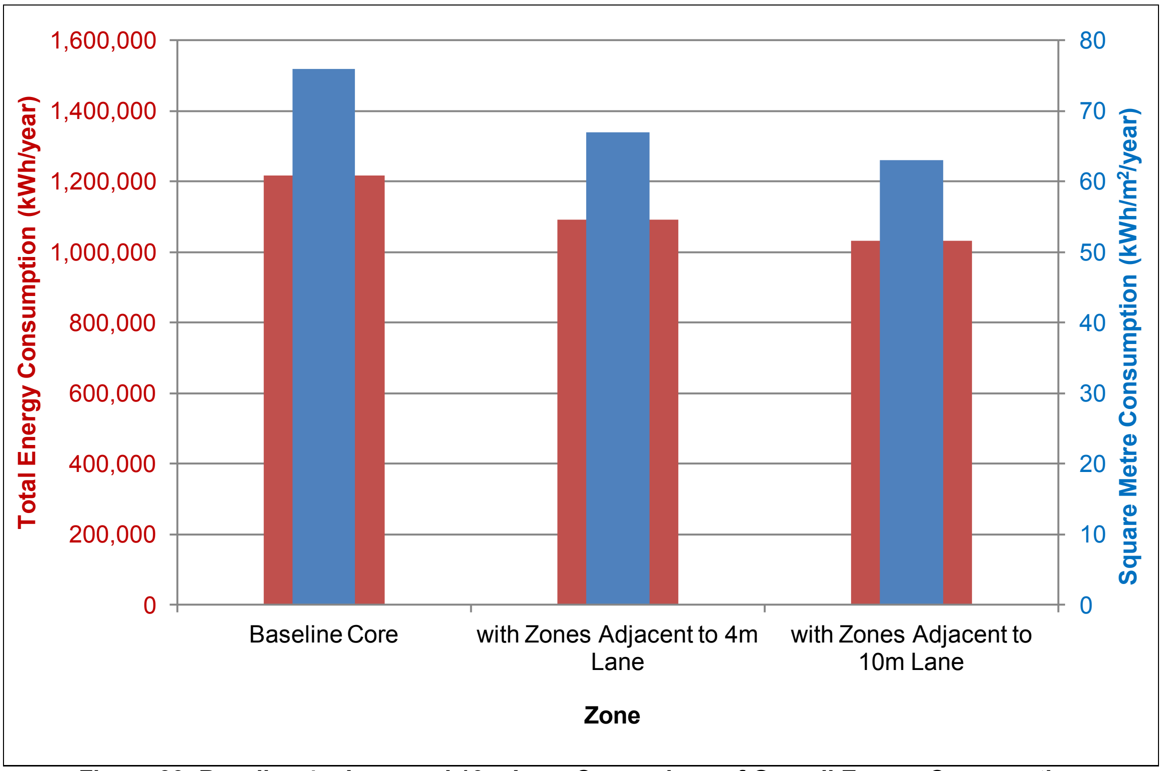


Figure 39: Baseline 4m Lane and 10m Lane Comparison of Overall Energy Consumption

6.4 CCP Model: Internal Courtyards

6.4.1 Daylight Autonomy

As with the lane analysis, the effects of courtyards were assessed on the fourth level.

Test cells were situated on each 'internal' façade facing the courtyard to represent the new internal perimeter zones created by the courtyard's insertion. Figure 40 displays DA results for each of the north, south and east/west (considered equal) facing cells.

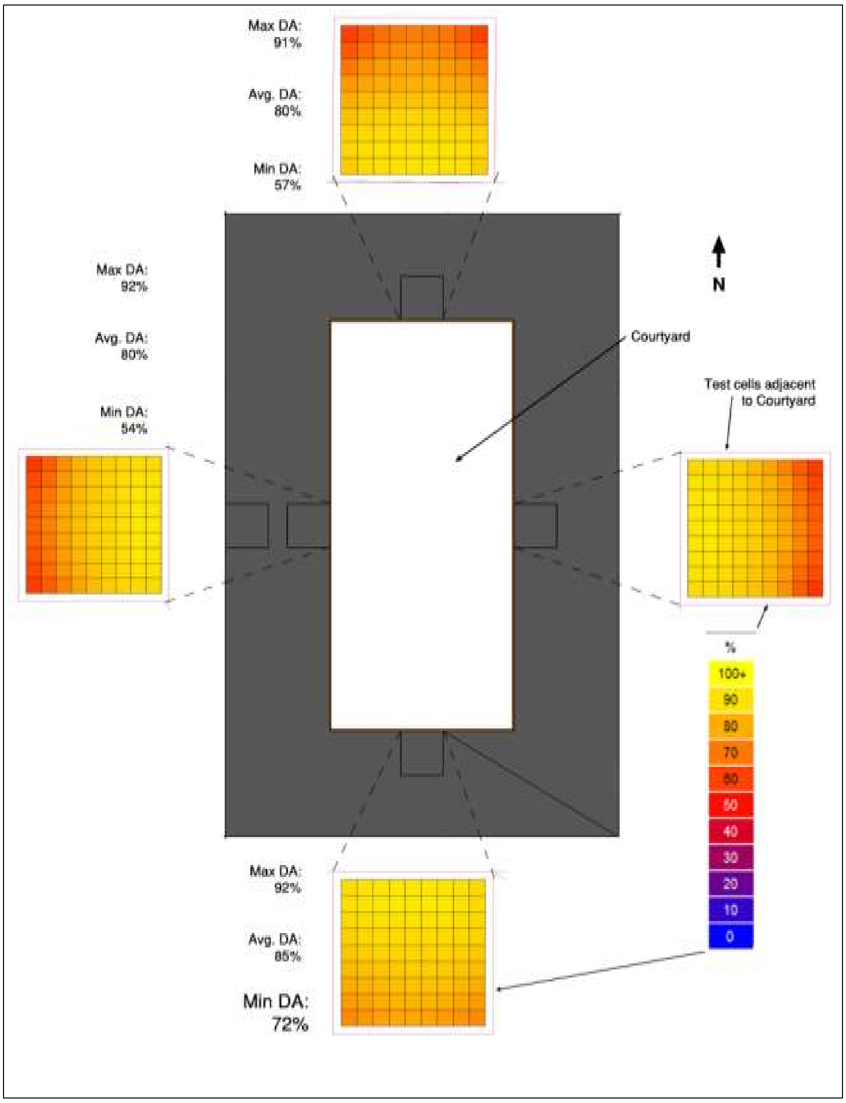


Figure 40: Daylight Autonomy Mapping of Level 4 Perimeter Zones facing Courtyards

As is evident just by looking at the colour rendering of these maps, all four cells experience very high DA. In fact, the lowest reading at any one point across all cells is 54%, meaning that all artificial lighting can be turned completely off for over half of the occupied year.

Even more impressive, average DA across all four cells is over 80%, meaning the majority of each cell's floor area is sufficiently lit for over 80% of the occupied year. Such DA performances are very high and can effectuate significant energy savings through reduced artificial lighting needs. Levels above this fourth level will experience equally or even more impressive daylighting conditions, but levels closer to ground will not benefit so prosperously.

6.4.2 Thermal Comfort

Passive temperatures reflect the high level of solar access to level four perimeter zones seen in the daylight analysis. Figure 41 portrays mostly comfortable temperatures in all courtyard adjoining scenarios but with definite overheating problems. The north-facing cell, modelled here without the shading, is not surprisingly the hottest with almost half of the occupied year experiencing temperatures above 25oC. This would readily be controlled with appropriate shading (Cory, Munn and Gates, Building Energy End-use Study (BEES) Year 5 Interim Report: Building Design Optimisation) and the natural ventilation that the courtyard makes feasible. East and west-oriented cells are more often comfortable at only 30% overheated; and south-facing cells manage to exceed comfortable temperatures for 19% of the occupied year, demonstrating that the heat gains from people and equipment inside the building are a significant contributor to the temperatures experienced indoors.

Baseline core passive temperatures were included in the graph to demonstrate a comparison between central core temperatures and new inner perimeter zone temperatures. This shows that the baseline core actually performs particularly well in terms of thermal comfort when compared to courtyard-facing cells, especially the north-oriented cell. However, the issue with the core zone is that 20% overheating must be cooled by purely artificial measures, whereas perimeter zones (even the north-facing zone) require little-to-no artificial cooling as they have access to natural ventilation.

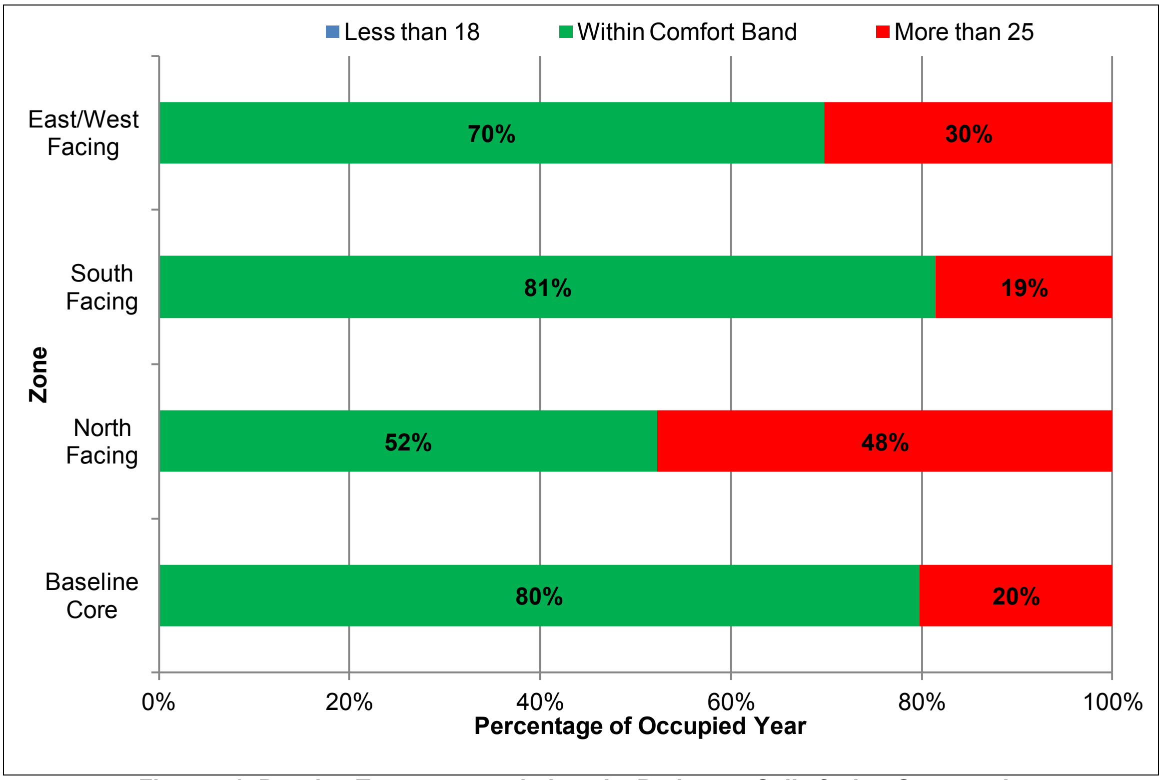


Figure 41: Passive Temperatures in Level 4 Perimeter Cells facing Courtyards

6.4.3 Total Energy Consumption

The square metre energy consumption rates for each courtyard-facing cell in Figure 42 illustrate the natural ventilation point made in the previous thermal comfort analysis section. Although the north-facing zone was passively the hottest of the four presented scenarios, it was also the least energy intensive. Due to natural ventilation reducing cooling requirements by 90%, and ample daylighting, the north-facing perimeter zone square metre consumption was diminished to just 20 kWh/m^2/year (from 76 kWh/m^2/year baseline core). South and east/west-facing cells were nearly as efficient at 25 and 33 kWh/m^2/year respectively. A table of energy consumption values for each zone tested in this study can be found in Appendix E.

Detailed studies would be required for each individual building designed to this open 'courtyard' model. The building form here is a caricature of how individual buildings might be arrayed around a city block to create internal sheltered courtyards. The study has demonstrated the benefit of narrow-plan buildings in terms of energy and internal environmental quality; however it is not a design specification for individual sites or city blocks. The basic principle is to ensure narrow plans to allow through flow of air for ventilation and access to daylight. How buildings such as this are arrayed on a city block requires much broader consideration of urban design principles and goals than this simple energy study.

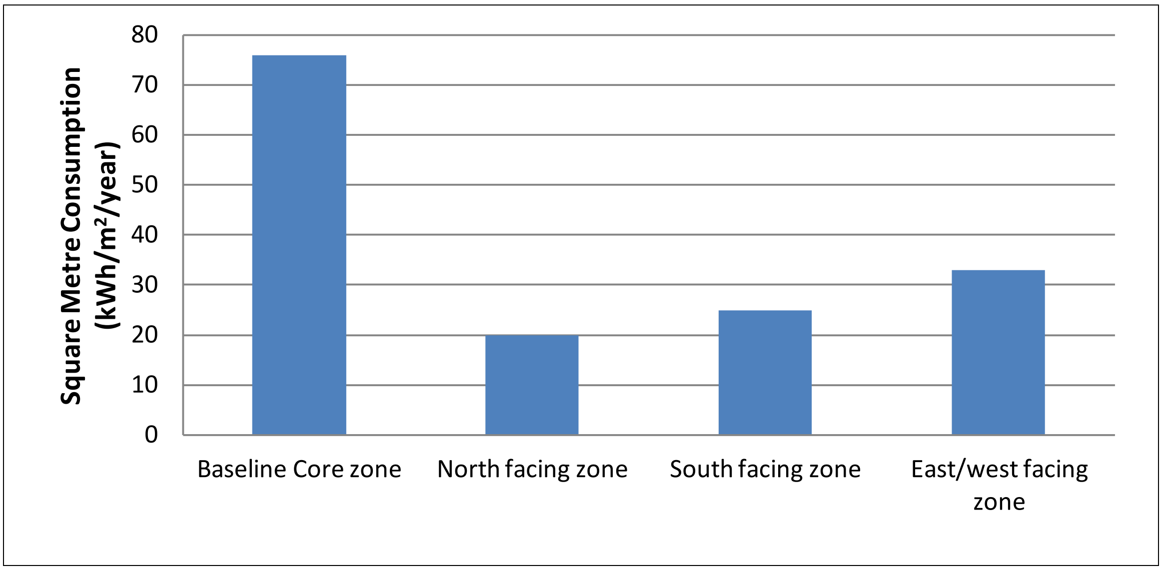


Figure 42: Level 4 Internal Perimeter Zones facing Courtyard Energy Comparison

Figure 42 and Figure 43 represent a study of solely the core zone affected by the insertion of one courtyard. The data takes effect in the yellow and grey portions of Figure 43. This is where baseline core has changed, either becoming internal perimeter zones or courtyard. The baseline core zone affected (one-third of a full 100m x 200m block) was 4,128 m^2. This area was reduced to 2,280 m^2 with the courtyard, none of which is now classified as ‘core’ zone.

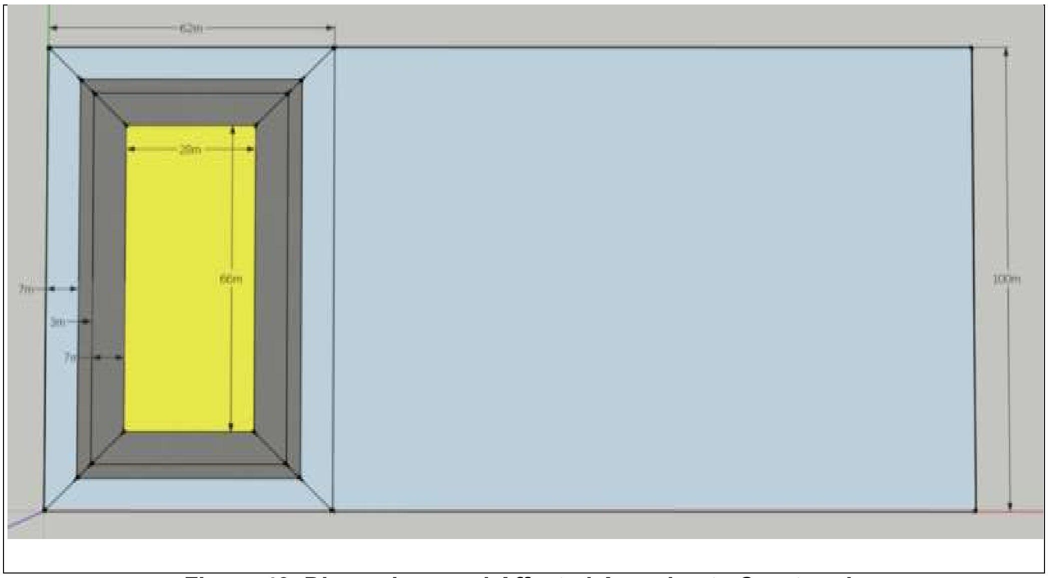


Figure 43: Dimensions and Affected Area due to Courtyards

Figure 42 portrays the total energy saving of 78% (average between the three new courtyard facing perimeter zones) realised through the insertion of a courtyard. Importantly here is the relationship between energy reduction and lost NLA, which is represented by the square metre energy rate which accounts for 'energy consumed' against 'area consuming' for both models. Here, although the floor area has been reduced by one third (34%), the overall energy use has been reduced by nearly two thirds (61%) from the 'baseline core' figure to the 'replaced by courtyard'. Clearly, the block is becoming more energy efficient on a square meter basis.

6.4.4 Total Daylight Hours

Total sunlight hours at ground level in the courtyard are not as high in the main east-west running streets but are on par with north-south running streets. Due to the 29m high building surrounding the courtyard, direct sunlight struggles to penetrate to that depth. Figure 44 illustrates how the area immediately south of the northern perimeter building is predominantly under shade, achieving only about 200 hours of sunlight per annum (in summer months). Sunlight manages to penetrate further to the south of the courtyard for longer periods of the year but only during midday hours. Across the entire courtyard area the average total sunlight hours is only 570 hours per year.

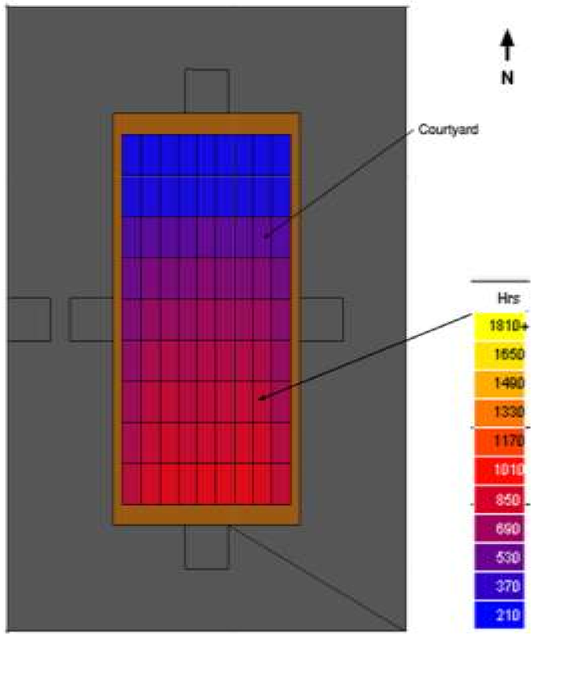


Figure 44: Total Sunlight Hours for Ground Level (of Seven Storeys) in Courtyard

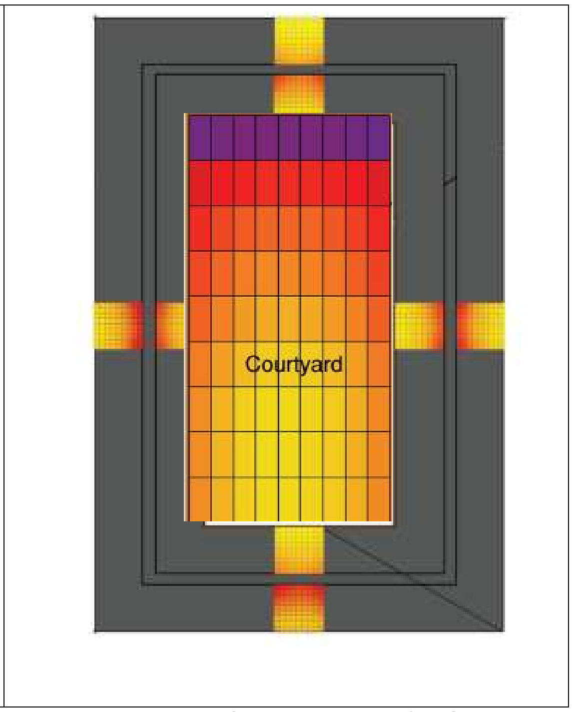


Figure 45: Total Sunlight Hours for Ground Level (of Four Storeys) in Courtyard

The effect of four storey (17m) instead of seven storey (29m) buildings can readily be understood from the Figure 45. It shows on the same light scale as Figure 44 the daylight in rooms and the solar access to the courtyard. The data in the picture is an exaggeration of reality. There is clearly more sun in a courtyard formed by shorter buildings.

However, with four storey (17m tall) forms, ideal wind shelter proportions would suggest courtyards that are more like 17m across, and therefore in the plan area shown there would be space for two smaller courtyards with a central building spanning the courtyard shown from East to West. This would increase the shading somewhat by comparison with that shown.

7. CONCLUSIONS AND RECOMMENDATIONS

The results from the modelling have shown a range of effects resulting from urban form features proposed by the CCP. All three features – step-backs, lanes and courtyards – have have been shown to improve daylighting and reduce energy consumption requirements in a standardised central city block/building.

Step-backs, due to the small area they influenced, made negligible improvments to overall performance (although would have a greater effect in conjunction with courtyards).

4m wide lanes could not offer highly useful daylight, but the ability for new perimeter zones to now utilise natural ventilation, which would make a considerable improvement to dominant cooling loads. 10m wide lanes also created benefits from the ability for adjoining perimeter zones to ventilate naturally. Additionally, zones benefit from the 10m wide lanes further than from the 4m wide lanes through the extra daylight being introduced to the urban canyon via the extra 6m width.

Courtyards, however, made the most substantial improvement to the Baseline Model. Considerable increases in daylight levels and ability to naturally (cross) ventilate the entire building resulted in an outstanding 61% energy reduction from the baseline.

Figure 46 presents the overall effectiveness of each CCP form feature against the baseline passive performance. This graph clearly shows the benefit courtyards, and lanes to an extent, have on passive performance.

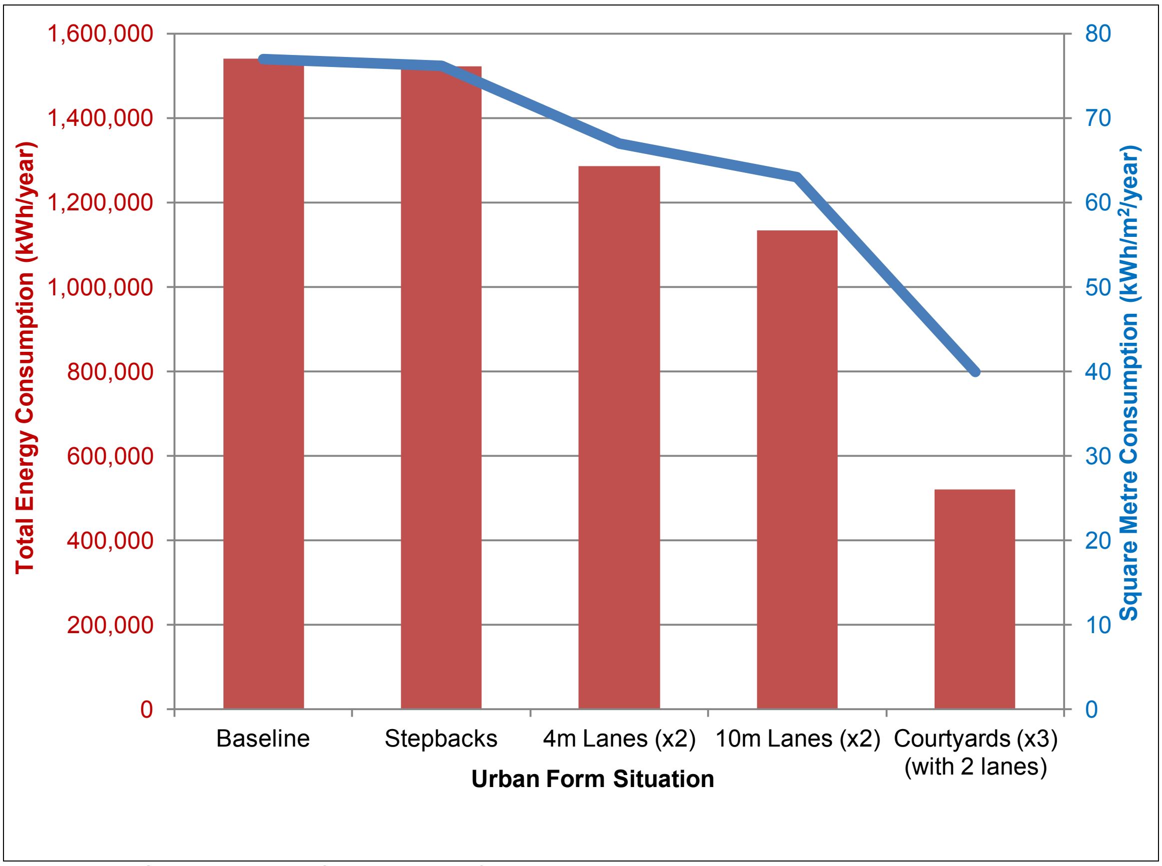


Figure 46: Overall Energy Consumption for each Urban Form against Baseline Model

Figure 46 is very useful in gauging what influence the lost NLA had on energy consumption. As was reported, step-backs effectuate negligible improvement. Lanes had a bigger effect but the most significant changes were seen through the insertion of courtyards. By breaking the large 200m x 100m blocks/buildings into three sections with lanes, each sub-block/building containing an internal courtyard (refer Figure 46) saw a substantial reduction in energy consumption. From the 1.54 million kWh/year baseline model down to 519,000 kWh/year, this combination of form changes implements a reduction of roughly two-thirds (65.6%). More tellingly and reliable however is the square metre rate.

Originally each square metre of floor area consumed 76 kWh/m^2/year; this could be minimised to just 40 kWh/m^2/year using lanes and courtyards. This is a reduction of almost one half (47.4%). The amount of floor area or NLA lost to achieve these energy consumption reductions was 34.7% (20,000 m^2 down to 13,056 m^2), or roughly one-third. This is a very important comparison. If, by employing lanes and courtyards, the energy used could be reduced by roughly one-half, yet only one-third of NLA is lost, then the rate of savings outweighs the rate of losses, in terms of energy consumption per square meter. This is a significant and substantial point for justifying the implementation of lanes and courtyards in central city Christchurch.

This finding alone, while significant in terms of energy reduction on an urban scale, can be argued not to offset in dollar 'savings' the costs in terms of lost rental. However, these figures should not be compared to the "financial losses" through rent as the study has set up an exaggerated scenario for study: prior to the earthquakes, the CBD of Christchurch was not built up to 100% of the whole city block to the full height allowed under the then operational height limits. What the study has taken care to show is if that porous and narrow plan buildings are more efficient than deep plan buildings. Thus, if the area built up previously was to be carefully planned to allow good daylight and natural ventilation the resulting buildings would be significantly lower in energy use per square metre.

There has not been time to examine the other aspects typically associated with well-designed naturally ventilated and naturally lit buildings: improved employee health/satisfaction/productivity. This is not necessarily in conflict with the property market preference for large floor plates intended to make an organisation 'more efficient' because all its employees are housed on single, or a small number of floors. Large floor plates can also provide all employees with access to natural light, to openable windows, to a delightful and attractive environment. This study shows they will also be more energy efficient.

Figure 47 portrays the geometric potential for courtyards and lanes to be combined. It demonstrates the floor area lost (in yellow) from the baseline model; and the zones that are now subject to daylight and natural ventilation (shown in brown). If this were to be implemented, large energy savings could be realised. The final data series in Figure 46, 'courtyards with lanes', illustrates the improvement that this combination would make to energy consumption.

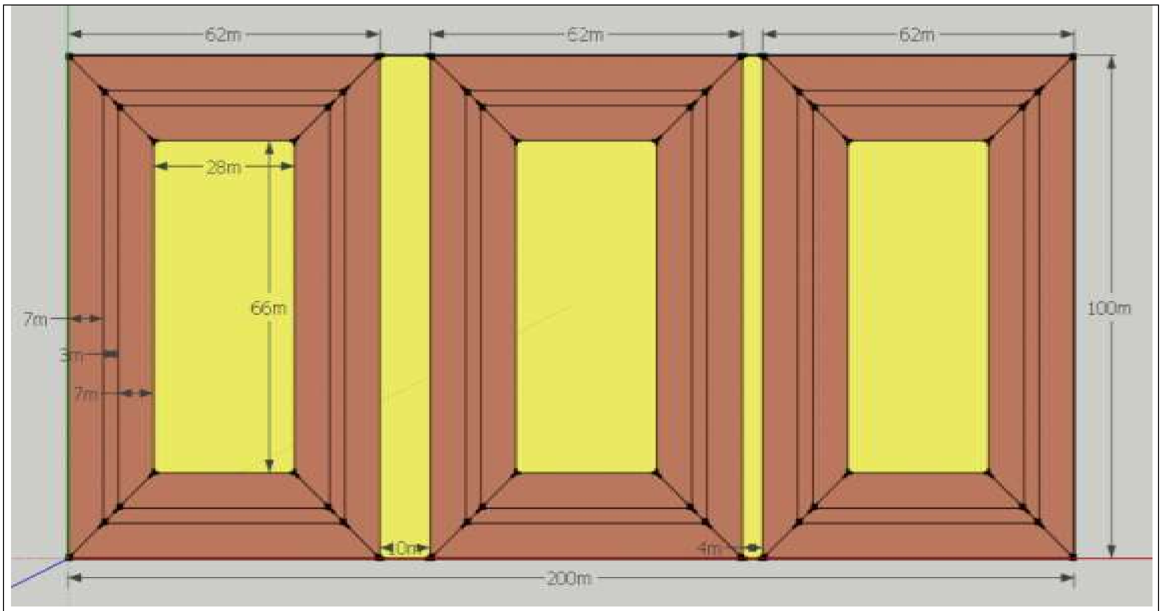


Figure 47: Model of Courtyard plus Lanes and Lost NLA, against Remaining NLA

Based on these findings it is clear that employing more open urban forms such as courtyards in conjunction with lanes (and the seven storey building height limit) would be highly beneficial to passive performance of Christchurch's CBD. Not only will it improve daylight, sunlight, capacity for natural ventilation and overall energy consumption, it would also create desirable working conditions across the entirety of each building. This model would increase proximity to outdoor commodities for all central city users and would contribute to the sunny, open and sustainable city the Christchurch people desire.

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APPENDIX A: WINDOW-TO-WALL RATIO (WWR) CALCULATIONS

To determine the minimum WWR for external windows to achieve suitable daylighting, Reinhart and LoVerso (2011) have devised the following calculation:

$$WWR > \frac{0.1 \cdot DF}{\tau_{vis}} \cdot \frac{90°}{\theta} \qquad (1)$$

Where:

DF = Daylight Factor An average Daylight Factor target of 5% should be targeted according to Reinhart and LoVerso (). DF of 5% is also prescribed in the 'British Standard 8206-2: Code of Practice for Daylighting' as a minimum for a well day-lit space (Littlefair).

τ_{vis} = Visible Transmittance Visible Transmittance will be 0.8 (80%) based on a standard value for a high performance, clear tint, double glazed window (GlassTech).

θ = Visible Sky Angle Visible Sky Angle needs to be calculated (refer Appendix B) for each of the three levels (G, 4 and 7) being tested as they will each be subject to different Visible Sky Angles (refer Figure 48).

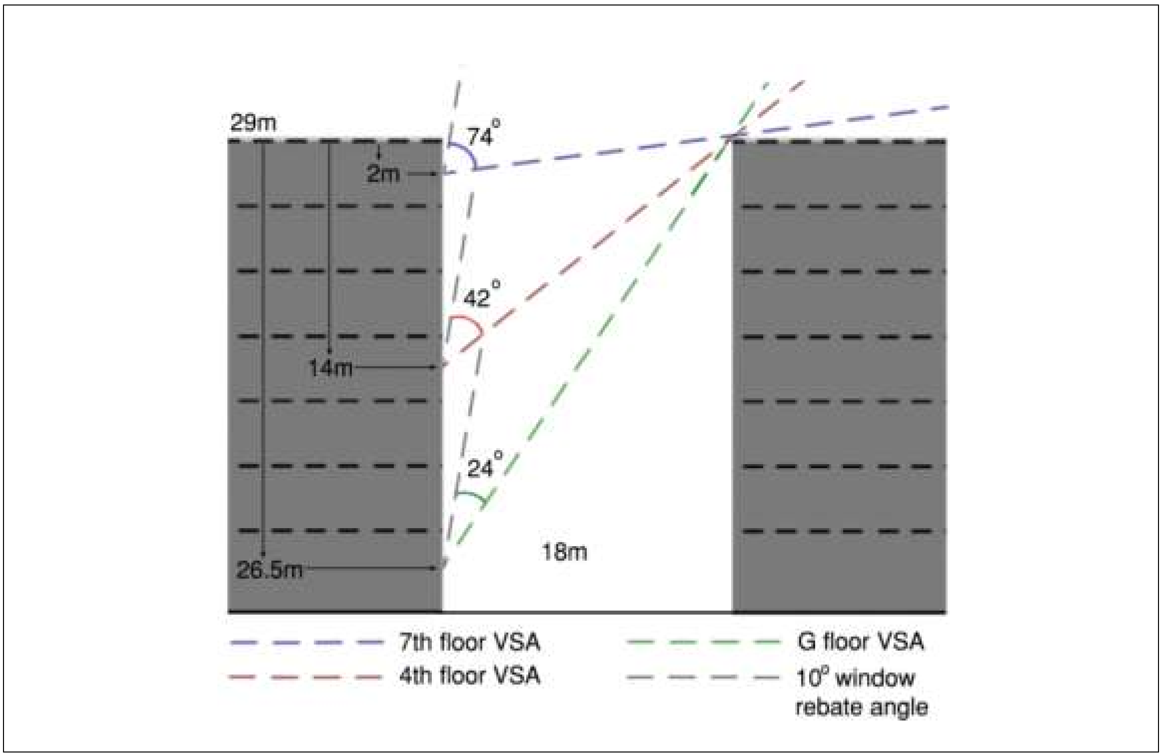

Figure 48: Visible Sky Angles (VSAs) at Mid-Height of each Subject Level

Ground floor WWR calculation:

$$WWR > \frac{0.1 \cdot 5}{0.8} \cdot \frac{90°}{\mathbf{24°}} \qquad (2)$$

According to Reinhart and LoVero's (2011) calculation, the ground floor WWR needs to equal 2.3 or greater. This indicates that a window of area 2.3 times greater than the available wall area is required to provide adequate daylighting to the ground floor space. This is not possible.

Fourth floor WWR calculation:

$$WWR > \frac{0.1 \cdot 5}{0.8} \cdot \frac{90°}{\mathbf{42°}} \qquad (3)$$

The fourth floor WWR is also too high to achieve, at 1.3 or greater. This indicates that a 5% average DF target is too high even in a seven storey height limit urban environment.

Seventh floor WWR calculation:

$$WWR > \frac{0.1 \cdot 5}{0.8} \cdot \frac{90°}{\mathbf{74°}} \qquad (4)$$

As expected, the seventh floor has a much lower minimum WWR of 0.76, which is achievable and within Reinhart and LoVero's 80% threshold- *"only zones with a minimum WWR below 80% can be realistically day-lit."* They then state that zones with a minimum WWR of higher than 0.8 (as ground and fourth floors are here) should be reconsidered.

To determine a more realistic WWR the GreenStar New Zealand Office 2009 tool can be used. The Indoor Environment Quality 'Daylight' credit requires (for maximum points) a DF of only 2.5% over 90% of the subject area (New Zealand Green Building Council) rather than the more stringent 5% British Standard. Assuming an average DF of 2.5%, Ground floor WWR would equate to 1.2, which is still larger than possible. However, it would also determine a minimum WWR of 0.67 for the fourth floor; and 0.38 for the seventh floor.

Ground floor spaces are shown to require a large window-to-wall ratio to maximise daylighting capacity in a low potential daylighting situation. Reinhart and LoVerso () state that *"a WWR of 84% corresponds to a 'fully glazed façade' i.e. a rough façade opening of 100%."* The CCP describes a preference for 'interactive frontages' on ground floor levels within the CBD to promote marketability in public places (Christchurch City Council) High WWRs contribute to the 'interactive frontage' concept, so will provide benefit to both daylighting and 'distinctive city' goals. Hence the 0.8 (rounded from 84%) WWR will be used in Ground floor situations in this study.

Both the Fourth and seventh levels can be sufficiently daylit with WWR's of 0.67 and 0.38 respectively. Typical inner city building façades are uniform across their entire height (with the exception of the Ground floor). This would suggest WWRs are equal for each level. In imitating this façade type, an average value of 0.5 (rounded from 0.525) from the two calculated minimum WWR figures will be used for both fourth and seventh levels.

Based on the above calculations and GreenStar New Zealand target DF levels, the **Ground level WWR will be 0.8 and fourth/seventh levels will be a WWR of 0.5**

APPENDIX B: VISIBLE SKY ANGLE (VSA) CALCULATIONS

B1 – Ground Floor

To find x^o:

Adjacent = 18m

Hypotenuse = 26.5m

Therefore x = 55.8^o

Visible Sky Angle = 90^o – (55.8+10) [10^o angle from the vertical allowed for window rebate into façade]

Ground floor VSA = 24^o

B2 – Fourth Floor

To find x^o:

Adjacent = 18m

Hypotenuse = 14m

Therefore x = 37.9^o

Visible Sky Angle = 90^o – (57.9+10) [10^o angle from the vertical allowed for window rebate into façade]

Ground floor VSA = 42^o

B3 – Seventh Floor

To find x^o:

Adjacent = 18m

Hypotenuse = 2m

Therefore x = 6.34^o

Visible Sky Angle = 90^o – (6.34+10) [10^o angle from the vertical allowed for window rebate into façade]

Ground floor VSA = 74^o

APPENDIX C: MODELLING AND SIMULATION PROCESS

C1 – Baseline Geometry for Daylighting Analysis

Following is an outline of the process used to create the Baseline Model geometry for the daylighting analysis only. Refer Figure 9 for visual description of the daylighting Baseline Model.

1) Central city grid (3 x 3 blocks) is laid out. Blocks are 100m in the north-south direction; and 200m in the east–west direction. Blocks are separated by 18m wide streets in all situations.
2) All nine city blocks are extruded to the predefined height of 29m. Each block consists of a single cuboid, which represents all individual buildings in a single entity.
3) The central block of the nine is the 'subject block' within which all testing will take place. All outer/surrounding blocks are employed as shading and reflectance objects to imitate a real urban environment.
4) On all façades of the subject block, and façades opposite subject block, each level is outlined. Ground level is 5m high with all other/upper levels being 4m high each.
5) Based on patterns seen in Architecture NZ magazine (Architecture NZ) levels G, 2, 4 and 6 will be glazing; and levels 1, 3 and 5 will be concrete. This is done to imitate typical surface reflectance of façades within a central city setting.
6) 'Test cells' are applied at the horizontal centre of each façade (north, south, east and west), at levels G, 4 and 7 (bottom, middle and top heights). Test cells are 7m deep (refer Section 4.2) by 7m wide (square floor area).
7) A clear, double-glazed window is inserted into the façade sharing wall of the test cell. The window size is the window-to-wall ratio (WWR) as defined in Appendix A.

The complete geometry is now exported to Ecotect where daylight analysis can be performed.

C2 – Baseline Daylight in Buildings Analysis in Ecotect/Daysim

Daylight Autonomy (DA) has been determined as the most appropriate measure for daylight to buildings for this study. The following process outlines how DA values were calculated for test cells in the Baseline Model.

1) Baseline Model geometry imported into Ectotect; and Christchurch *.epw weather file based on National Institute of Water and Atmospheric research (NIWA) measured data attached.
2) Analysis grid of 100 data points (10 wide x 10 deep) setup in each test cell (one at a time) at predefined working plane height of 0.7m above floor level.
3) Model exported to Daysim for simulation. Import process defines: Intermediate (mid-season) sky; occupied hours of 8am-5pm; and DA minimum of 320 Lux.
4) Daysim calculation data analysed in Daysim and exported back into Ecotect for illuminance maps where required.

C3 – Baseline Sunlight to Street Analysis in Ecotect

Total sunlight hours have been determined as the most effective measure for sunlight available to the street for this study. The following process outlines how total sunlight hours values were calculated for test cells in the Baseline Model.

1) Baseline Model geometry imported into Ectotect; and Christchurch *.epw weather file based on National Institute of Water and Atmospheric research (NIWA) measured data attached.
2) Analysis Grid of 100 data points (20 wide by 5 along street) setup over street at ground level in front of subject façade.
3) Because total sunlight hours are a measure which considers only direct solar beam rays, this test can be carried out in Ecotect (Ecotects limitation is that it does not consider internally reflected ray factors). Measured across the entire year between the hours of 7am and 7pm (Christchurch City Council). The total sunlight hours figure is out of an assumed 4,380 total sunlight hours based on the 12 hours per day, 365 days a year model.
4) Results are applied to the Ecotect total sunlight hours map relative to its urban context with average figures calculated for basic quantification and comparisons.

C4 – Baseline Geometry for Thermal and Energy Analysis

Following is an outline of the process used to create the Baseline Model geometry for the thermal and energy (refer Figure 10 consumption analysis only). Points of major difference to the daylighting model are underlined for easy reference.

1) Central city grid (3 x 3 blocks) is laid out. Blocks are 100m in the north-south direction; and 200m in the east–west direction. Blocks are separated by 18m wide streets in all situations.
2) All nine city blocks are extruded <u>as OpenStudio shading objects</u> to the predefined height of 29m. Each block consists of a single cuboid, which represents all individual buildings in a single entity.
3) The central block of the nine is the 'subject block' within which all testing will take place. All outer/surrounding blocks are employed as shading and reflectance objects to imitate a real urban environment.
4) On all façades of the subject block each level is outlined. Ground level is 5m high with all other/upper levels being 4m high each. <u>Reflectance of opposite façades is not required</u> for thermal and energy analysis as they are for lighting so is not applied.
5) <u>'Test cells' are the BEES template</u> ('EnergyPlus object') identified in Section 4.3. This OP5 template consists of four 'perimeter' zones and one 'core' zone. One of these templates will be applied at levels G, 4 and 7 (bottom, middle and top heights) and will represent the entire level. To replicate the daylighting analysis test cells, the perimeter zones are 7m deep, but they cover the full length of the façade.
6) A clear, double-glazed window is inserted into the façade sharing wall of the test cell. The window size is the window-to-wall ratio (WWR) as defined in Appendix A.
7) The complete geometry is now exported to EnergyPlus where thermal comfort and energy consumption analyses can be performed.

C5 – Baseline Thermal Performance in EnergyPlus Building Analysis

'Percentage Time within Comfort Band' (temperature in degrees Celsius, ^{o}C) has been determined as the method of measuring thermal performance for this study. The following process outlines how thermal comfort values were calculated for test cells in the Baseline Model.

1) Baseline geometry opened in EnergyPlus. Christchurch 'epw' weather file (NIWA) attached and global position located.
2) Correct materials applied to test cell walls, windows etc.
3) 'Ideal loads' heating ventilation and air conditioning (HVAC) system applied to model. This method ensures artificial HVAC is only used when temperatures rise or fall out of the predefined 18-25^{o} comfort band.

4) The ‘output’ employed to deliver useful data for the ‘percentage time within comfort band’ thermal performance measurable is ‘zone operative temperature’. This is an hourly temperature recording for the occupied hours (8am-5pm weekdays)
5) ‘Zone operative temperature’ figures are exported to MS Excel where they are compiled into readable data sets and presented for analysis.

C6 – Baseline Energy Consumption in EnergyPlus Building Analysis

Energy Consumption, measured in kWh has been determined as the method for measuring overall passive performance in buildings. The following process outlines how energy consumption values were calculated for test cells in the Baseline Model.

This measurable is simulated in the same ‘run’ as the thermal comfort measurable but with a different output. ‘Energy end uses’ (for ‘interior lighting’, ‘heating’ and ‘cooling’ only) measures how much energy was required to supplement natural lighting and temperatures to maintain comfort in the test cells. Energy consumption figures are also exported to MS Excel for analysis and presentation.

APPENDIX D: STEP-BACK ENERGY CONSUMPTION CALCULATIONS

D1 – Baseline Energy Consumption:

- core zone 16,000 m^2 at 76 $kWh/m^2/year$ (according to simulations)= 1,216,000 kWh/year
- east, west and south perimeter zones total 2,600 m^2 at 112 $kWh/m^2/year$ = 291,000kWh/year
- subject north perimeter zone of 1,400 m^2 at 79 $kWh/m^2/year$ = 110,600 kWh/year
- **Totals 1,617,600 kWh/year**

D2 – Step-back Energy Consumption

- core zone 16,000 m^2 at 76 $kWh/m^2/year$ = 1,216,000 kWh/year
- east, west and south perimeter zones total 2,600 m^2 at 112 $kWh/m^2/year$ = 291,000 kWh/year
- subject north perimeter zone of 1,400 m^2 at 78 $kWh/m^2/year$ (average of levels G, 4 and 7) = 109,200 kWh/year
- **Total 1,616,200 kWh/year**

APPENDIX E: ENERGY CONSUMPTION RATES

Table 1: Energy Consumption Rates

Scenario	Scenario and Zone	Energy per Zone ($kWh/m^2/year$)	Ventilation Mode
Baseline	Core	76	Artificial Cooling
	North	79	
	East/West	83	
	South	58	
Step-backs	North	78 (33 with Nat. Vent.)	
Lanes	10m East/West	63	Naturally Ventilated
	4m East/West	67	
Courtyards	North Facing	20	Naturally Ventilated
	South Facing	25	
	East/West Facing	33	

NOTE: Energy figures did not include equipment loads, just cooling, heating and lighting. This was done because passive form changes do not influence equipment loads. All testing and results are consistent with this parameter.