Office

Energy Efficiency Training and Information Project

Commercial Buildings

Wantirna
South
VIC

Research group

High Performance Architecture research cluster, School of Built Environment, Faculty of Arts, Design and Architecture, UNSW

https://www.be.unsw.edu.au/research/research-clusters-and-groups/high-performance-architecture-research-cluster

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Cover image:
Knox Civic Centre in Wantirna South, Melbourne.

Contents

1. Executive Summary

A complete renovation package ... can lead to energy savings of 62.9 %

Global climate change is exposing existing buildings to conditions they were not designed for, with a growing need to reduce the operational cost and carbon dioxide emissions. Thus, established buildings need energy retrofits. Almost 80% of 2050 buildings already exist today [1], and we must prioritise improving the efficiency of established buildings. The largest fraction of the energy consumption in an office building is related to energy uses for heating, ventilation, air conditioning and refrigeration (HVAC&R) applications, lighting, and appliances [2]. This report uses a real-life case study to visualise the impact of energy optimisation strategies in office buildings.

A dynamic thermal model of the office building is simulated with the TRNSys software tool, reproducing the thermal features and building services in the real building. This report summarises the findings of the performed analysis on the existing conditions. It provides recommendations for improving the indoor conditions and minimising the energy consumption in the Knox Civic Centre in Wantirna South, Vic, a rather large low-rise office building selected as a case study. The structural and energy performance features of the studied office building are representative of the typology and construction period (1990s).

The building is an exemplar case of energy refurbishment, with several interventions carried out from 2008. Here, as a baseline scenario we consider the pre-retrofit condition (as in 2007), simulating different retrofit strategies in consideration of currently available technology.

The baseline scenario for determining feasible interventions is based on the fact that energy consumption for heating, cooling and lighting is the most significant issue to address, with values of 11.0, 16.4 and 43.3 kWh/m²a, respectively. Hence, the main effort lies in reducing heating, cooling and lighting requirements. The windows and glazed areas, in general, are not up to date with contemporary standards, and since they account for a big percentage of the envelope's overall surface, their contribution to energy losses in the cooling period is significant. Therefore, there is a potential for retrofitting. Also, the uninsulated walls and poorly insulated roof, which in such a low-rise building has a major impact on energy performance, are focal points for reducing heating loads. The advances in Building Automation and Control systems over the last decade have been dramatic, and so has the retrofitting potential.

The simulations proved that the natural lighting levels in the spaces close to the windows are relatively high, depending on the area and depth of the space. It is recommended that the full height windows facing north should be externally shaded using automated blinds or horizontal louvres. These shading elements would reduce the natural lighting levels close to the windows, minimise the glare issues and result in more uniform lighting levels. Based on the results, the following recommendations are technically viable and relatively easy to implement:

- Improvement of the lighting systems with LED (as implemented in 2021) and daylight controls.
- Refurbishment of the windows, double glazed ones, of high energy efficiency to reduce solar loads in summer and achieve airtightness throughout the year.
- Installation of ceiling fans, the introduction of night ventilation patterns in the operation of the HVAC&R system and window shading during the cooling period to reduce cooling loads. →

- Installation of mechanical ventilation with heat recovery to reduce heating loads.
- Installation of state-of-the-art Building Automation and Controls, together with a Building Management System, to interlock the use of HVAC&R and lighting systems with both the weather conditions and the operational requirements.
- Refurbishment of the roof, fitting 80 mm of mineral wool under the existing roof, reducing both heating and cooling loads.
- Finally, improving the insulation of external walls. Insulation consists of 80 mm of mineral wool covered with plasterboard, leading to a reduction in both heating and cooling loads.

In conclusion, a complete renovation package that includes replacement of the building’s windows and glazed surfaces, insulation of the external walls and roof, combined with an upgrading of the lighting system, the installation of ceiling fans and the use of night-time ventilation, mechanical ventilation with heat recovery and window shading patterns, linked all with the implementation of a state-of-the-art BAC system, can lead to energy savings of 62.9%, resulting in an energy consumption of 38.0 kWh/m²a, compared to the baseline of 102.2 kWh/m²a. Also, using NABERS Energy reversed calculator, for the building block considered in this study, if fully retrofitted, the NABERS star rating can increase from 2.09 (pre-retrofit, as in 2007) to 3.89 stars (based on simulation results) [17].

2. Regulations, Standards, and guidelines

The regulatory documents and Standards used for the analysis and the proposals are:

- National Construction Code of Australia 2019 Volume One.
- ANSI/ASHRAE 62.1-2019 Ventilation for acceptable indoor air quality
- ASHRAE Handbook Fundamentals 2017, Chapter 18: Nonresidential cooling and heating load calculation
- ISO 17772-1-2017 Energy performance of buildings -Indoor environmental quality, Part 1: Indoor environmental input parameters for the design and assessment of energy performance of buildings
- AS 1668.2-2012 The use of ventilation and air conditioning in buildings, Part 2: Mechanical ventilation in buildings
- AS/NZS 1680.1-2006: Interior and workplace lighting, Part 1- General principals and recommendations.
- AS/NZS 1680.2.1-2008: Interior and workplace lighting, Part 1- Specific applications. Circulation spaces and other general areas.
- AS/NZS 1680.2.2-2008: Interior and workplace lighting, Part 1- Specific applications. Office and screen-based tasks. ■

3. Introduction

The selected case study building is a typical office building built in Australia in the 1990s, representative of many other buildings constructed in the same period. The aim of selecting Knox Civic Centre is the potential for methodology replication and findings expansion to other similar buildings.

The Knox Civic Centre is an exemplar case of energy retrofit, with staged interventions carried out by Council starting in 2008, delivering substantial energy savings. These interventions were performed between 2008 and 2021, and include the installation of a cool roof, a 5 kWp rooftop PV plant, energy-efficient lights and heat-extraction from the atrium (Figure 1). Considering the pre-COVID period, the energy-savings account for 27% of the energy consumption (4-year average pre-retrofit vs 4-year average retrofitted pre-COVID), or approximately $91,000 per annum with the 2021 energy costs, initially of approximately $322,000 (Figure 2). →

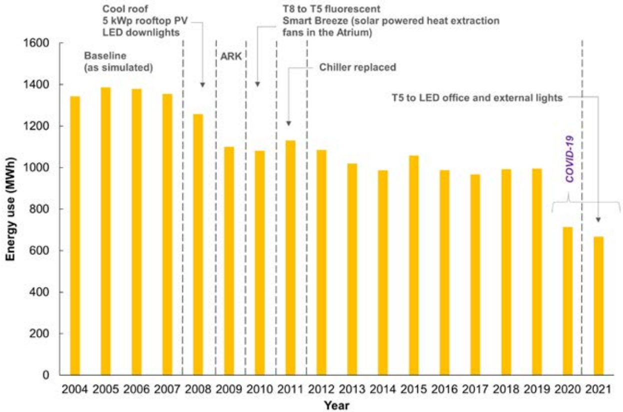

Figure 1. Energy use of the Knox Civic Centre before and after retrofits. ARK refers to a system for voltage optimisation.

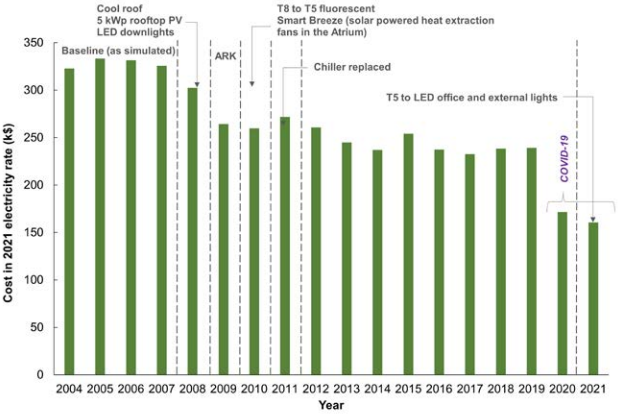

Figure 2. Energy cost (computed using the 2021 electricity rate) to operate the Knox Civic Centre.

As the building serves as a case study helpful to consider opportunities for similar buildings, here we simulate the building in its pre-retrofitted state (2007) to consider the potential for energy improvements with the currently available technology. Further, it offers insight into additional opportunities for energy efficiency, beyond those already implemented, and complementing the information available thanks to metering. Also, multiple interventions on the real buildings were performed at the same time (e.g., cool roof coating, 5 kWp rooftop PV and LED downlights all in 2008), and simulations allow for the assessment of single interventions, instead. Furthermore, every year the climate conditions are different, and it is not possible to compare the relative savings due to subsequent interventions, which can instead be done with building energy simulations, using the same weather file.

Clearly, one sample office building cannot completely fit all similar buildings. Each office has differences; however, even though the required procedure may differ, the logic and methodology presented here offer a high-quality framework to improve the energy efficiency in such buildings.

Assessing the energy performance of an office building is a complicated task. It starts with determining the building's construction features, including the efficiency of the building envelope, lighting, HVAC&R, equipment etc. Considering the building's features, all calculations are based on the 'as-built' condition of the building elements (U-values, shading, air-permeability, etc.). The efficiency of the HVAC&R system (Coefficient of Performance (COP) and Seasonal Energy Efficiency Rating (EER) are selected based on the provided information by their manufacturers, and installed lighting and plug loads were determined either by data provided by the building operators or following standards and regulations.

Additionally, two types of specific conditions that have a significant impact on such a building's performance must be considered:

(a) the operational parameters (hours of operation, set temperatures for heating and cooling, natural ventilation patterns, use of artificial lighting, etc.) and

(b) the microclimate on the building's site (shading by natural obstructions and other buildings, albedo and thermal storage of surrounding areas, etc.). ■

4. Knox Civic Centre in Melbourne

4.1. Case study description

4.1.1. Climate

The Knox Civic Centre is located at 511 Burwood Highway, Wantirna South Vic 3152 (37.871S, 145.245E). The building is in the eastern part of Melbourne, 86 m above sea level. In Köppen's climate classification, Knox's council area is categorised as Cfb, meaning that it has a temperate oceanic climate [3]. There is no significant precipitation difference between seasons. The average rainfall is 855 mm, with an average of 115 days of rain each year. Due to its geographical location, the relative humidity is distributed evenly throughout the year (67-85% in the morning and 46-68% in the afternoon). Winters are usually very cloudy and frequently wet. January and February are the hottest months, with a mean maximum temperature of 26.5°C, and the coldest month is July, with a mean minimum temperature of 5.9°C. The primary climatic information is illustrated in Figure 3. →

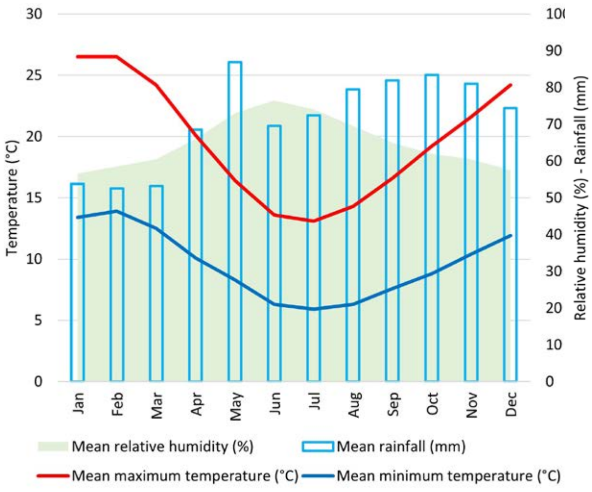

Figure 3. Climatic data for the council area of City of Knox [4].

4.1.2. Building description

This case study office building was rebuilt after a fire in 1998, and here it is considered in its 2007 condition, before energy efficiency interventions (Figure 4). According to the National Construction Code, its classification is Class 6 – office building used for professional or commercial purposes [5]. The Knox civic centre provides services to 255 people at the busiest hours. The under-ceiling height of this two-story office building varies between is 2.7 m. Figure 3 illustrates the treemap chart of the gross internal area of case study buildings. The total gross floor area is 6,174 m².

4.1.3. NABERS rating

Based on the documents provided by Knox City Council, the performance was internally estimated equivalent to a NABERS Energy 3.5 star in 2011. Its annual energy use was 1,453,341 kWh (228.3 kWh/m²), and the annual greenhouse gas emission was 1,435,302 kg CO_2 (225 kg CO_2/m²).

4.1.4. Energy consumption and sources

This building has a 5 kWp rooftop PV plant (installed in 2008), not considered in the baseline simulation. Electricity is used for cooling, heating, lighting, and appliances, and natural gas is used in cooking and domestic water heating. ➔

Figure 4. Northern view of Knox Civic Centre.

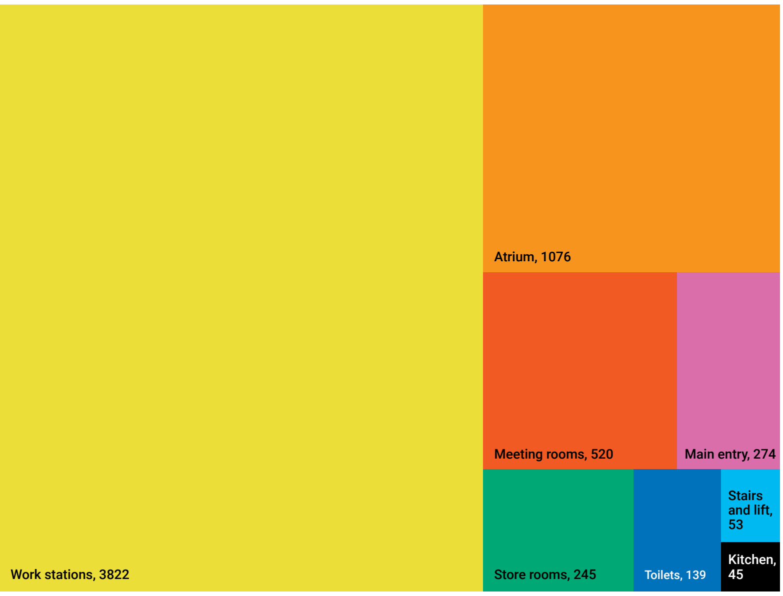

Figure 5. Gross floor divided area of case study building.

4.2. Building modelling input parameters

The modelling parameters combine collected data from the building inspection, utility bills and Australian and global standards. Each modelling assumption will be briefly explained in this section, presenting the relative references.

4.2.1. Occupancy

The case study office building has capacity for 255 people [6], and the occupancy schedule is selected based on the national code of construction [5].

4.2.2. Geometric data

Knox Civic Centre has two floors. Table 1 shows the primary purpose of each area of the building (Figure 5).

4.2.3. Building Components

A significant part of energy consumption is to maintain comfort leaks through the building envelope. As a key step in assessing the potential benefits of improving windows, walls, roofs and floors, the current thermal performance should be determined. Surveying the case study office building, the thermal properties of the building envelope are assessed based on construction features and age. This information is used to model the building and develop a thermal model. Here, the performance descriptors of external walls, roof and windows are introduced.

4.2.3.1. External walls

The external wall of the case study building includes five main layers. There is a fibre-cement cladding on the exterior, followed by an air gap and concrete blocks, a second air gap and plasterboard on the interior. The R-value of the external walls is 0.667 m².K/W, and the solar absorbance coefficient is 0.55. Also, using the average annual wind velocity in the area (3.6 m/s) [4], the convective heat transfer coefficient is calculated as 17.6 W/(m².K) [7]. →

Table 1. Building geometric information and floor area (air-conditioned, not air-conditioned, and gross floor area).

Zone	Level	Air-con. area (m²)	Not air-con. area (m²)	Gross floor area (m²)
Main entry	+1	274	0	274
Stairs	GF and +1	53	0	53
Atrium	GF and +1	1,076	0	1,076
Kitchen	GF and +1	45	0	45
Meeting rooms	+1	520	0	520
Workstations	GF and +1	3,822	0	3,822
Toilets	GF and +1	0	139	139
Stores and plant room	GF	0	245	245
Total		**5,790**	**384**	**6,174**

Table 2. Building Components - Performance Descriptors – Construction – External Walls.

Material	Thickness (mm)	Conductivity (W/m.K)	Capacity (kJ/kg.K)	Density (kg/m³)	Resistance (m².K/W)	Ref.	Section and page
Fibre cement cladding	1.2	0.25	1	1360	-	[5]	Section J, page 388
Air space	20	-	-	-	0.10	[5]	Section J, page 388
Concrete block	200	0.85	1	1250	-	[5]	Section J, page 388
Air space	50	-	-	-	0.10	[8]	Section 5.3, page 5
Plaster board	10	0.17	1	880	-	[5]	Section J, page 388

R-value: 0.667 m².K/W

4.2.3.2. Roof

The roof of the case study office building consists of six layers. On top, there is a field-applied reflective coating on metal sheeting, followed by an anti-con blanket and an air gap, and then mineral wool insulation and a plasterboard false ceiling. The R-value of the roof is 1.036 m^2.K/W, and the solar absorbance coefficient is 0.25, with a thermal emittance of 0.90, since a solar reflective coating was installed. The initial solar absorbance of the coating was 0.10, which we increased to 0.25 to take into consideration the geometry of the metal sheeting and weathering and soiling, leading to performance loss after ten years of exposure. Also, using average annual wind velocity (3.6 m/s) [4], the convective heat transfer coefficient is calculated as 17.6 W/(m^2.K) [7].

4.2.3.3. Windows

External windows in the case study buildings are single glazed with aluminium frame. The selected shading and glazing in the model are presented in Table 4.

4.2.4. Domestic hot water

The required hot water for the Knox Civic Centre is calculated based on Table 2m, NCC volume 1 page 355 [5]. Therefore, considering the need for a 50°C temperature increase and water heat capacity (4.19 KJ/kg.°C), 150 MJ heating energy is required for daily heating domestic water. ➔

Table 3. Building Components - Performance Descriptors – Construction – Roof.

Material	Thickness (mm)	Conductivity (W/m.K)	Capacity (kJ/kg.K)	Density (kg/m^3)	Resistance (m^2.K/W)	Ref.	Section and page
Ballast Gravel	150	2.0	0.91	1700	-	[8]	Section 8.3, page 10
Water proofing	4	0.23	1	1100	-	[8]	Section 8.3, page 9
Concrete	200	0.85	1	1250	-	[5]	Section J, page 388
Air cavity	100	-	-	-	0.16	[9]	Section 5.3, page 5
Mineral wool	40	0.042	1.03	50	-	[8]	Section 8.2, Table 4 Page 18
Plaster board	10	0.17	1	880	-	[5]	Section J, page 388

R-value: 1.036 m^2.K/W

Table 4. Building Components - Performance Descriptors - Openings Shading.

Shading type & material	External Shading is applied on the southern, eastern, and northern sides of building		
Glazing	**Value**	**Unit**	**Ref.**
Glazing U-value	2.8	(W/m^2.K)	
Glazing solar heat gain coefficient	0.64	N/A	
Window frame material	Aluminium	N/A	
Window frame ratio or width	15	%	
Glazing layout – WWR	40	%	
Glazing type	Single glazed	N/A	

Table 5. Domestic hot water.

Demand-side	Occupancy	Unit Hot water demand	Daily hot water demand (lit)
	255	4 lit/person	1,020

4.2.5. Internal gains

The information regarding the thermal comfort in Knox Civic Centre is provided by the building facility management. Lighting and personal heat gain assumptions in the model are based on Australian and international standards.

4.2.6. Ventilation and infiltration

The supplied fresh air flow rates and the infiltration rates are assumed based on international standards.

4.2.7. Thermal Comfort

The thermal comfort parameters have been considered as in Table 8, using the PMV method, according to the National Construction Code.

4.2.8. Energy resources and HVAC&R systems

Electricity and natural gas are the energy sources of Knox Civic Centre. Based on the information provided by building facility management, the coefficient of performance (COP) and energy efficiency ratio (EER) of the VRV systems are considered as 3.0 and 2.5, respectively. ➔

Table 6. Temperature setpoints, lighting and personal heat gain.

	Section	Value	Unit	Ref.	Section and page
Cooling setpoint temperature	All	23	°C	[6]	Annex O, page 53
Heating setpoint temperature	All	22	°C	[6]	Annex O, page 53
Personal latent gain	All	55	W/person	[11]	Chapter 18.4
Personal sensible gain	All	75	W/person	[11]	Chapter 18.4
Lighting heat gain	All	11	W/m²	[5]	Section J, page 355

Table 7. Ventilation and infiltration.

	HVAC&R	Value	Unit	Ref.	Section and page
Fresh air	On	10	L/s.person	[12]	Appendix A, Table A1
	Off	5	L/s.person		
Infiltration	On	1	ACH	[13]	Section 2.7
	Off	0.5	ACH		

Table 8. Thermal comfort parameters.

Factor	Value	Unit	Ref.	Section and page
Clothing Factor	Summer 0.6 – Winter 1	clo	[14]	Section 5, page 8
Metabolic rate	1.0	Met	[14]	Section 5, page 7
Relative air velocity	Less than 0.2	m/s	[14]	Section 5, page 11

4.2.9. Schedules

The schedules of occupancy, lighting and appliances of the case study office building are selected based on the National Construction Code (p. 348-349 Vol 1) with some adjustments following the documentation provided by the building facility management [5].

Table 9. Occupancy, lighting and appliances schedules.

Time	Weekday occupancy	Weekday lighting	Weekday equipment	Weekend occupancy	Weekend lighting and equipment	Air-conditioning
00:00-01:00	0.00	0.10	0.10	0.00	0.10	Off
01:00-02:00	0.00	0.10	0.10	0.00	0.10	Off
02:00-03:00	0.00	0.10	0.10	0.00	0.10	Off
03:00-04:00	0.00	0.10	0.10	0.00	0.10	Off
04:00-05:00	0.00	0.10	0.10	0.00	0.10	Off
05:00-06:00	0.00	0.10	0.10	0.00	0.10	Off
06:00-07:00	0.00	0.10	0.10	0.00	0.10	Off
07:00-08:00	0.10	0.40	0.65	0.00	0.10	On
08:00-09:00	0.20	0.90	0.80	0.05	0.10	On
09:00-10:00	0.70	1.00	1.00	0.05	0.10	On
10:00-11:00	0.70	1.00	1.00	0.05	0.10	On
11:00-12:00	0.70	1.00	1.00	0.05	0.10	On
12:00-13:00	0.70	1.00	1.00	0.05	0.10	On
13:00-14:00	0.70	1.00	1.00	0.05	0.10	On
14:00-15:00	0.70	1.00	1.00	0.05	0.10	On
15:00-16:00	0.70	1.00	1.00	0.05	0.10	On
16:00-17:00	0.70	1.00	1.00	0.05	0.10	On
17:00-18:00	0.35	0.80	0.80	0.00	0.10	On
18:00-19:00	0.10	0.60	0.65	0.00	0.10	On
19:00-20:00	0.05	0.60	0.55	0.00	0.10	Off
20:00-21:00	0.05	0.50	0.10	0.00	0.10	Off
21:00-22:00	0.00	0.10	0.10	0.00	0.10	Off
22:00-23:00	0.00	0.10	0.10	0.00	0.10	Off
23:00-00:00	0.00	0.10	0.10	0.00	0.10	Off

4.3. Evaluating Lighting Condition

This section aims to recommend appropriate solutions for improving the natural and artificial lighting environment and minimising the energy consumption for lighting the interior spaces of Knox Civic Centre in Wantirna South. The steps taken in this regard are:

1. The analysis and simulations of the existing lighting conditions, based on information from building management;
2. The assessment of the compliance of the energy performance and the lighting conditions established with relevant regulations, standards and guidelines; and
3. Research, simulation and presentation of appropriate techniques and methods to achieve minimum energy consumption for lighting and heating loads from artificial lighting, complying with the Australian building regulations.

4.3.1. Lighting evaluation method

Proposing strategies for improving lighting conditions or reducing energy use requires a detailed analysis of the existing natural and artificial lighting conditions. The material available for the specific building included architectural drawings and lighting drawings, including lighting fixtures' positions and specifications. Some photographs of the building exterior were also provided.

Using the provided data and reasonable assumptions about the type of the lighting systems, the building was modelled in the software Rhinoceros, and the lighting conditions were simulated in the add-on tool Climate Studio. Climate Studio is an environmental performance analysis software with advanced lighting calculation capabilities. The simulation results were then compared to the requirements and recommendations of the Australian NCC [5]. Based on this comparison, areas with installed power that exceeded the required were identified. Based on the findings of the assessment, two scenarios were tested. These scenarios are described in Table 10. The installed lighting density evaluated in this section is calculated individually. The space codes are presented in Figure 6 and Figure 7. The calculated lighting power density for each space is shown in Table 11. →

Table 10. Scenarios for reduced energy consumption for lighting.

Base-case scenario	The total Lighting Load (kW), as stated in the lighting drawings and specifications. The installed power density for lighting as described in the provided material is included in Table 11.
Scenario 1	Reduce the existing power density for lighting to the maximum permitted by NCC.
Scenario 2	Scenario 2 has the same lighting power density as Scenario 1. However, daylight controls are used in all spaces with daylight availability.

Table 11. Installed lighting power density (W/m^2) in all spaces.

Level	Space	Lighting power density W/m²	Level	Space	Lighting power density W/m²
Ground	1	18.70	1	37	10.45
	2	16.00		38	13.04
	3	9.26		39	8.00
	4	13.80		40	8.00
	5	7.80		41	16.30
	6	15.70		42	15.30
	7	16.80		43	14.70
	8	11.70		44	17.20
	9	8.00		45	14.20
	10	12.30		46	13.90
	11	11.60		47	8.30
	12	11.60		48	16.25
	13	10.30		49	25.50
	14	4.70		50	15.16
	15	10.14		51	7.50
	16	8.30		52	13.40
	17	10.14		53	15.12
	18	6.30		54	12.24
	19	6.30		55	10.40
	20	6.30		56	15.00
	21	11.00		57	11.20
	22	7.35		58	10.00
	23	18.20		59	10.00
	24	14.80		60	14.60
	25	15.30		61	10.00
	26	16.20		62	15.15
	27	14.60		63	15.00
	28	7.65		64	15.00
	29	11.90			
	30	15.00			
	31	12.75			
	32	9.60			
	33	6.30			
	34	6.30			
	35	6.30			
	36	6.30			

4.3.2. Lighting analysis result

The results are analysed in two parts:

1) The assessment of the existing natural conditions;

2) The calculation of the existing lighting power density (W/m²), and the proposal of scenarios to reduce the energy consumption for lighting. ➔

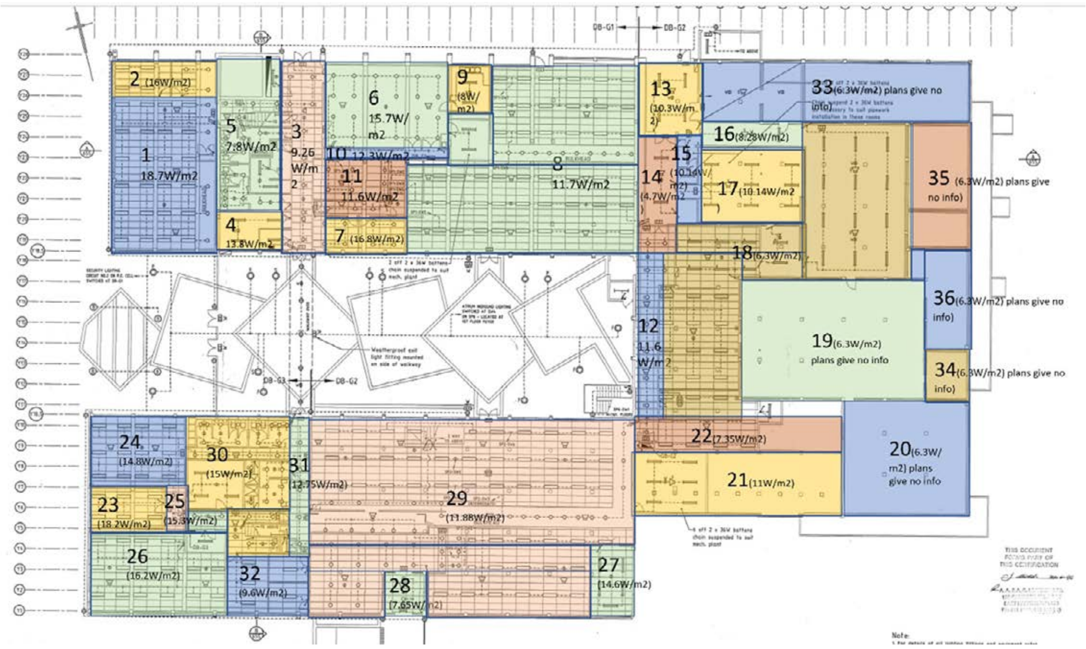

Figure 6. Coding of the ground floor spaces.

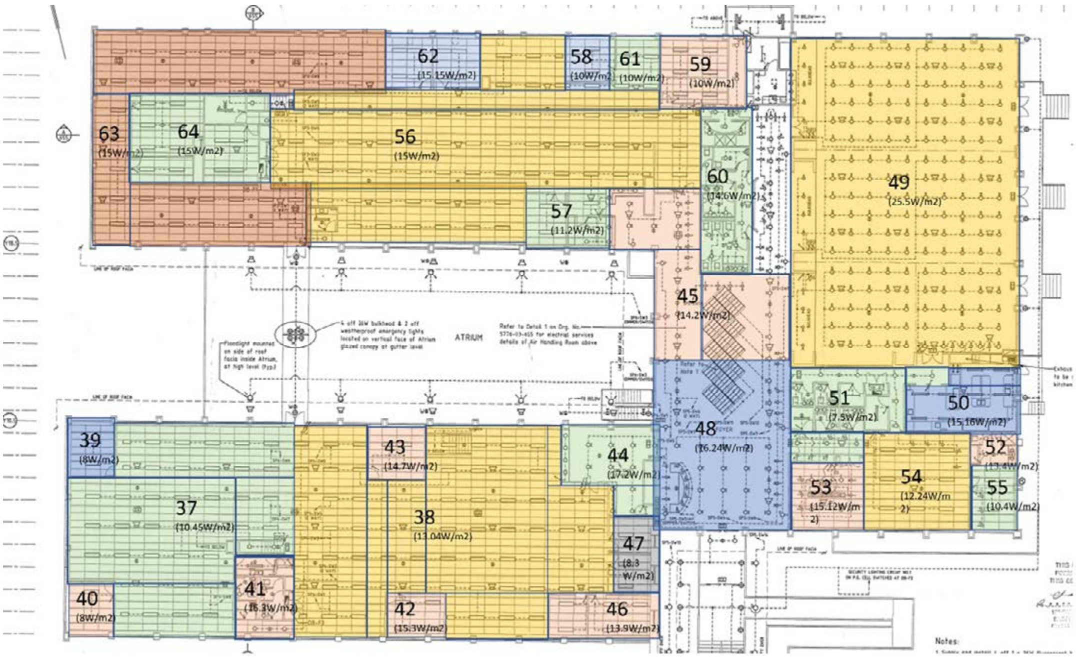

Figure 7. Coding of level 1 spaces.

4.3.2.1. Natural lighting

The building has many openings in the south and north facades, as well as on the “interior” elevations facing the atrium. The east façade includes translucent glazing on Level 1. The continuously occupied spaces close to the ground level perimeter receive adequate daylight, and many have Daylight Factors above 2%. There are spaces with small areas and full-height windows with high Daylight Factors (e.g., spaces 6, 11-13, 16, 22, 34), where the lighting levels and the thermal loads should be reduced. The spaces where the daylight availability should be higher are the deep spaces like spaces 2 and 8, or very large spaces, such as spaces 5, 10 and 28. The spaces behind the North façade could benefit from exterior shading, which could have the form of rollers/ blinds or louvres.

Spatial Daylight Autonomy (sDA) is the percentage of the regularly occupied floor area that is “daylit.” In this context, “daylit” locations are those meeting target illuminance levels (300 lux) using daylight alone for at least 50% of occupied hours. Such locations are said to be 50% daylight autonomous. The sDA calculations are based on annual, climate-based simulations. The sDA of the spaces studies are very high, and it appears that the spaces with windows will have light levels of 300 lux only from the incoming daylight for more than 50% of the occupied hours. Spaces with lower sDAs could host uses that require lower general lighting levels, such as storage spaces, staff rooms, filing and printing stations, etc., in which case the sDA would be much higher.

4.3.2.2. Artificial lighting

According to the lighting drawings and specifications, the lighting power density values in the building’s spaces vary significantly; however, each space has a much higher power density than the NCC limits. Specifically, the lighting power density ranges from 6.30 to 25.50 W/m². Evidently, there is huge potential for reduction of the energy consumption of the building by using more efficient lighting fixtures (as progressively done in the past ten years in Knox Civic Centre) and daylight linked controls. ■

Table 12. Average Daylight Factors and Spatial Daylight Autonomy (codes and areas as in Figures 8 and 9).

Level	Space	Area (m²)	Average Daylight Factor (%)	Uniformity	sDA (%)
Ground	1	53.00	3.88	0.35	100.00
	2	13.00	1.08	0.27	41.67
	3	32.90	2.63	0.36	100.00
	4	13.70	3.63	0.29	100.00
	5	362.6	1.76	0.12	37.42
	6	11.4	7.86	0.55	100.00
	7	75.7	1.98	0.08	0.55
	8	14.40	1.44	0.33	97.92
	9	9.30	2.20	0.48	100.00
	10	214.50	1.86	0.27	33.57
	11	7.20	5.14	0.59	0.00
	12	7.00	5.10	0.58	0.00
	13	7.60	4.40	0.46	20.00
	14	60.00	1.78	0.38	100.00
	15	119.5	1.72	0.28	61.54
Level 1	16	8.20	5.47	0.58	100.00
	17	8.20	3.57	0.46	100.00
	18	526.00	1.75	0.09	46.54
	19	10.80	4.74	0.58	100.00
	20	13.50	3.73	0.42	33.33
	21	6.20	3.71	0.58	100.00
	22	11.70	5.66	0.54	100.00
	23	5.30	2.30	0.57	100.00
	24	5.10	0.83	0.55	8.33
	25	637.00	2.36	0.04	32.86
	26	18.6	2.74	0.44	100.00
	27	8.70	4.56	0.49	100.00
	28	550.30	1.41	0.05	33.03
	29	24.00	4.27	0.50	100.00
	30	8.30	3.54	0.44	0.00
	31	5.00	6.29	0.69	0.00
	32	22.40	2.81	0.35	100.00
	33	51.50	2.83	0.28	100.00
	34	12.30	11.18	0.53	100.00
	35	5.20	6.35	0.49	0.00
	36	27.70	5.80	0.16	11.59

Figure 8. Coding of ground floor spaces for Table 12.

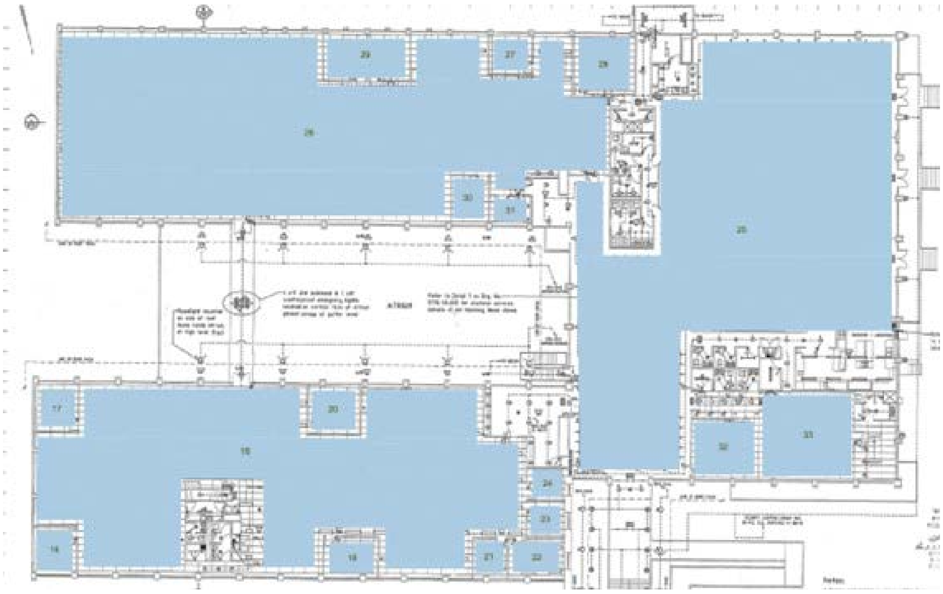

Figure 9. Coding of level 1 spaces for Table 12.

5. Simulation approach

The simulation includes two main parts. First, the building was defined in SketchUp software and then energy modelling was conducted in TRNSys.

5.1. SketchUp

SketchUp is a 3D modelling computer program for a wide range of drawing applications such as architectural, interior design, landscape architecture, and civil and mechanical engineering. The model was designed based on actual building dimensions, rotation, and shadings (adjacent building and external shadings). The case study building is defined in the SketchUp model because of the importance of load determination (Figure 10). →

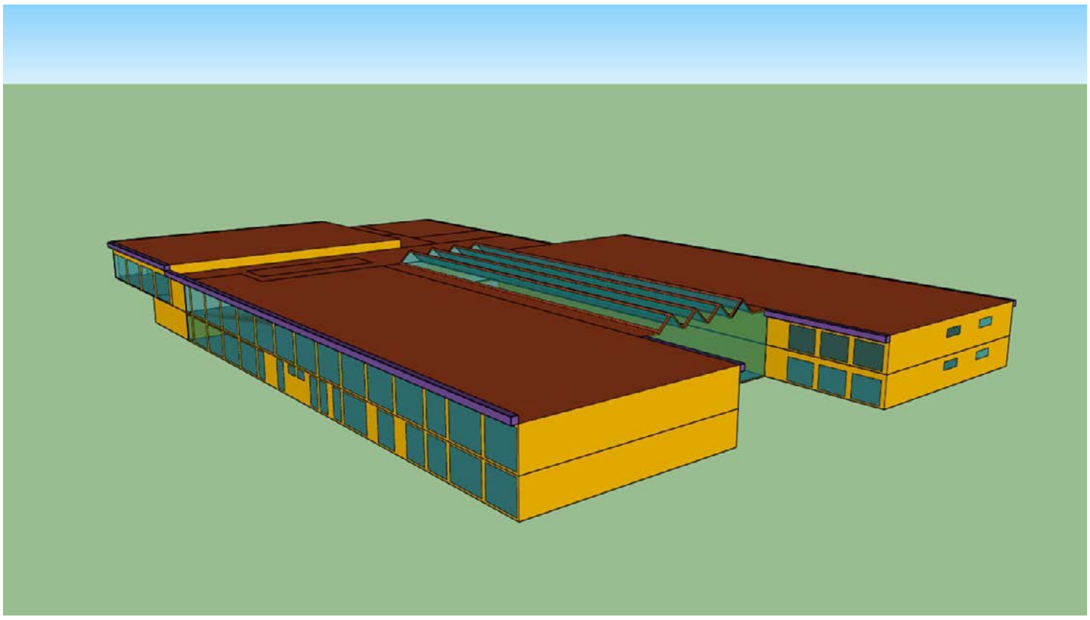

Figure 10. SketchUp model.

5.2. TRNSys

The TRNSys software tool is used to simulate the behaviour of transient systems. TRNSYS has an extensive library of components, which can help model the performance of all parts of the system. TRNBuild is the tool used to enter input data for multizone buildings. It allows specifying all the building structure details and everything required to simulate the thermal behaviour of the building, such as windows optical properties, heating and cooling schedules, etc. [15].

After importing the case study building model into TRNSys, all building structural parameters (walls, windows, doors, etc.), schedules (occupancy, lighting, and appliances), internal loads, and HVAC&R systems (setpoint, ventilation, infiltration, and comfort) were defined in TRNBuild. The model was finalised by adding the proper climatic data (temperature, relative humidity, radiation, etc.) using the CSIRO weather database.

5.3. Retrofit approaches

Evaluating the energy performance of a building is a complicated task. It initiates with determining the building's constructional characteristics, including the efficiency of the building envelope, lighting, HVAC&R equipment, etc. Considering the building's features, all calculations were based on the 'as-built' condition of the building elements (U-values, shading, air-permeability, etc.), of the HVAC&R system (Coefficient of Performance and Seasonal Energy Efficiency Rating as provided by manufacturers or (for older systems) by regulations), whilst installed lighting and plug loads were determined either by data from management or following standards and regulations.

Additionally, other specific conditions that have a significant impact on the building's performance are:

(a) the operational parameters (hours of operation, set temperatures for heating and cooling, natural ventilation patterns, use of artificial lighting, etc.) and

(b) the microclimate on the building's site (shading by natural obstructions and other buildings, albedo and thermal storage of surrounding areas, etc.).

Finally, a baseline or reference condition should be determined, against which the effectiveness of interventions can be evaluated.

This baseline condition cannot be straightforwardly derived from metered energy consumption since the latter is affected by the aforementioned building's specific operational and microclimate conditions and the weather conditions of the specific period.

While the metered consumption values are real, they do not necessarily represent a base for an objective assessment. Therefore, the building has to adopt standard reference conditions, as foreseen by national regulations and standards, which allow a good degree of replicability for the simulative calculations that allow a detailed breakdown of energy consumption by source and use and a reliable assessment of the improvements achieved by the interventions considered.

In this line of approach, all operational parameters for the baseline scenario were considered following national standards, regulations and recommendations, or NCC, ASHRAE and ISO standards. Simulations were carried out on an hourly basis, hence resulting in a high temporal analysis, whilst the thermal zoning was based on the differentiation of thermal conditions. This approach not only allows a reliable and cohesive assessment for the specific building but enables using the outcomes as a pilot for further similar projects. →

5.3.1. Lighting retrofit

The aim of the next step of the study was to develop scenarios that would enable reduced energy consumption for lighting and would provide an approximation of how much energy can be saved. Based on the provided information about the installed lighting sources, a base case scenario is developed. As the use of each of the spaces is not known, the maximum permitted lighting power density of office use by the NCC, i.e., 4.50W/m², was used for Scenario 1.

For Scenario 2, the power density of Scenario 1 was used and combined with continuous dimming of the light sources depending on daylight availability. The energy consumption for each of the scenarios is provided in Table 13. The proposed scenarios resulted in a reduction of the total lighting load (kW) and the annual energy (kWh) ranging from 28 to 95% (Table 13).

5.3.2. Windows retrofit and wall insulation

The windows now installed in the Knox Civic Centre are single glazed with aluminium frame. The thermal break (insulation within a window) is a constant barrier between the inside and outside window frames that avoid conductive thermal energy loss. This barrier securely bonds the interior and exterior metal frames of the window. This thermal break creates thermal energy loss resistance and, combined with double-pane glazing, keeps the interior space of the window at a more comfortable temperature. The proposed window is thermally-broken aluminium framed, double glazed, with Low-E external glass pane, with an average U-value of 1.78 W/m²K, an SHGC value of 0.66 and Air-tightness values of Class 3 with less than 2.5 L/s.m² at 100 Pa. The latter reduces the infiltration rate of the building to 0.30 1/h. Application of 80 mm of mineral wool covered with plasterboard on external walls, leading to a total thickness of 0.29 m and a total R-value of 2.67 m²K/W.

5.3.3. Roof insulation

Insulation is a cost-effective way to save energy and improve the indoor environment. Roof insulation refers to the addition of a layer of Mineral wool (thickness of 8 cm) between the ceiling and the external roof, leading to an average R-value of 3.04 m²K/W. ➔

Table 13. Illumination power density and energy consumption for the base case and the proposed scenarios.

Level	Space	Area (m²)	Base case scenario		Scenario 1		Scenario 2		Percentage of energy savings (%)
			W/m²	kWh/year	W/m²	kWh/year	W/m²	kWh/year	
Ground	1	122.6	18.70	6,555.0	4.50	1,577.0	1.04	779.0	88.12
	2	30.8	16.10	1,410.0	4.50	397.0	3.45	63.0	95.53
	3	50.5	9.27	1,337.0	4.50	650.0	1.49	203.0	84.82
	4	20.9	13.78	825.0	4.50	269.0	5.48	47.0	94.30
	5	78.5	7.80	1,751.0	4.50	1,010.0	0.57	1,010.0	42.32
	6	79.3	15.74	3,559.0	4.50	1,020.0	0.55	184.0	94.83
	7	24.8	16.77	1,191.0	4.50	319.0	3.96	56.0	95.30
	8	295.0	11.72	9,863.0	4.50	3,793.0	0.08	983.0	90.03
	9	18.1	7.96	413.0	4.50	232.0	3.91	41.0	90.07
	10	8.8	12.27	309.0	4.50	113.0	4.91	113.0	63.43
	11	49.2	11.63	1,634.0	4.50	634.0	0.20	634.0	61.20
	12	30.9	10.10	1,026.0	4.50	398.0	1.10	69.0	93.27
	13	27.9	10.32	822.0	4.50	359.0	0.66	76.0	90.75
	14	33.6	4.67	451.0	4.50	432.0	0.77	432.0	4.21
	15	14.2	10.14	410.0	4.50	182.0	2.82	182.0	55.61
	16	17.4	8.28	412.0	4.50	224.0	0.57	224.0	45.63
	17	63.9	10.14	1,853.0	4.50	822.0	0.11	822.0	55.64
	18	240.0	6.30	4,324.0	4.50	3,088.0	0.03	3,088.0	28.58
	19	172.9	6.30	3,115.0	4.50	2,225.0	0.19	2,225.0	28.57
	20	112.1	6.30	2,020.0	4.50	1,443.0	0.29	1,443.0	28.56
	21	97.9	11.03	3,080.0	4.50	1,260.0	0.31	1,260.0	59.09
	22	78.4	7.35	1,648.0	4.50	1,009.0	0.37	1,009.0	38.77
	23	23.7	18.23	1,233.0	4.50	305.0	1.20	144.0	88.32
	24	58.4	14.79	2,471.0	4.50	751.0	0.45	134.0	94.58
	25	6.8	15.29	296.0	4.50	87.0	0.74	87.0	70.61
	26	79.7	16.26	3,694.0	4.50	1,026.0	0.30	186.0	94.96
	27	24.6	14.63	1,027.0	4.50	316.0	0.19	51.0	95.03
	28	13.6	7.65	299.0	4.50	175.0	0.72	30.0	89.97
	29	444.1	11.88	15,116.0	4.50	5,716.0	0.05	1,617.0	89.30
	30	105.6	15.04	4,531.0	4.50	1,359.0	0.18	614.0	86.45
	31	20.4	12.75	743.0	4.50	558.0	0.24	172.0	76.85
	32	37.4	9.63	1,027.0	4.50	512.0	0.08	93.0	90.94
	33	131.7	6.30	2,373.0	4.50	1,695.0	0.02	1,695.0	28.57
	34	17.4	6.80	313.0	4.50	224.0	0.18	224.0	28.43
	35	61.7	6.30	1,112.0	4.50	794.0	0.04	794.0	28.60
	36	39.8	6.30	717.0	4.50	512.0	0.35	512.0	28.59
1	37	255.0	10.45	7,618.0	4.50	3,281.0	0.05	939.0	87.67
	38	364.5	13.04	13,554.0	4.50	4,692.0	0.03	2,969.0	78.10
	39	18.0	8.00	412.0	4.50	232.0	0.14	38.0	90.78
	40	18.0	8.00	412.0	4.50	232.0	0.12	45.0	89.08
	41	27.0	16.30	1,259.0	4.50	348.0	0.10	348.0	72.36
	42	18.8	15.32	822.0	4.50	242.0	0.17	242.0	70.56
	43	19.6	14.69	825.0	4.50	253.0	0.56	45.0	94.55
	44	43.3	17.20	2,132.0	4.50	558.0	0.24	120.0	94.37
	45	93.4	14.22	3,793.0	4.50	1,202.0	0.02	246.0	93.51
	46	31.1	13.89	1,235.0	4.50	400.0	0.06	400.0	67.61
	47	25.9	8.34	614.0	4.50	333.0	0.23	333.0	45.77
	48	141.4	16.24	6,553.0	4.50	1,820.0	0.01	1,113.0	83.02
	49	534.6	25.44	38,989.0	4.50	6,880.0	0.02	2,934.0	92.47
	50	47.5	15.16	2,058.0	4.50	611.0	0.04	611.0	70.31
	51	71.5	7.47	1,533.0	4.50	920.0	0.09	920.0	39.99
	52	9.7	13.40	371.0	4.50	125.0	0.17	125.0	66.31
	53	33.6	15.12	1,452.0	4.50	432.0	0.23	432.0	70.25
	54	69.3	12.24	2,426.0	4.50	892.0	0.02	892.0	63.23
	55	21.4	10.37	636.0	4.50	275.0	0.06	275.0	56.76
	56	455.2	15.03	19,530.0	4.50	5,859.0	0.00	2,080.0	89.35
	57	28.5	11.23	913.0	4.50	367.0	0.05	68.0	92.55
	58	21.5	10.05	448.0	4.50	202.0	0.33	32.0	92.86
	59	37.0	10.00	861.0	4.50	387.0	0.03	66.0	92.33
	60	59.3	9.65	2,476.0	4.50	763.0	0.10	763.0	69.18
	61	15.7	10.00	448.0	4.50	175.0	0.07	50.0	88.84
	62	38.0	15.16	1,648.0	4.50	489.0	0.10	83.0	94.96
	63	191.5	0.00	8,217.0	4.50	2,465.0	0.02	558.0	93.21
	64	73.6	15.05	3,157.0	4.50	947.0	0.04	947.0	70.00

5.3.4. Ceiling fans

Ceiling fans are a simple and cost-effective method to enhance the indoor air quality in summer and receive points in energy rating stars. They provide additional air movement by increasing the relative air velocity resulting in the apparent temperature felt on exposed skin being 3°C colder than the actual air temperature, thereby reducing the need for additional cooling. The proposed scenario will be modelled by increasing the cooling setpoint temperature to 26°C.

5.3.5. Auto night ventilation, window shading and heat recovery

Intensive ventilation through windows during the night is a cost-saving and energy-efficient method of cooling buildings in summer. It uses the natural pressure differences between at least two openings (e.g., windows, doors) of a building to the outside for air exchange. Such a pressure gradient already exists in weak winds.

Night ventilation takes place between 20:00 and 8:00 with an additional flow rate of 4 ACH and is activated during the cooling period and only when the difference between indoor and outdoor temperature is greater than 3 K, the outdoor temperature is greater than 15°C, and indoor temperature is greater than the heating setpoint. Window shading is modelled by applying a shading factor of 0.7 during the cooling period (October-April). The efficiency of the heat recovery ventilation is 80%.

5.3.6. Automation and controls

Even HVAC&R systems of the highest efficiency do not run optimally if they do not consider variations in ambient air temperature and solar radiation, the presence of users in the various rooms and the thermal response of the building's envelope. In that sense, one of the most important tools to improve energy efficiency is the use of sensors, automation and control systems that interlock the use of HVAC&R, DHW and lighting systems with both weather conditions and operational requirements.

The impact of Building Automation And Control Systems (BACS) and Building Management Systems (BMS) is expressed and quantified by a series of standards, like the EN ISO 52127 and 15232. According to those standards, four energy efficiency classes (A, B, C, D) are defined to evaluate the performance of the building automation:

- A: high energy performance BACS and BMS
- B: systems with advanced BACS and BMS
- C: standard BACS
- D: non-energy-efficient BACS

Table 14 depicts typical features of the four mentioned classes. The impact of the automation level on the building's energy consumption is also quantified according to Standard 15232 (Table 15). This approach allows a rough evaluation of the impact of BACS systems on the energy performance of the building in a year. The impact of each function (e.g. cooling/heating and lighting) is calculated using the pertinent standards. ➔

Table 14. Functions and assignments to energy performance classes.

	Heating/Cooling control	Ventilation / Air conditioning control	Lighting Control	Solar protection
A	• Individual room & communication between controllers • Indoor temperature control of distribution network water temperature • Total interlock between heating & cooling control	• Demand/presence dependent airflow control at room level • Variable setpoint with load-dependent compensation of supply temperature • Room/exhaust/ supply-air humidity control	Automatic • Daylight control • Occupancy detection manual on / auto off • Occupancy detection manual on / dimmed • Occupancy detection auto on / auto off • Occupancy detection auto on / dimmed	Combined light/blind/ HVAC&R control
B	• Individual room control with communication between controllers • Indoor temperature control of distribution network water temperature • Partial interlock between heating & cooling control (dependent on HVAC system)	• Time-dependent airflow control at room level • Variable setpoint with outdoor temperature compensation of supply temperature control • Room/exhaust/ supply-air humidity control	Automatic • Daylight control • Occupancy detection manual on / auto off • Occupancy detection manual on / dimmed • Occupancy detection auto on / auto off • Occupancy detection auto on / dimmed	Motorized operation with automatic blind control
C	• Individual room automatic control by thermostatic valves or electronic controller • Outdoor	• Time-dependent airflow control at room level • Constant setpoint of supply temperature control • Supply-air humidity limitation	Manual • Daylight control • On/off switch + additional sweeping extinction signal • Manual on/off	Motorized operation with manual blind control
D	• No automatic control • No control of distribution network water temperature • No interlock between heating and cooling control	No airflow control at room level No supply temperature control No air humidity control	Manual • Daylight control • On/off switch + additional sweeping extinction signal • Manual on/off	Manual operation of blinds

The result of the evaluation is two sets of BAC efficiency factors (fBAC,hc and fBAC,e). The first one estimates the energy for heating and cooling, and the second one the electric energy for lighting and auxiliary factors. Fraser suites Sydney is between Class D and C and can fairly easily be upgraded to Class B by installing:

- Individual room controls with communication between them and the chillers/boilers and air handling units
- Time-dependent controls of ventilation
- Variable control of setback temperatures
- Humidity control of the ventilation and
- Lighting controls

In that way even if the building is not of Class C (which is an assessment to be on the safe side), heating, cooling and DHW loads can be reduced by at least 25%, apart from savings achieved due to the refurbishment of the building's envelope. Similarly, electrical loads can be reduced by a further 15%.

Table 15. Functions and assignment to energy performance classes for non-residential buildings. Standard automation is used as reference.

	BAC efficiency factors $f_{BAC,hc}$ BAC efficiency factors $f_{BAC,e}$							
	D	C	B	A	Energy saving adopting classes			
Building use	No autom.	Standard autom.	Advanced autom.	Full autom.	D→A	D→B	C→A	C→B
Offices	1.51	1	0.80	0.70	54%	47%	30%	20%
	1.10		0.93	0.87	36%	27%	30%	20%
Lecture Hall	1.24	1	0.75	0.35	60%	40%	50%	25%
	1.06		0.94	0.89	53%	29%	50%	25%
Education buildings (schools)	1.20	1	0.88	0.80	33%	27%	20%	12%
	1.07		0.93	0.86	25%	18%	20%	12%
Hospitals	1.31	1	0.91	0.86	34%	31%	14%	9%
	1.05		0.95	0.90	18%	13%	14%	9%
Hotels	1.31	1	0.85	0.68	48%	43%	32%	25%
	1.04		0.96	0.92	36%	21%	32%	15%
Restaurants	1.23	1	0.77	0.68	45%	37%	32%	23%
	1.08		0.95	0.91	35%	26%	32%	23%
Wholesale and retail	1.56	1	0.73	0.47	62%	53%	40%	27%
	1.08		0.95	0.91	44%	32%	40%	27%

6. Results

6.1. Base building modelling

The results of the Knox Civic Centre simulation are presented in this section. The hourly energy demand for heating and cooling (sensible and latent) is illustrated in Figure 11. Also, the monthly energy demand is presented in Figure 12. →

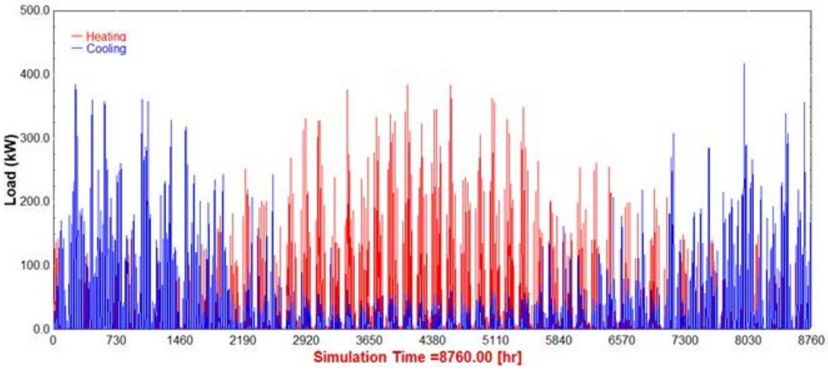

Figure 11. Hourly energy demand for HVAC&R purposes.

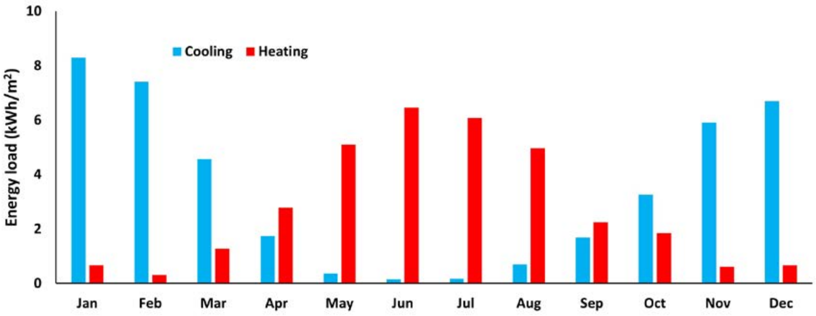

Figure 12. Monthly energy demand for HVAC&R purposes.

TRNSys calculates thermal loads through an energy balance that affects the air temperature inside the building:

$q_{BAL} = q_{DQAIRdt} + q_{HEAT} - q_{COOL} + q_{INF} + q_{VENT} + q_{TRANS} + q_{GINT} + q_{WGAIN} + q_{SOL}$

q_{BAL}: the energy balance for a zone and should always be close to 0;

$q_{DQAIRdt}$ is the change of internal energy of the zone (calculated using the combined capacitances of the building and the air within it);

q_{INF} is the gains by infiltration;

q_{VENT} is the gains by ventilation;

q_{TRANS} is transmission into the surface from an inner surface node;

qG_{INT} is internal gains by convection and radiation;

q_{WGAIN} represents gains by convection and radiation through walls, roof and floor;

q_{SOL} is absorbed solar gains on all inside surfaces;

q_{HEAT} is the power of ideal heating;

q_{COOL} is the power of ideal cooling.

Therefore, the ratio of each parameter in total energy gain can be decided for heating and cooling seasons (Figures 13 and 15). Also, the amount of heating and cooling energy is illustrated in Figures 14 and 16. The monthly energy gain of the office building and the influence of each factor in the total energy demand is presented in Figure 17. ➔

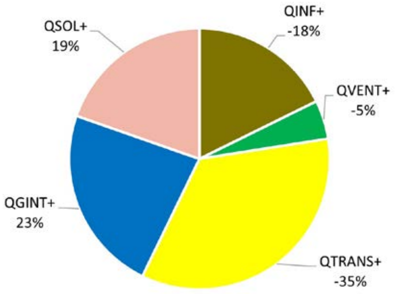

Figure 13. Whole building energy gain – heating season (May-September).

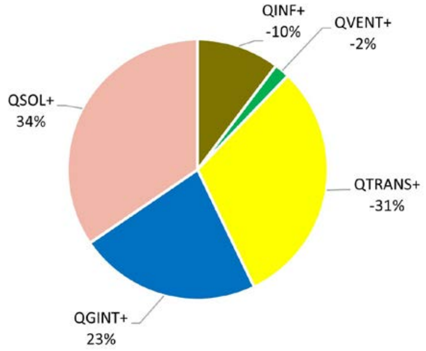

Figure 15. Whole building energy gain – cooling season (October-April).

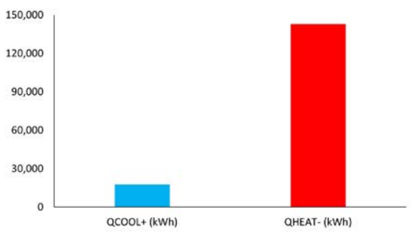

Figure 14. Whole building energy gain for heating and cooling load- heating season (May-September).

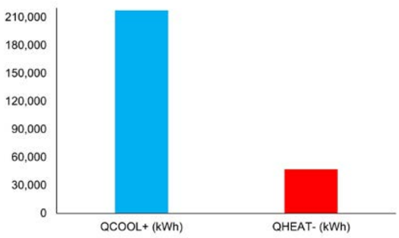

Figure 16. Whole building energy gain for heating and cooling load- cooling season (October-April).

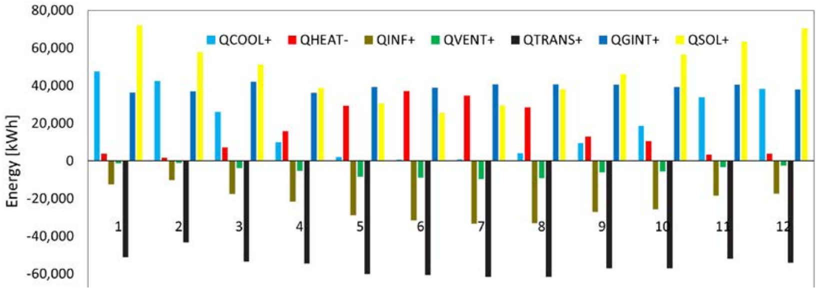

Figure 17. Monthly building energy gain.

6.2. Retrofit scenarios

The investigated retrofit cases in this report are presented in Table 16. ➔

Table 16. Retrofit cases.

Cases	Description
Baseline	The base-case scenario considers the maximum lighting power density permitted by the NCC for each type of space. For the cases where a range of power densities is allowed by NCC, the maximum value is considered. Heating and cooling setpoint and setback temperatures are set according to the NCC.
Case A	Baseline + lighting scenario 1: The illumination power density was decreased in many spaces, either using the information for the actual lighting systems of the building or by adopting the minimum power density as required by the NCC. No controls.
Case B	Baseline + lighting scenario 2: The power density of lighting scenario 1 was used and combined with continuous dimming of the light sources depending on daylight availability in.
Case C	Case B + windows retrofit: New windows are aluminium framed, with a thermal break in the frame, double glazed, with Low-E external glass pane, with an average U value of 1.78 W/m²K, a glazing g-value of 0.66 and Air-tightness values of Class 3 with less than 2.5l/s.m² at 100 Pa. The latter reduces the infiltration rate of the building to 0.30 1/h.
Case D	Case C + Automation and Controls: The baseline class of automation is estimated according to EN15232, and then the new class and energy efficiency are estimated according to the potential improvements. Class C is the estimated class for the baseline, and it is considered that class A is reached after the improvements.
Case E	Case D + Installation of ceiling fans: Ceiling fans are modelled by increasing the cooling setpoint temperature to 26°C.
Case F	Case E + night ventilation + window shading + heat recovery ventilation: Night ventilation takes place between 20:00 and 8:00 with an additional flow rate of 4 ACH and is activated during the cooling period and only when the difference between indoor and outdoor temperature is greater than 3 K, the outdoor temperature is greater than 15°C, and indoor temperature is greater than the heating setpoint. Window shading is modelled by applying a shading factor of 0.7 during the cooling period (October-April). The efficiency of the heat recovery ventilation is 80%.
Case G	Case F + roof insulation: Roof solution refers to the addition of a layer of mineral wool (thickness of 80 mm) between the ceiling and the external roof, leading to an average total thickness of 0.13 m and an average R-value of 3.04 m²K/W.
Case H	Case G + walls insulation: Application of 80 mm of mineral wool covered with plasterboard on external walls, leading to a total thickness of 0.29 m and a total U-value of 2.67 m²K/W.

While office buildings typically present a higher cooling than heating energy consumption, this low-rise building already features a solar-reflective roof coating (initial solar absorbance of 0.10, assumed equal to 0.25 to take into account weathering and soiling), which minimises solar heat gains through the roof. Therefore, the largest fraction of site energy is represented by artificial lighting.

Between the presented scenarios, Case H has the most retrofitting steps. Table 17 shows the influence of different retrofitting cases on heating and cooling loads. Also, Table 18 demonstrates the impact of different retrofit scenarios on electricity consumption in the case study office building. The result shows that by improving the building condition, 62.9% of the required electricity can be reduced. A more detailed illustration of the retrofitting impact is presented in Figures 18-20. →

Table 17. Simulation results – Heating and cooling loads.

	Heating loads	Cooling loads	Heating + Cooling	Heating loads	Cooling loads	Heating + Cooling
Unit	kWh/(m²a)			difference (%)		
Baseline	33.1	41.0	74.1	-	-	-
Case A (Baseline + lighting scenario 1)	42.2	35.8	78.0	27%	-13%	5%
Case B (Baseline + lighting scenario 2)	46.9	34.2	81.1	42%	-16%	9%
Case C (Case B + windows retrofit)	26.7	37.9	64.6	-19%	-7%	-13%
Case D (Case C + Automation & Controls)	26.7	37.9	64.6	-19%	-7%	-13%
Case E (Case D + ceiling fans)	25.6	28.3	53.9	-23%	-31%	-27%
Case F (Case E + Night ventilation + Window shading + MVHR)	32.2	10.9	43.1	-3%	-73%	-42%
Case G (Case F + External roof insulation)	17.1	8.9	26.0	-48%	-78%	-65%
Case H (Case G + External walls insulation)	13.1	9.3	22.4	-60%	-77%	-70%

Table 18. Simulation results - Site energy.

	Heating	Cooling	Lighting	DHW	Appliances	Total	Total difference	Total difference
Unit	kWh/(m²a)							%
Baseline	11.0	16.4	43.3	2.6	28.9	102.2	0.0	0%
Case A (Baseline + lighting scenario 1)	14.1	14.3	14.0	2.6	28.9	73.8	-28.4	-27.8%
Case B (Baseline + lighting scenario 2)	15.6	13.7	0.8	2.6	28.9	61.6	-40.6	-39.7%
Case C (Case B + windows retrofit)	8.9	15.2	0.8	2.6	28.9	56.4	-45.9	-44.9%
Case D (Case C + Automation & Controls)	6.2	10.6	0.8	2.6	28.9	49.2	-53.1	-51.9%
Case E (Case D + ceiling fans)	6.0	7.9	0.8	2.6	28.9	46.2	-56.0	-54.8%
Case F (Case E + Night ventilation + Window shading + MVHR)	7.5	3.1	0.8	2.6	28.9	42.9	-59.4	-58.1%
Case G (Case F + External roof insulation)	4.0	2.5	0.8	2.6	28.9	38.8	-63.4	-62.1%
Case H (Case G + External walls insulation)	3.1	2.6	0.8	2.6	28.9	38.0	-64.3	-62.9%

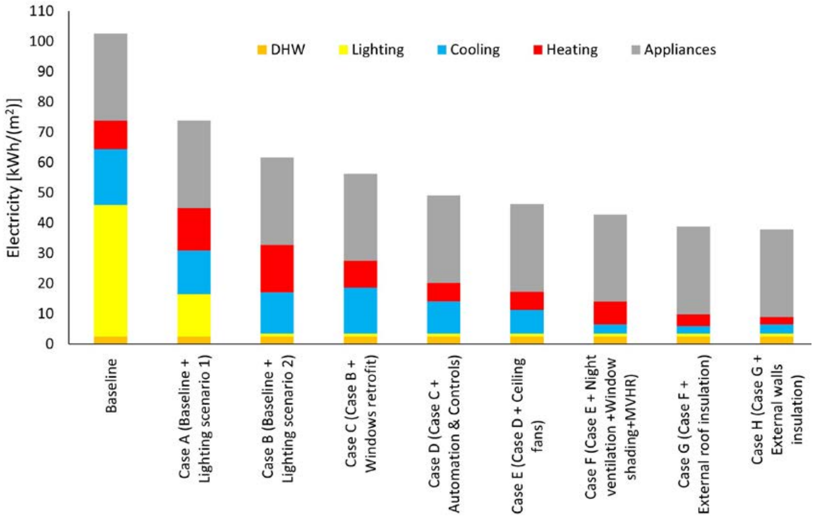

Figure 18. Site energy of the retrofit scenarios.

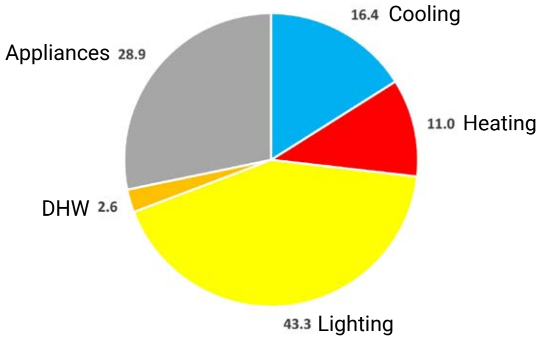

Figure 19. Share of site energy for the baseline (kWh/m²a).

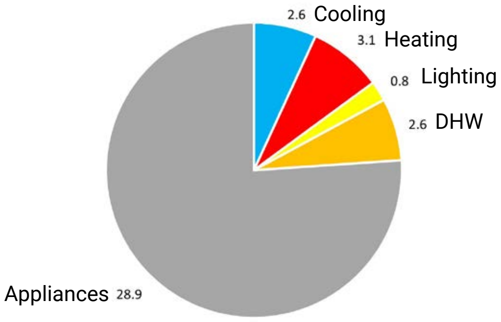

Figure 20. Share of Site energy for retrofit scenario – case H (kWh/m²a).

6.3. Future climate simulation

In this section, the case study office building is simulated in 8 representative cities in Australia. CSIRO has current and future weather models. Therefore, this database is selected to investigate the impact of geographical locations and climate change on the case study building energy demand. Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases are called Representative Concentration Pathways (RCPs) [16]. The word representative indicates that each RCP provides one of many possible scenarios that would lead to a specific radiative forcing characteristic. The term pathway denotes that not only the long-term concentration levels are of interest, but also the path taken over time to reach that outcome is important. RCP4.5 is selected as the future pathway to compare different cities. RCP4.5 is an intermediate condition in which radiative forcing is stabilised at approximately 4.5 W/m² after 2100.

Table 19 presents the energy load and final energy demand for the office building in 8 representative cities. The results indicate that in all representative cities, the cooling site energy will rise between 6.7-12.8% by 2030.

To evaluate the impact of retrofitting the case study office building, the base case and highly retrofitted scenario (Case H) were simulated in Melbourne. As it is presented in Table 20, the total base case site energy will rise sharply until 2030. This is because of the climate change impact, which causes a considerable increase in the cooling demand. The simulation results demonstrated that the unretrofitted office's total electricity demand would rise by 0.4%. Also, the results show that the cooling load in 2030 can be reduced by 76.4% in the case of a complete refurbishment of the Knox Civic Centre. The resulting reduction in the total electricity demand of the building is 63.2%. →

Table 19. Current and future energy demand of the case study office building based on CSIRO weather database.

Location	Period	Water heating	Heating site energy	Space cooling	Cooling site energy	Lighting site energy	Appliances site energy	Total site electricity demand	Increase in total cooling site energy	Increase in total heating site energy	Increase in total electricity site energy
		(kWh/m²)							%		
Adelaide	Present	2.6	6.6	55.9	23.3	43.3	28.9	104.7	-	-	-
	2030	2.6	5.4	62.2	25.9	43.3	28.9	106.1	11.2	-18.2	1.3
Brisbane	Present	2.6	1.8	95.0	39.6	43.3	28.9	116.2	-	-	-
	2030	2.6	1.4	104.6	43.6	43.3	28.9	119.8	10.1	-22.2	3.1
Canberra	Present	2.6	14.5	46.1	19.2	43.3	28.9	108.5	-	-	-
	2030	2.6	12.6	49.4	20.6	43.3	28.9	108.0	7.3	-13.1	-0.5
Darwin	Present	2.6	0.0	194.2	80.9	43.3	28.9	155.7	-	-	-
	2030	2.6	0.0	207.1	86.3	43.3	28.9	161.1	6.7	-	3.5
Melbourne	Present	2.6	11.0	39.4	16.4	43.3	28.9	102.2	-	-	-
	2030	2.6	9.3	44.4	18.5	43.3	28.9	102.6	12.8	-15.5	0.4
Perth	Present	2.6	4.7	73.0	30.4	43.3	28.9	109.9	-	-	-
	2030	2.6	3.8	80.9	33.7	43.3	28.9	112.3	10.9	-19.1	2.2
Sydney	Present	2.6	3.6	61.2	25.5	43.3	28.9	103.9	-	-	-
	2030	2.6	3.0	67.9	28.3	43.3	28.9	106.1	11.0	-16.7	2.1
Hobart	Present	2.6	14.3	26.2	10.9	43.3	28.9	100.0	-	-	-
	2030	2.6	13.0	28.1	11.7	43.3	28.9	99.5	7.3	-9.1	-0.5

Table 20. The comparison between the base case and fully retrofitted scenario.

Location	Period	Water heating	Heating site energy	Space cooling	Cooling site energy	Lighting site energy	Appliances site energy	Total site electricity demand	Cooling site energy increase	Heating site energy increase	Total site electricity increase
		(kWh/m²)							%		
Melbourne Base case	Present	2.6	11.0	41.0	16.4	43.3	28.9	102.2	-	-	-
	2030	2.6	9.3	46.3	18.5	43.3	28.9	102.6	-12.5%	12.8%	0.4%
Melbourne retrofitted	Present	2.6	3.1	9.3	2.6	0.8	28.9	38.0	-	-	-
	2030	2.6	2.5	10.9	3.1	0.8	28.9	37.8	-10.5%	19.2%	-0.6%

6.4. Discussion and recommendations

We established a baseline for energy consumption and then we undertook a simulation based on various energy efficiency upgrades. The findings suggest that heating, cooling, and lighting energy usage are relatively high. Electricity usage of appliances and the energy required for hot water generation are also significant. The following suggestions are made to reduce energy consumption:

- The simulations proved that the natural lighting levels in the spaces close to the windows are relatively high, depending on the area and depth of the space. It is recommended that the full height windows facing North should be externally shaded using automated blinds or horizontal louvres. These shading elements would reduce the natural lighting levels close to the windows, minimise the glare issues and result in more uniform lighting levels.
- The artificial lighting analysis showed that the lighting system is of very high-power density. The light sources described are old technology sources which consume great amounts of energy. Following the lighting guidance provided by the National Construction Code for the relevant space use, a significant reduction of the energy consumed for lighting can be achieved through the upgrade to LED sources. Characteristically, the consumption reduction was between 28 and 95%.
- Thermal insulation of the roof and external walls leads to reducing both heating and cooling loads.
- Refurbishment of the windows, with new aluminium framed, double glazed ones, of high energy efficiency to reduce thermal losses in winter, solar loads in summer, and achieve airtightness throughout the year.
- Install ceiling fans or replace the old ones to reduce cooling demands.
- Installing cutting-edge Building Automation and Controls and a Building Management System to coordinate the use of HVAC&R with both weather and operating requirements.
- Installation of mechanical ventilation with heat recovery to reduce eating loads.
- Implementing night ventilation patterns in the HVAC&R system's operation as well as window shading during the cooling season to reduce cooling demands.

In conclusion, a complete renovation package that includes replacement of the building's windows and glazed surfaces, insulation of the external walls and roof, combined with an upgrading of the lighting system, the installation of ceiling fans and the use of night-time ventilation, mechanical ventilation with heat recovery and window shading patterns, linked all with the implementation of a state-of-the-art BAC system, can lead to energy savings of 62.9%, resulting in an energy consumption of 38.0 kWh/m²a, compared to the baseline of 102.2 kWh/m²a.

Finally, using NABERS Energy reversed calculator, for the building block considered in this study and if the building is fully retrofitted, the NABERS star rating can increase from 2.09 (pre-retrofit, 2007) to 3.89 stars (computed based on the simulation results) [17].

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Attachment 1

The following figures show daylight factor distribution in Knox Civic Centre.

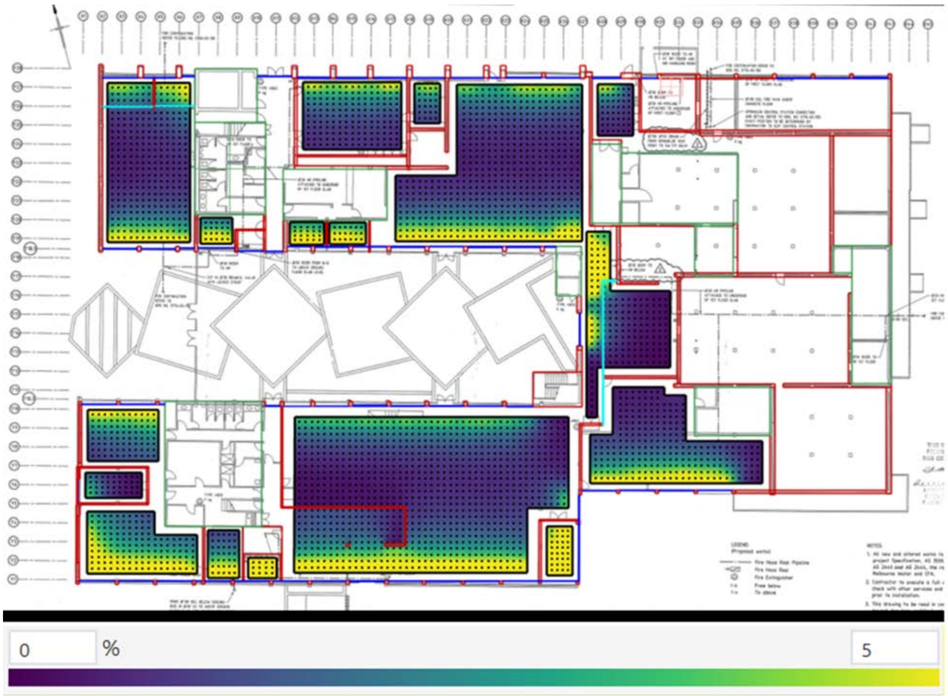

Fig. A1. Distribution of Average Daylight Factor on the ground floor.

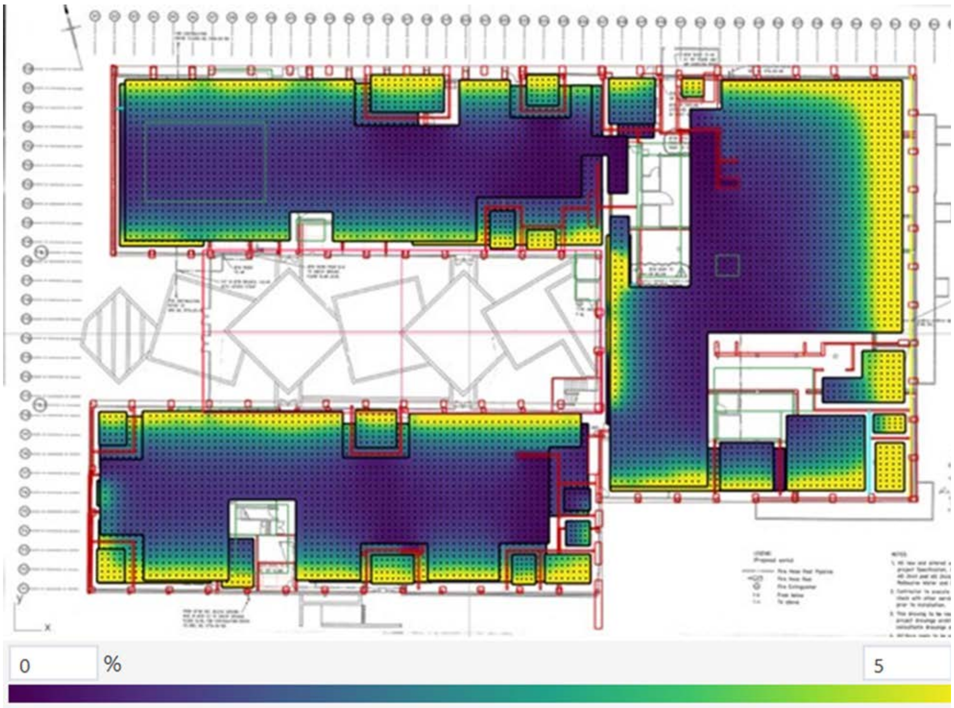

Fig. A2. Distribution of Average Daylight Factor on the 1st floor.

Attachment 2

This section demonstrates all the input information used for Energy modelling of 511 Burwood Highway, Wantirna South, VIC. The data was provided by Knox City Council, including, site photos floor plans, and elevations.

Fig. A3. Aerial view of the building.

Fig. A4. Exterior view of the building.

Fig. A5. Exterior view of the building.

Fig. A6. Exterior view of the building.

Fig. A7. Exterior view of the building.

Fig. A8. Exterior view of the building.