

Million Cool Roofs

Study of Passive Cooling Strategies

Background and Approach

As part of the Million Cool Roofs Project, a range of passive cooling strategies were investigated to determine the impact these may have to the thermal conditions of the houses. The aim was to reduce the internal temperatures, with the study based on August conditions in Mexico. All cases are modelled with no wind present for conservatism.

The investigation was conducted using the Arup developed software BEANS (Building Environment Analysis Suite). The strategies investigated were:

1. Reflective Roofs
2. Reflective Walls
3. Upsized ventilation portals (20% and 50% increases)
4. House Orientation
5. Blinds (inside and outside)
6. Glazing (double glazing and solar glazing)
7. Insulation
8. Pitched Roofs (fully pitched and half pitched)

The strategies listed were first individually compared to a base case, with results presented in the first sections.

Numerical values presented from the report are taken w.r.t the centre of the house. Spatial plots presented show the spatial variation around the house. Strategies such as reflective roofs, reflective walls, upsized ventilation portals, insulation and pitched roofs affect temperatures around the general space of the house, and thus the central point gives a good indication of the effectiveness of these methods. Strategies such as orientation, blinds and glazing reduce temperatures more largely in areas which are effected from direct solar gain from the sun through windows. Hence spatial plots are more useful in these cases. For the spatial plots, the 15th August was chosen to present as represents a sunny day, where the effectiveness of strategies which limit solar gain from the sun can be seen most.

Combinations of the most successful strategies were then modelled and are presented in subsequent sections.

Base Case

The layout modelled is presented in Figure 1, with the Ecoblocks and concrete walls highlighted. In this base case, the Ecoblocks have a low albedo of 0.4, and concrete blocks a higher albedo of 0.6, as are already painted white.

The floor and roof are both made from concrete slabs, with the roof albedo for the base case at around 0.3. A single window glazing of around 3mm thickness has been applied to all windows.

The lattice ventilation portals on the houses has been modelled in BEANS with ventilation control. The total open area is approximated at 2.4m^2 , at around 2.3m from ground level.

Note that internal walls were not included in this study, as the house was modelled as a single zone in BEANS. Including internal walls would potentially reduce the penetration of the solar gains through the glazing and into the house.

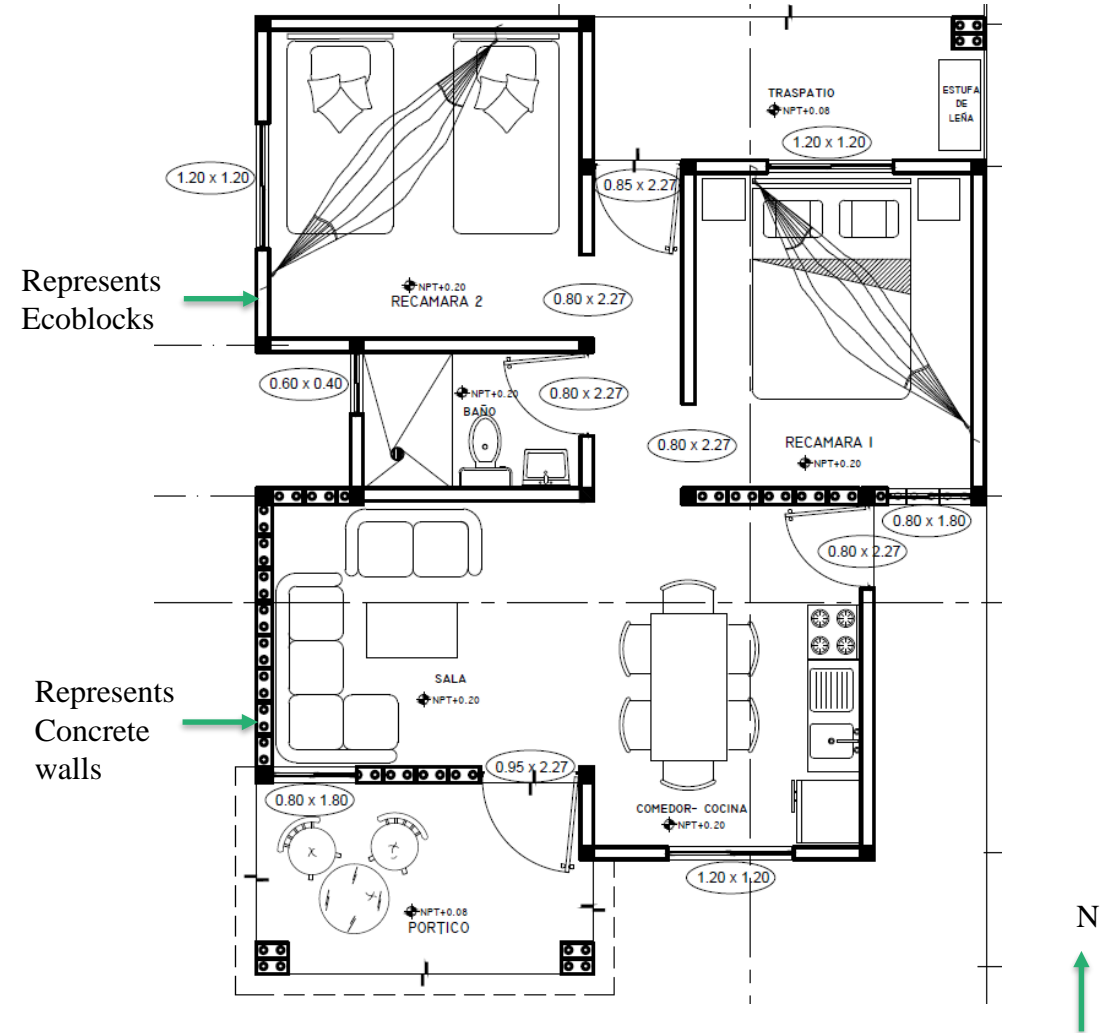


Figure 1: Housing layout modelled for base case

Reflective Roofs and Reflective Walls

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Reflective Roof

A reflective roof strategy was modelled for passive cooling. In this case, the roof albedo was increased to 0.85 to represent the painting of the roof.

Results show an average **0.7 °C** decrease in internal operative temperatures for the reflective roof case, when compared to the base case. This is due to the painted roof reflecting more sunlight than the base case, so less is absorbed by the roof. This then reduces the roof surface temperature, and in turn reduces the internal temperature of the house.

Figure 2 represents the operative temperatures at 3pm for each day in August. This shows the impact of the reflective roof, where the maximum reduction in internal operative temperatures is around 1.8°C.

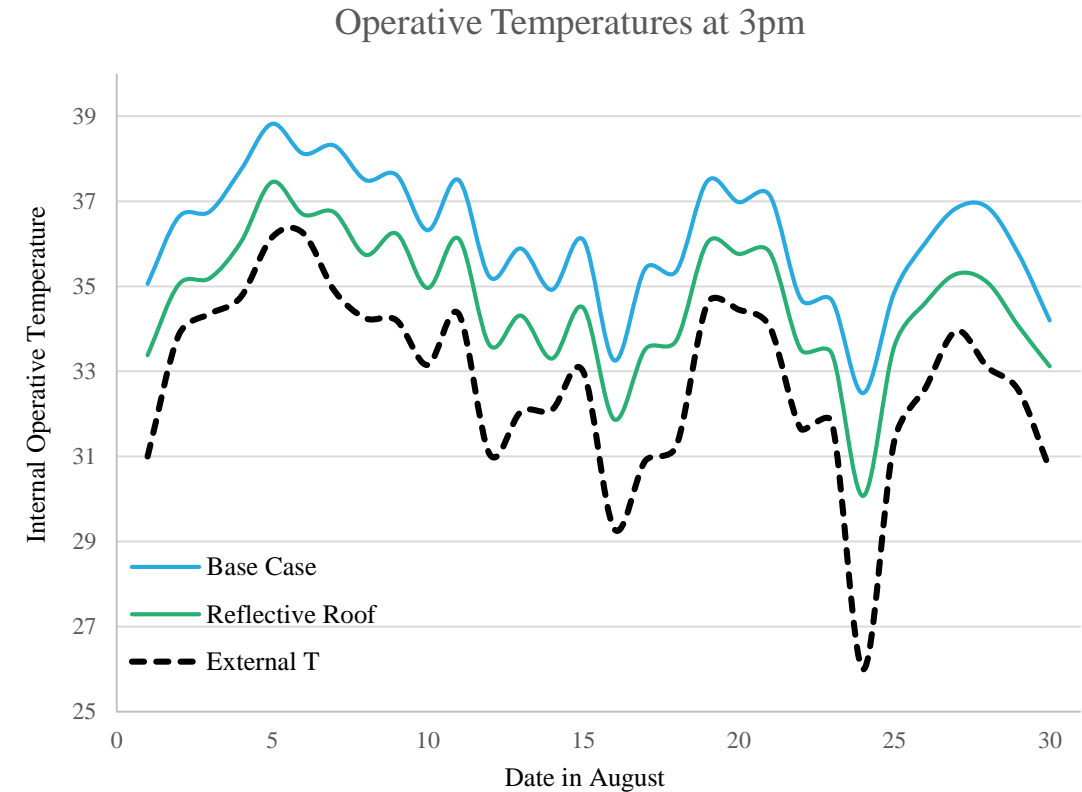


Figure 2: Internal operative temperatures for 3pm in August, comparing the reflective roof strategy against the base case.

Reflective Roof

An additional study looked at a range of roofs with different albedos to test their effectiveness. Results in Table 1 are compared to the base case where the roof albedo is 0.3. Results show the higher the albedo, the lower the internal room temperatures.

The average decrease is taken from the whole month of August, whereas the maximum is just the one occurrence. The weather file used for August includes cloudy days as well as sunny days, hence the magnitude of the trends for average and maximum decreases differs slightly.

| | Albedo 0.75 | Albedo 0.85 | Albedo 0.95 |
|---|----------------|----------------|----------------|
| Average decrease in operative temperature from base case (°C) | -0.5 | -0.7 | -0.8 |
| Maximum decrease in operative temperature from base case (°C) | -1.5 | -1.8 | -2.3 |

Table 1: Results of study comparing different albedo roofs.

Reflective Walls

A reflective wall strategy was modelled for passive cooling. In this case, the albedo of the Ecoblocks was increased to 0.6 to represent the painting of the walls. The concrete walls were already painted in the base case.

Results show an average 0.4 °C decrease in internal operative temperatures for the reflective walls case, when compared to the base case. This is due to the painted walls reflecting more sunlight than the base case, so less is absorbed by the walls. This then reduces the walls surface temperature, and in turn reduces the internal temperature of the house.

Figure 3 represents the operative temperatures at 7pm for each day in August. This shows the impact of the reflective walls, where the maximum reduction in internal operative temperatures is around 0.85°C.

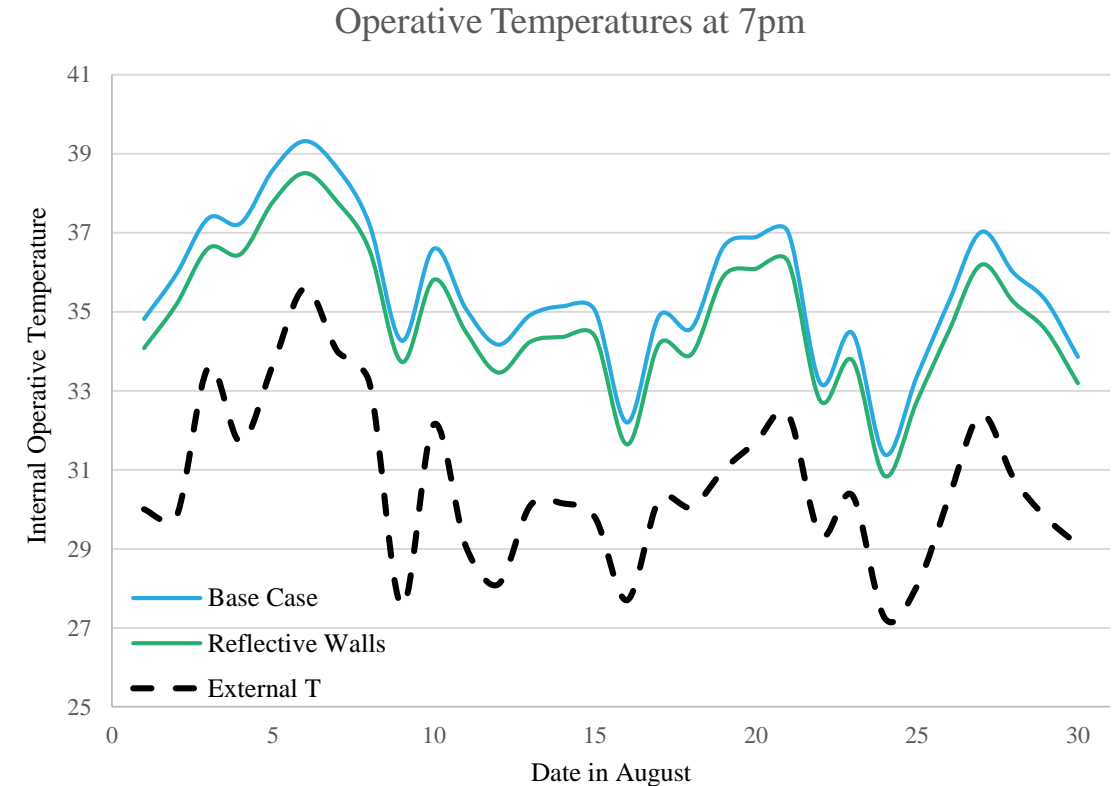


Figure 3: Internal operative temperatures for 7pm in August, comparing the reflective walls strategy against the base case.

Reflective Roofs and Reflective Walls

When comparing the reflective roof and walls cases, the reflective walls are less effective at reducing internal temperatures. This is because the concrete walls are already painted in the base case. Furthermore, it is expected the roof would have more impact due to its more direct orientation to the sun when absorbing sunlight.

Both passive strategies demonstrate greater cooling effects towards the latter half of the day. This is because both strategies reduce absorption of sunlight throughout the day. The effect is accumulated throughout the day, and thus the greatest difference seen towards the evening.

The plots in Figure 4 are taken from BEANS. They demonstrate spatial mean radiant temperatures for the base case, reflective roof case and reflective walls case at 4.30pm. Both strategies are effective at cooling the whole house.

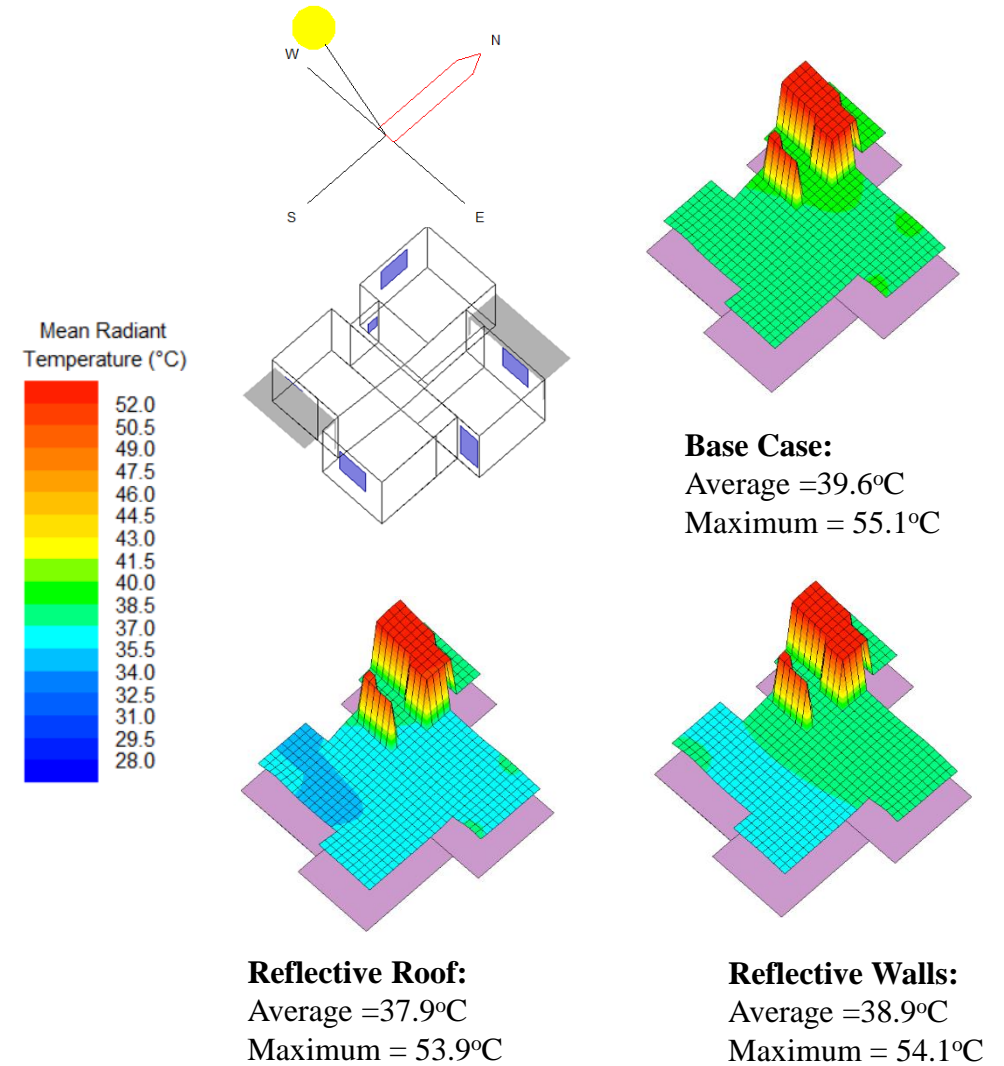


Figure 4: Spatial mean radiant temperatures for 4.30pm in August. The position of the sun is also shown along with house orientation. External temperature is 33.5°C.

Upsized Ventilation Portals

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Upsized Ventilation Portals

Lattice ventilation portals around the houses provide ventilation, such as those seen in Figure 5. The amount of ventilation is quantified as air change rates per hour. This is driven by the temperature difference between the internal and external spaces. A greater temperature difference drives more ventilation.

Strategies such as the reflective roofs and reflective walls are successful at reducing the internal temperatures, however also reduce that temperature difference between the internal and external spaces. This reduces the air change rates.

A strategy to consider is upsizing these ventilation portals, to allow higher ventilation rates which also reduce internal temperatures. An increased free area of 20% and 50% from the base case were considered.



Figure 5: Houses where lattice ventilation portals can be seen above the windows.

Upsized Ventilation Portals

Both upsized cases of 20% and 50% show an increased air change rate, which causes some reductions in internal operative temperatures.

The results are summarised in Table 2. The maximum difference in air change rates usually occur at night (10pm/11pm) when the temperature difference between the internal and external spaces is the greatest.

| | 20% Upsize | 50% Upsize |
|--|------------|------------|
| Average difference in operative temperature from base case (°C) | -0.17 | -0.36 |
| Maximum difference in operative temperature from base case (°C) | -0.26 | -0.57 |
| Average difference in air change rate from base case (per hour) | +0.85 | +2.05 |
| Maximum difference in air change rate from base case (per hour) | +1.23 | +2.99 |

Table 2: Comparisons of operative temperature and air change rate for upsized vents against the base case.

Orientation

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Building Orientation

Building orientation is an important passive strategy to consider. This is because the orientation can control the amount of solar gain entering the house through the windows.

In this section a range of orientations from the base case were considered, in 45°C intervals. Results are shown for a morning time of 9.30am, and evening time of 5.30pm. The evening time was chosen as is before sunset. Noon time temperature results have been omitted as show similar internal temperatures for all orientations. This is because at noon, the sun is at its peak in the sky. This is when most sunlight hits the roof directly and so orientation has less of an effect.

Note that internal walls were not included in this study, as the house was modelled as a single zone in BEANS. Therefore the effect of internal walls in the different orientations is not taken into account. Including internal walls would potentially reduce the penetration of the solar gain through the glazing and into the house.

Building Orientation – 9.30am

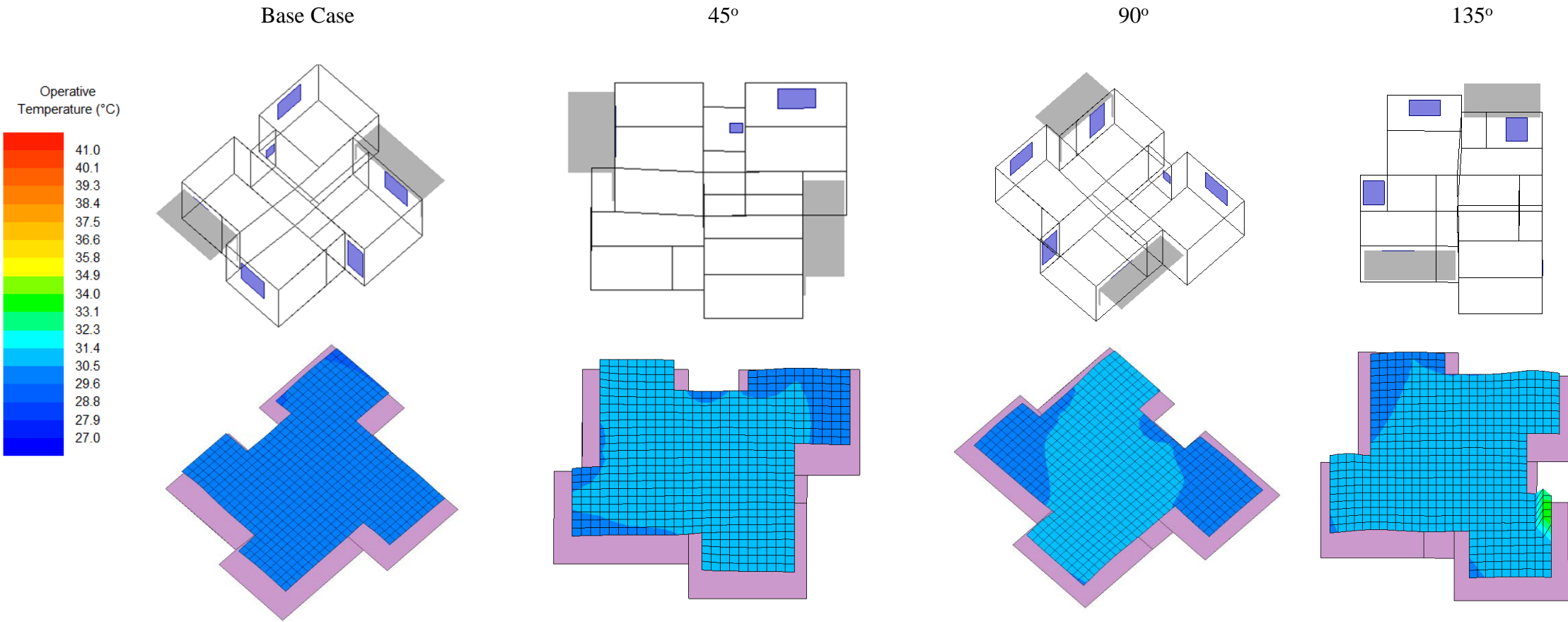
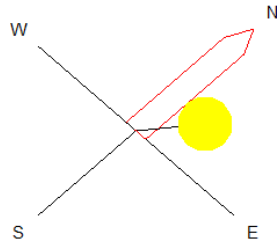
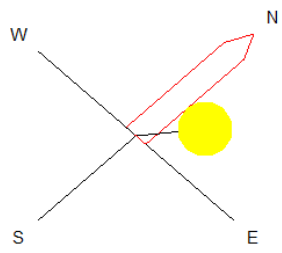


Figure 6a: Spatial operative temperatures for 9.30am in August for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 27°C.



Building Orientation – 9.30am

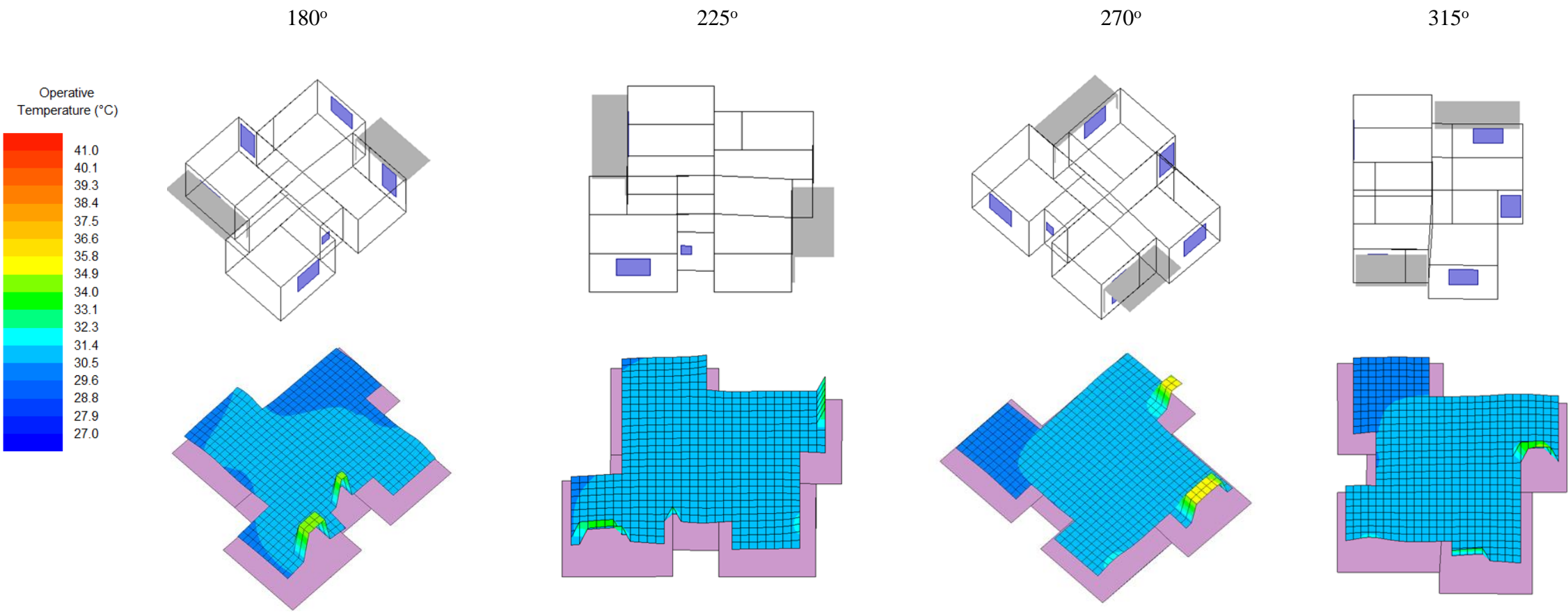


Figure 6b: Spatial operative temperatures for 9.30am in August for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 27°C.

Building Orientation

The results in Figures 6a and 6b show the spatial operative temperatures for the different orientations at 9.30am on the 15th August. The base case in Figure 6a shows lower temperatures than the other orientations at this time. This is because there are no windows facing East which let in sunlight and cause higher solar gain.

This is further demonstrated in Figure 7, where the base case consistently has the lowest temperatures. The highest temperatures are seen for 270°. This case has three windows facing East and thus a large amount of solar gain from the morning sun causing these higher temperatures.

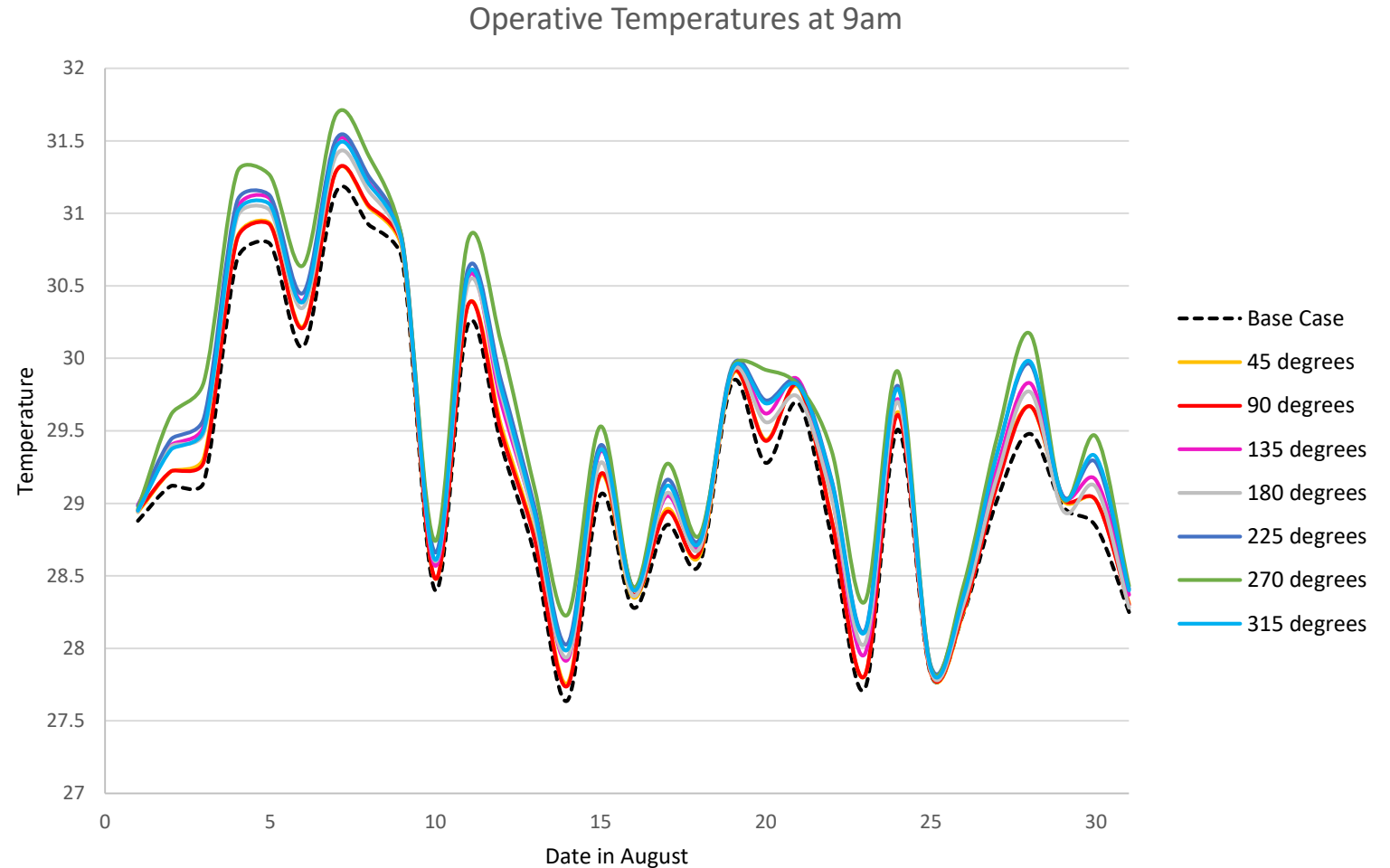
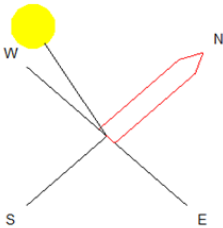


Figure 7: Internal operative temperatures for 9am in August, comparing different orientations.



Building Orientation – 5.30am

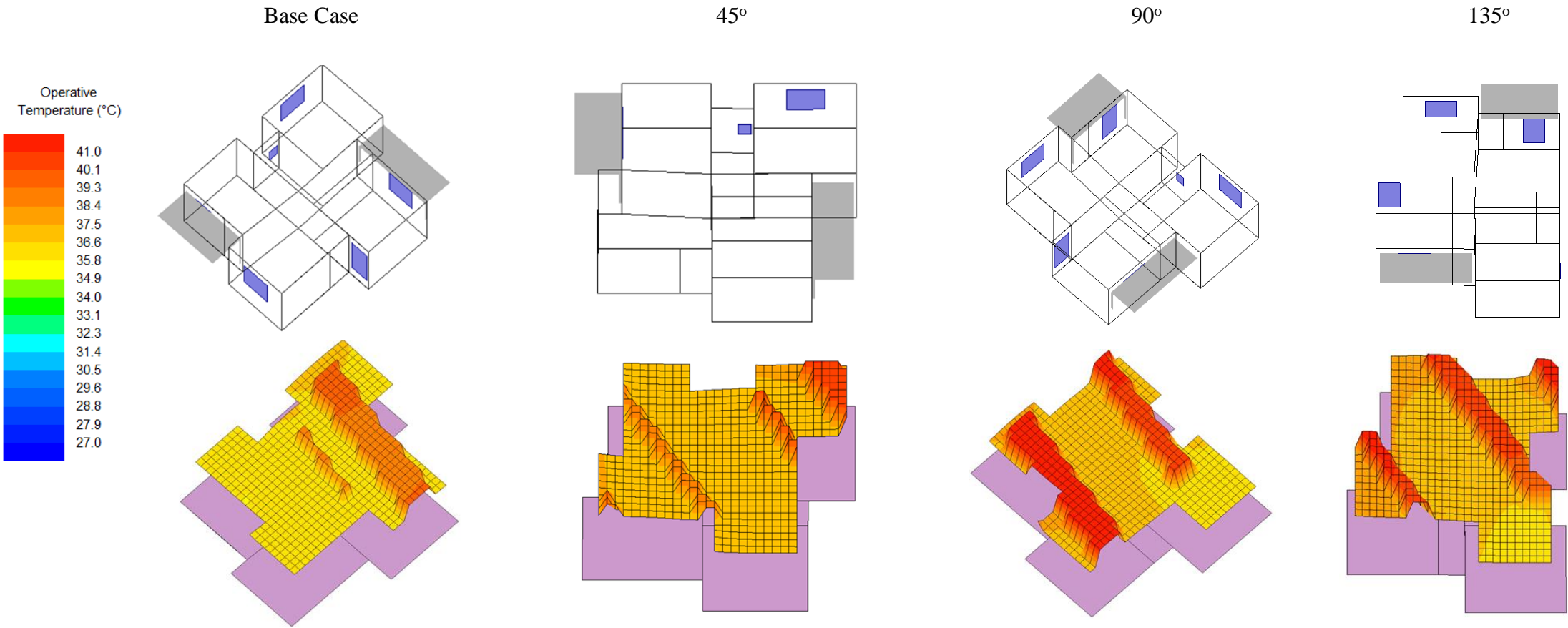
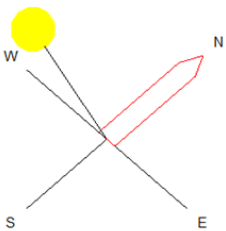


Figure 8a: Spatial operative temperatures for 5.30am in August for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 32.9°C.



Building Orientation – 5.30am

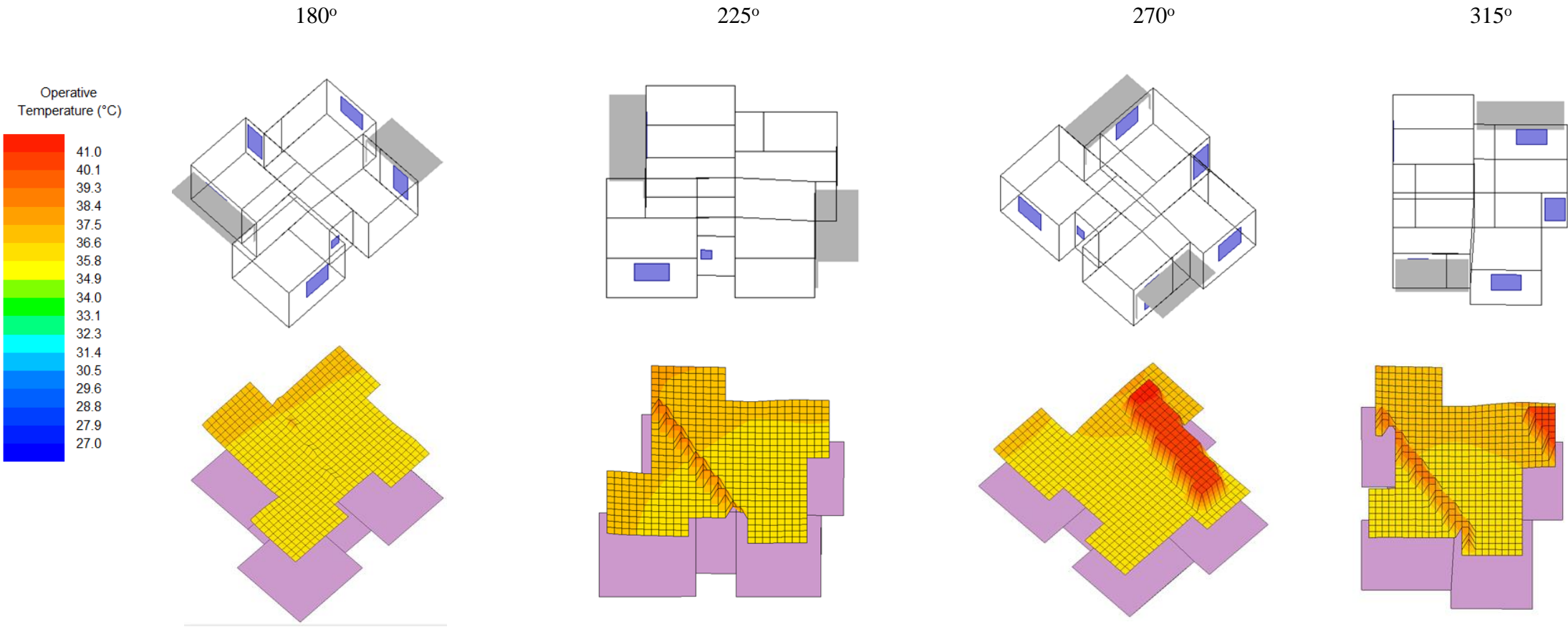


Figure 8b: Spatial operative temperatures for 5.30am in August for different building orientations. The position of the sun is also shown along with house orientation. External temperature is 32.9°C.

Building Orientation

The results in Figures 8a and 8b show the spatial operative temperatures for the different orientations at 5.30am on the 15th August. The orientation of 180° gives the lowest temperatures than the other orientations at this time. This is because there are no windows facing West which let in sunlight and cause higher solar gain.

This is further shown in Figure 9, where the 180° orientation case consistently has the lowest temperatures. The highest temperatures are seen for 90° and 135°. These cases have three large windows facing West, and thus a large amount of solar gain from the evening sun causing these higher temperatures. **To minimize evening temperatures, building orientation should minimize windows facing West.**

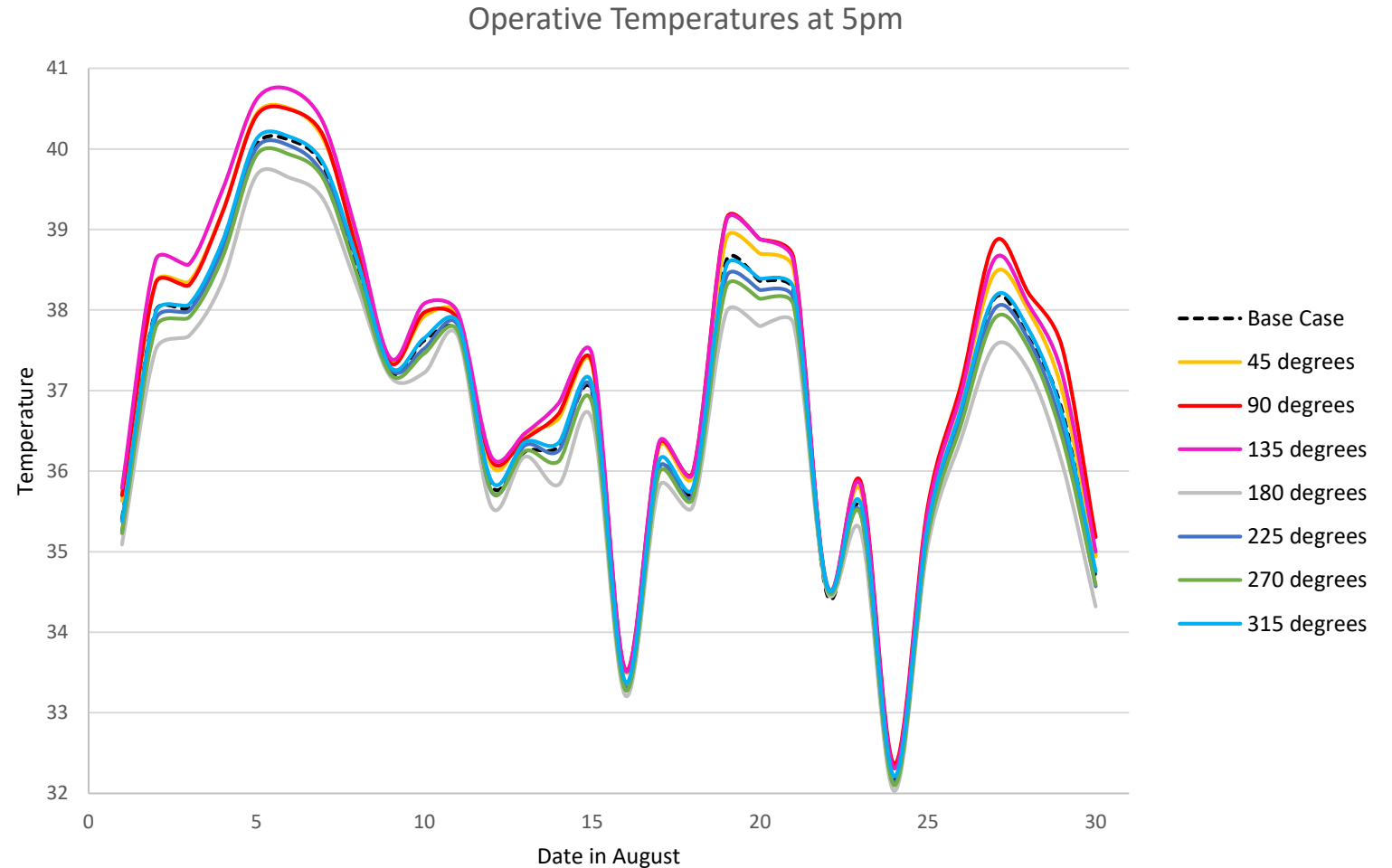


Figure 9: Internal operative temperatures for 5pm in August, comparing different orientations.

Blinds

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Blinds

Blinds are effective strategies at reducing the solar gain through windows, which causes higher internal temperatures. Whilst providing blinds are out of remit for the constructors, design additions which allows blinds to be installed could be incorporated. Furthermore, recommendations to tenants to install blinds can be made using these results.

Both internal and external blinds were modelled. The results compared to the base case are shown in Figure 10. These are presented at 3.30pm where the blinds are drawn.

Both internal and external blinds show reductions in internal temperatures around the house. External blinds prove to be the most successful blind strategy.

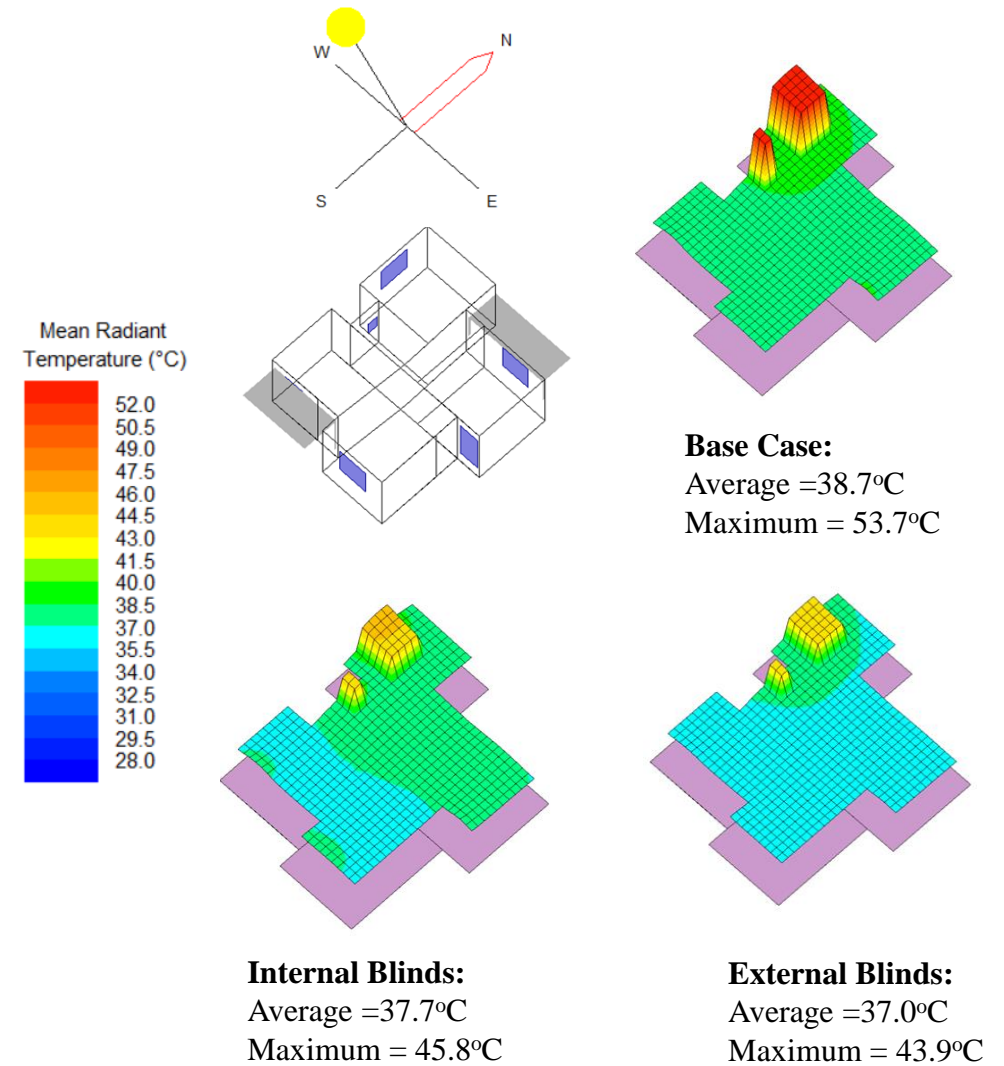


Figure 10: Spatial mean radiant temperatures for 3.30pm in August. The position of the sun is also shown along with house orientation. External temperature is 33°C.

Blinds

Internal and external blinds both prove to be highly successful strategies at passive cooling. This is because the blinds are effective at limiting the amount of solar radiation penetrating through to the internal space. This can be seen by the Sankey diagrams in Figure 11.

The Sankey diagram for the base case shows 82% of the incoming energy absorbed through the window into the inside space. The internal blind reduces this to 33%. However 36% of the energy absorbed by the internal blind is re-emitted inside. For the external blind, the amount re-emitted inside is only 6% as the majority is emitted to the outside. Therefore external blinds are most effective.

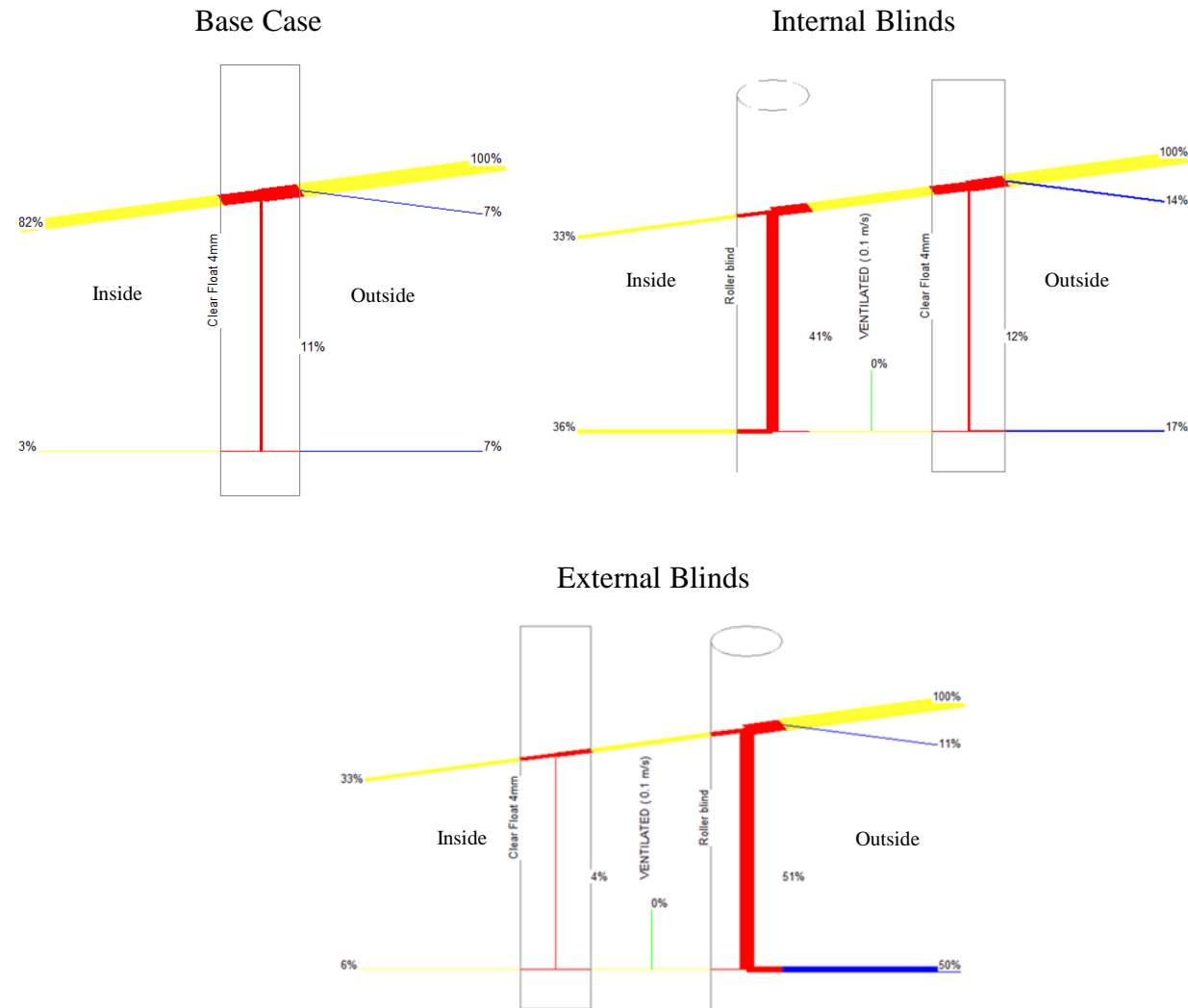


Figure 11: Sankey diagrams showing energy flow through the windows and blinds. The inside and outside domains are labelled. 100% represents incoming energy direct from the sun.

Glazing

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Glazing

Glazing is also an effective strategy at reducing the solar gain through windows. Both double glazing and solar glazing were tested. Solar glazing represents low emissivity glass, which aims to reduce absorption through the surface.

The results compared to the base case are shown in Figure 12. These are presented at 4.30pm.

Both double glazing and solar glazing show very similar results regarding the effectiveness at reducing operative temperatures. However, solar glazing is likely a much less complex and more cost effective strategy, since it can be incorporated as single panes in simple window framing.

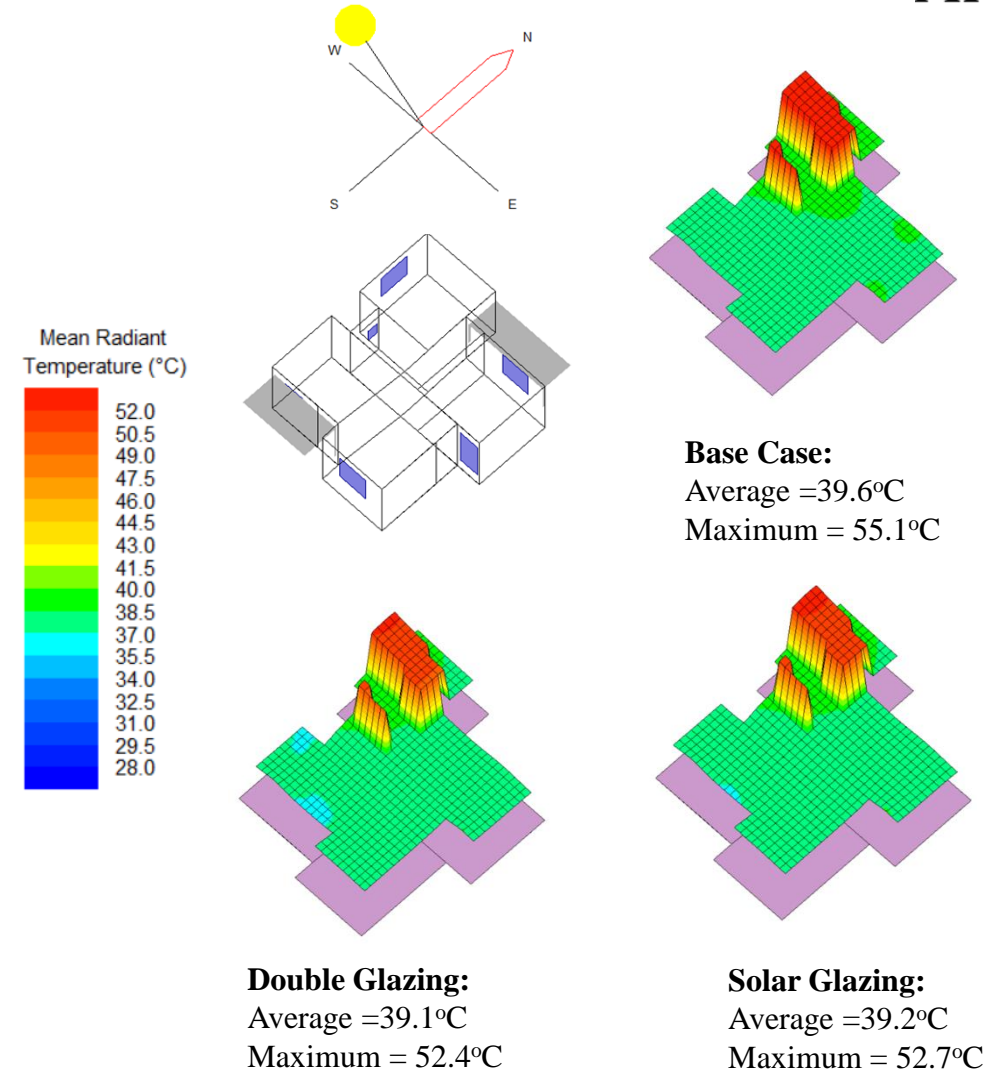


Figure 12: Spatial mean radiant temperatures for 4.30pm in August. The position of the sun is also shown along with house orientation. External temperature is 33.5°C.

Glazing

Double glazing and solar glazing both prove to be successful strategies at passive cooling. This is because they reduce the amount of energy absorbed into the inside space. This can be seen by the Sankey diagrams in Figure 13.

The Sankey diagram for the base case shows 82% of the incoming energy absorbed through the window into the inside space. Both solar glazing and double glazing reduces this to 68%.

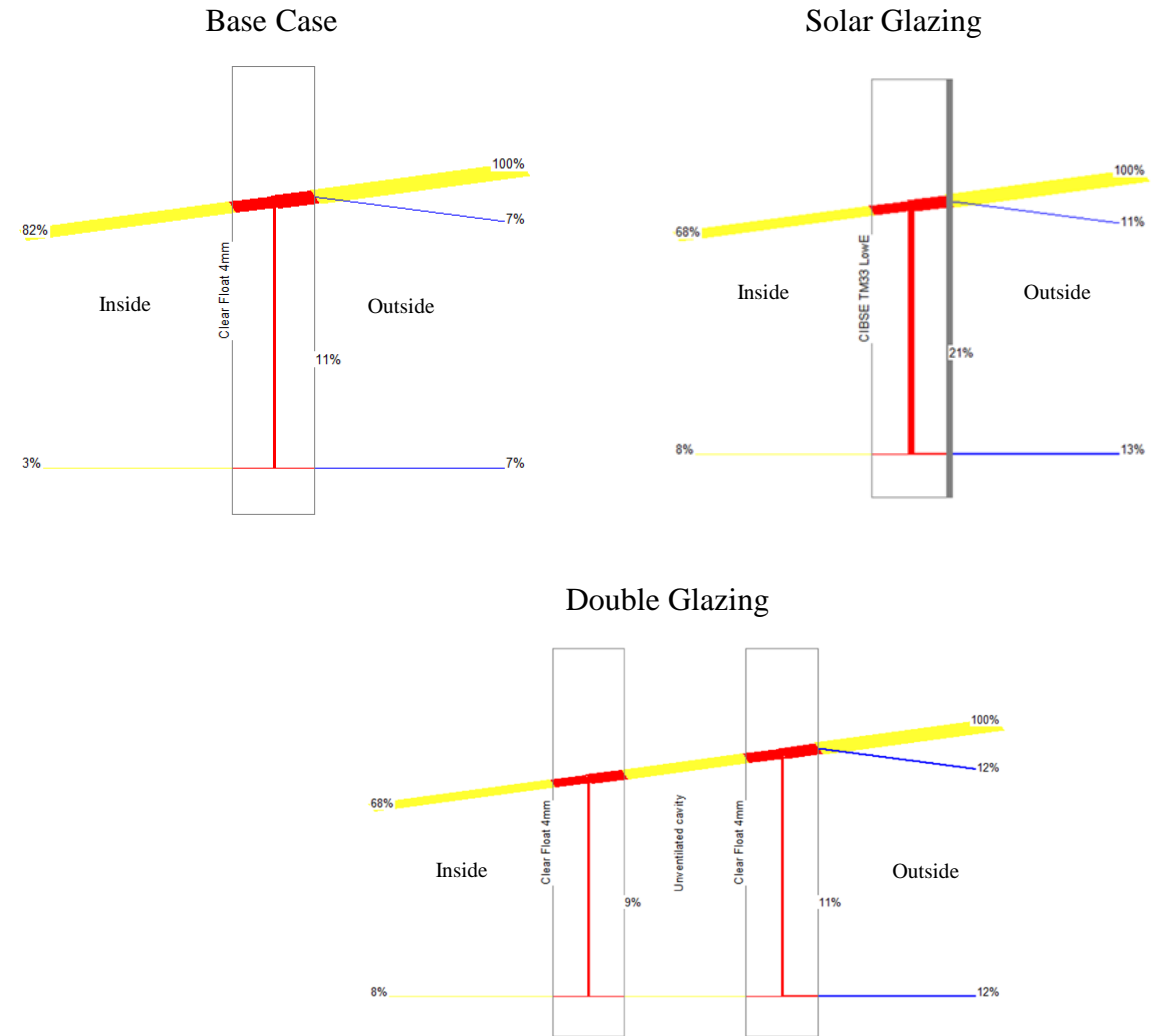


Figure 13: Sankey diagrams showing energy flow through the windows. The inside and outside domains are labelled. 100% represents incoming energy direct from the sun.

Insulation

Study of Passive Cooling Strategies

Insulation

An internal insulation strategy was considered using mineral wool. The results show internal insulation does not reduce internal temperatures, but instead an increase from the base case is seen. This is because internal insulation changes the thermal mass of the structure.

Figure 14 shows the operative temperatures at 12pm (noon) for each day in August. This shows the insulation can increase temperatures by up to 1°C compared to the base case.

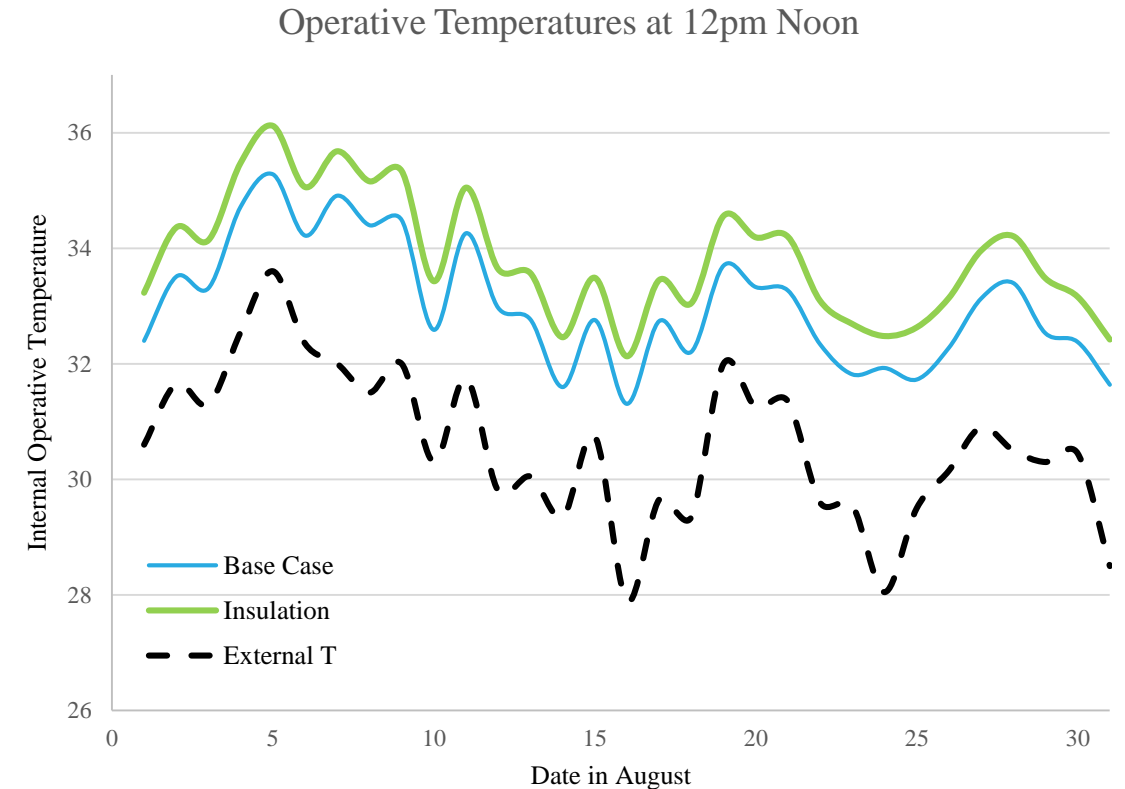


Figure 14: Internal operative temperatures for 12pm in August, comparing the insulation strategy against the base case.

Pitched Roof

Study of Passive Cooling Strategies

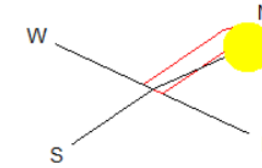
Pitched Roof

A pitched roof case was considered to examine the passive cooling effects.

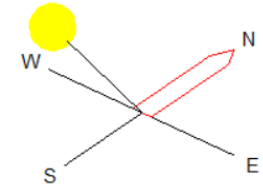
A flat roof has its whole surface area orientated towards the sun for most of the day, whereas a pitched roof does not. This can be seen in Figure 15. As the sun moves from East to West, for most of the day only half of the pitched roof is orientated towards the sun. Furthermore, at noon, the flat roof has the surface directly orientated towards the sun, whereas pitched roofs do not.

A half pitched roof case was also considered, also shown in Figure 15. This is to allow residents to potentially build a second storey, which was seen as desirable from the community feedback.

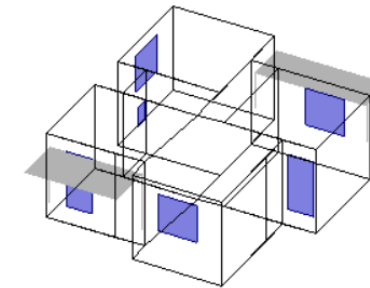
Morning Sun Position



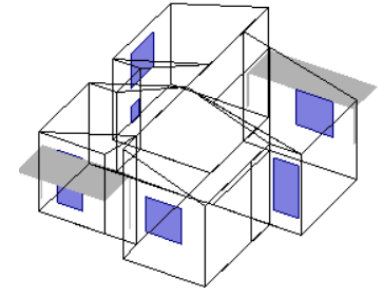
Evening Sun Position



Base Case (Flat Roof)



Pitched Roof



Half Pitched Roof

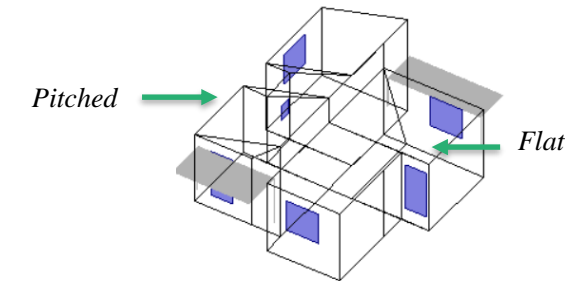


Figure 15: Models of base case, pitched roof and half pitched roof.

Pitched Roof

Pitched roofs also have the benefit of increasing the height of the houses. This means that the hotter air sits higher inside the house. In the pitched roof cases modelled, the lattice ventilation portals have remained at the same height w.r.t ground as the base case. It is expected that with a pitched roof, this vertical height would increase, which would increase the air change rates and thus provide more natural ventilation

Both the pitched roof and half pitched roof cases show an average decrease in operative temperatures compared to the base case of **0.06°C**. Figure 16 shows the spatial plots for 12pm (noon) when the sun is more direct on the flat roof.

The pitched roof and half pitched roof strategies show very similar results, allowing flexibility in design to allow for a second storey. However the results show much smaller benefits than other strategies presented.

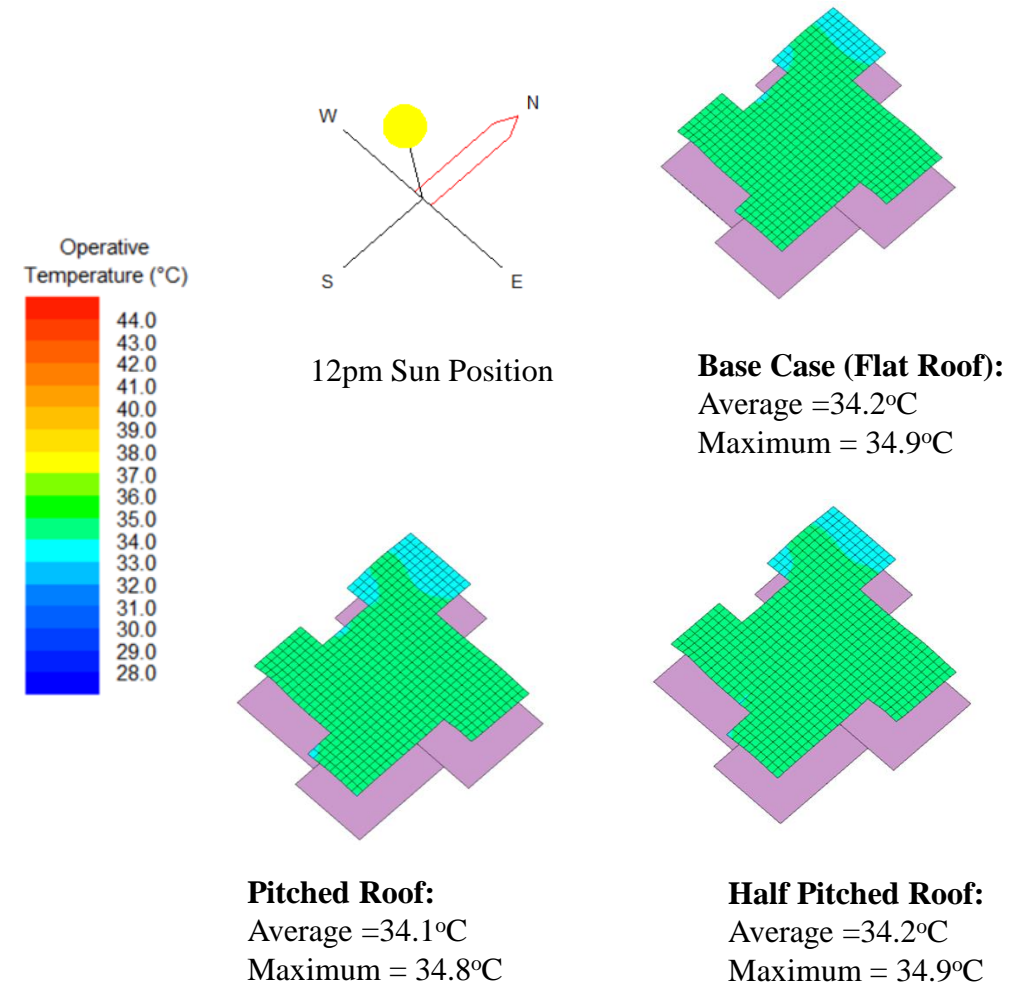


Figure 16: Spatial operative temperatures for 12pm in August. External temperature is 31.8°C.

Summary of Individual Strategies

Study of Passive Cooling Strategies

Summary and Conclusions

Section 1 has individually compared different passive cooling strategies to a base case. As described in the introduction, some strategies are effective for the whole house, and some for sections which are effected by solar gain coming in through the windows. Table 3 summarises the strategies and associated effectiveness, from dark green as most effective, to red having a negative impact.

| | Whole House Conditions | Sectional Conditions |
|-----------------------------------|------------------------|----------------------|
| Reflective Roof | | |
| Reflective Walls | | |
| Upsized Ventilation Portals (50%) | | |
| House Orientation (180°) | | |
| Inside Blinds | | |
| Outside Blinds | | |
| Double Glazing | | |
| Solar Glazing | | |
| Insulation | | |
| Pitched Roof | | |
| Half Pitched Roof | | |

Figure 17: Summary of effectiveness of passive cooling strategies

The most effective strategy for the whole house conditions is the reflective roof. Reflective walls and upsized ventilation portals also prove successful. For the sectional conditions relating to windows, orientating the house away from West (180°) and outside blinds and most successful. Inside blinds are also effective, but less so than outside blinds. Solar gazing and double glazing also had meaningful impacts, however solar glazing is more cost efficient as more simple to install.

- The strategies which have been identified as most effective in passive cooling for the base orientation are:
- Reflective Roof
 - Reflective Walls
 - External Blinds
 - Upsized ventilation portals
 - Solar Glazing

These will be modelled in Section 2 in combinations, as well as one case at 180° orientation.

Combinations

Study of Passive Cooling Strategies

Background and Approach

The strategies which have been identified as most effective in passive cooling for the base orientation are:

- Reflective Roof
- Reflective Walls
- External Blinds
- Upsized Ventilation Portals
- Solar Glazing

These were modelled in combinations, as well as one case at 180° orientation. The cases are shown in Figure 18.

| | CURRENT WORKFLOW | | NEW PRACTICE | FAMILY RESPONSIBILITY | ALL RETROFIT | BEST PERFORMANCE |
|-------------------------------------|------------------|---------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Case | Combo1 | Combo2 | Combo3 | Combo4 | Combo5 | Combo6 |
| Pitched roof | None | None | None | None | None | None |
| Thatched roof | None | None | None | None | None | None |
| Building orientation | Average | Average | Average | Average | Average | Min |
| Natural ventilation | Upsize | Upsize | Upsize | Upsize | Upsize | Upsize |
| Additional insulation | None | None | None | None | None | None |
| Reflective external walls | As built | Full coverage | Full coverage | Full coverage | Full coverage | Full coverage |
| Blinds / external shutters / shades | None | None | None | Included | Included | Included |
| Overhangs / porticos | As built | As built | As built | As built | As built | As built |
| Glazing | None | None | Single, solar control | None | Single, solar control | Single, solar control |
| Reflective roofs | Included | Included | Included | Included | Included | Included |

Figure 18: Combination of passive cooling strategies modelled

Results

The results from the combinations are presented below in Figure 18 for the overall space conditions. Spatial results for various times of the day are presented in the next slides for the 15th August. The results show that as we move from Combo 1 to Combo 6, the internal temperatures decrease.

Combinations of passive cooling strategies prove to be more successful than individual strategies. Combo 6 shows the most effective strategy, where the house is orientated 180° from base. This orientation will be recommended for new plots of houses.

The upsize of the ventilation portals between the combinations is constant (50% from base). Whilst the internal operative temperature decreases, the air changes also decreases, as the difference in temperature between the internal and external space has decreased. However all combinations show a greater air change rate than the base case.

| Difference from base | | |
|----------------------|-----------|-------------|
| | Operative | Air changes |
| | °C | /hr |
| | | |
| Base | | |
| Combo 1 | -0.96 | 1.53 |
| Combo 2 | -1.29 | 1.07 |
| Combo 3 | -1.34 | 1.05 |
| Combo 4 | -1.62 | 0.76 |
| Combo 5 | -1.66 | 0.73 |
| Combo 6 | -1.71 | 0.70 |

Figure 19: Results from combination of passive cooling strategy study.

Combination Results – 9.30am

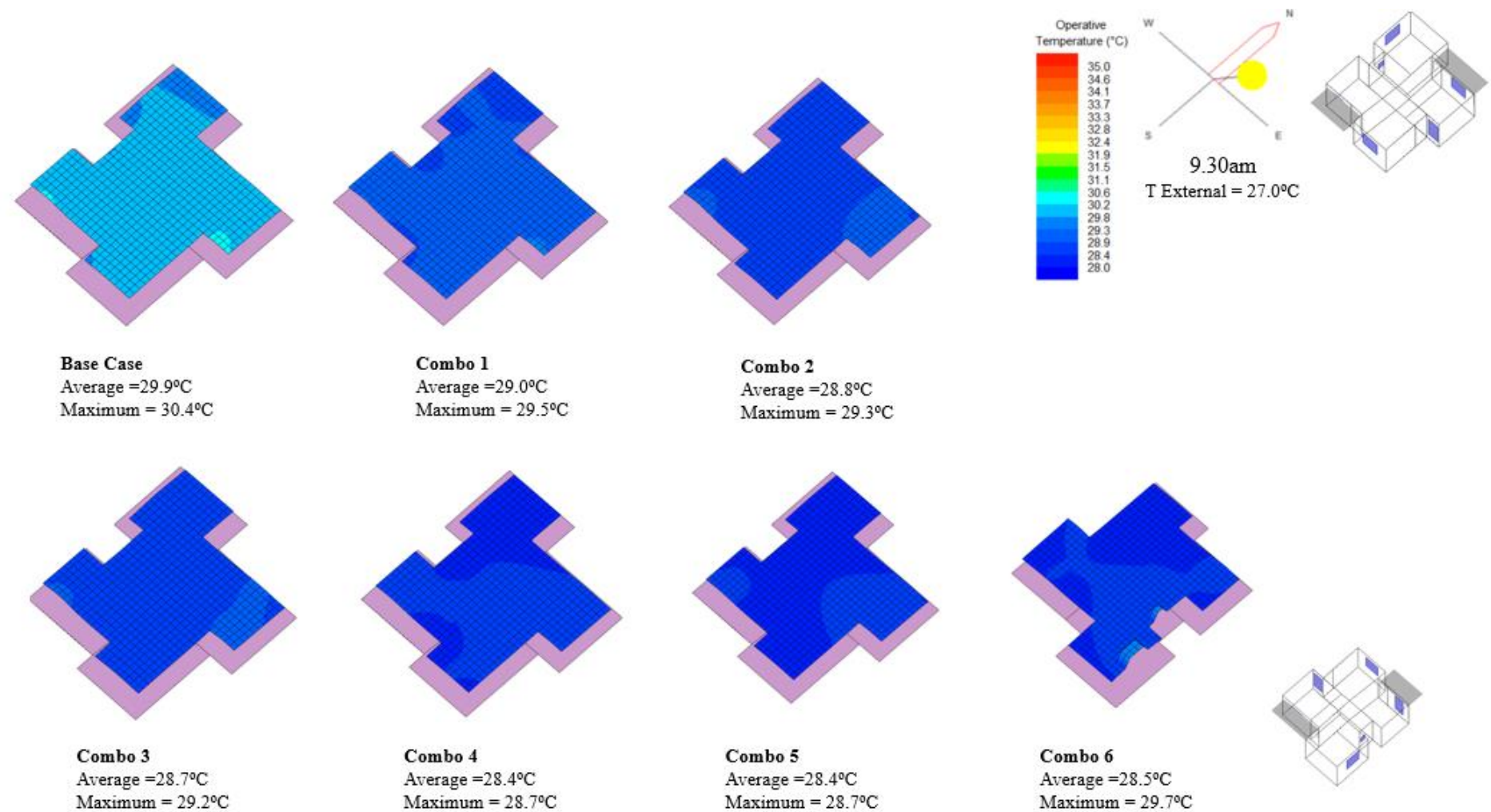
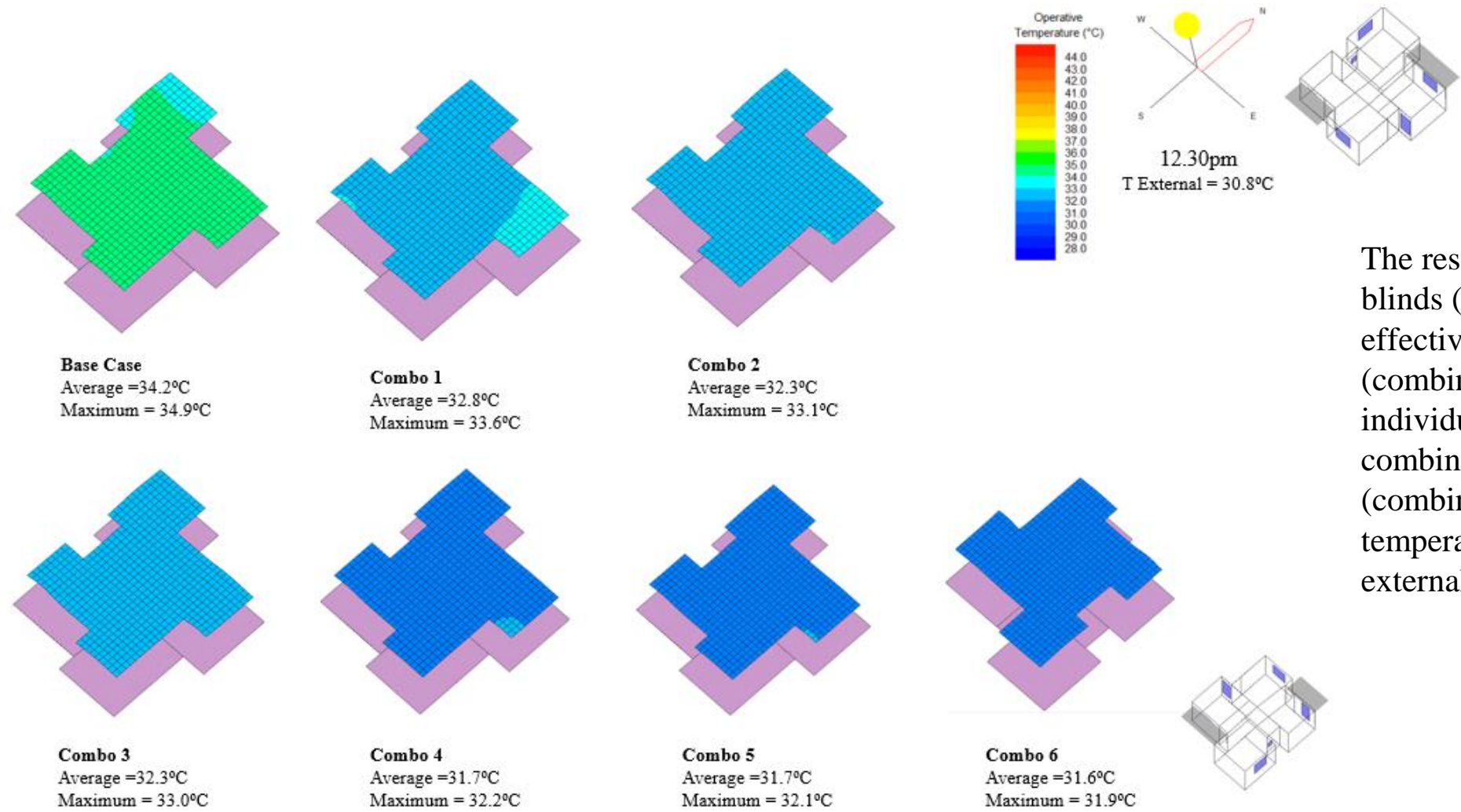


Figure 20: Spatial plots from combination of passive cooling strategy study at 9.30am

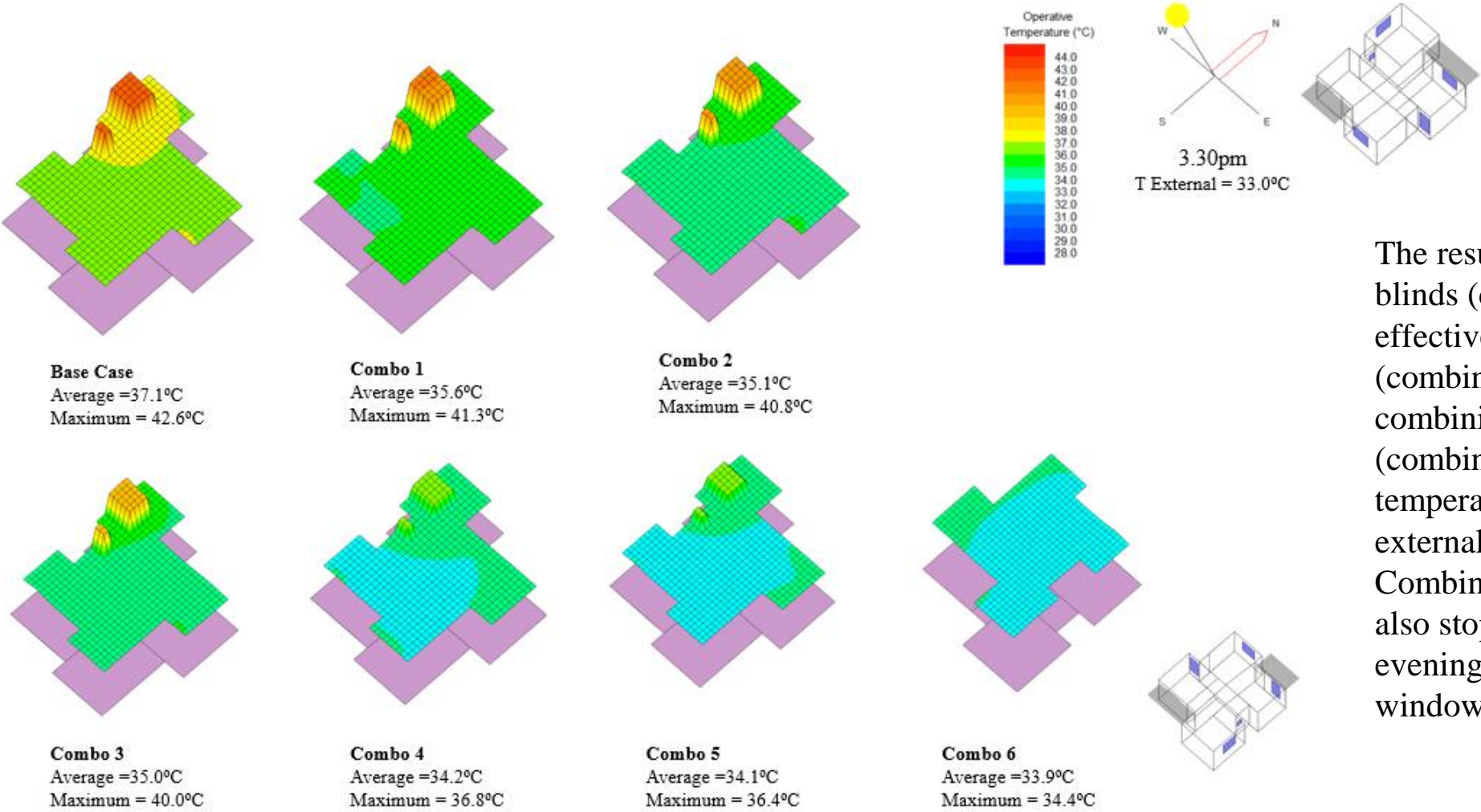
Combination Results – 12.30pm



The results here show external blinds (combination 4) are more effective than solar glazing (combination 3), as seen in the individual strategies. However combining the blinds and glazing (combination 5) shows minimal temperature differences than the external blinds alone.

Figure 21: Spatial plots from combination of passive cooling strategy study at 12.30pm

Combination Results – 3.30pm



The results here also show external blinds (combination 4) are more effective than solar glazing (combination 3). However combining the blinds and glazing (combination 5) shows minimal temperature differences than the external blinds alone. Combination 6 is most effective as also stops the solar gain from the evening sun entering through the windows.

Figure 22: Spatial plots from combination of passive cooling strategy study at 3.30pm

Combination Results – 7.30pm

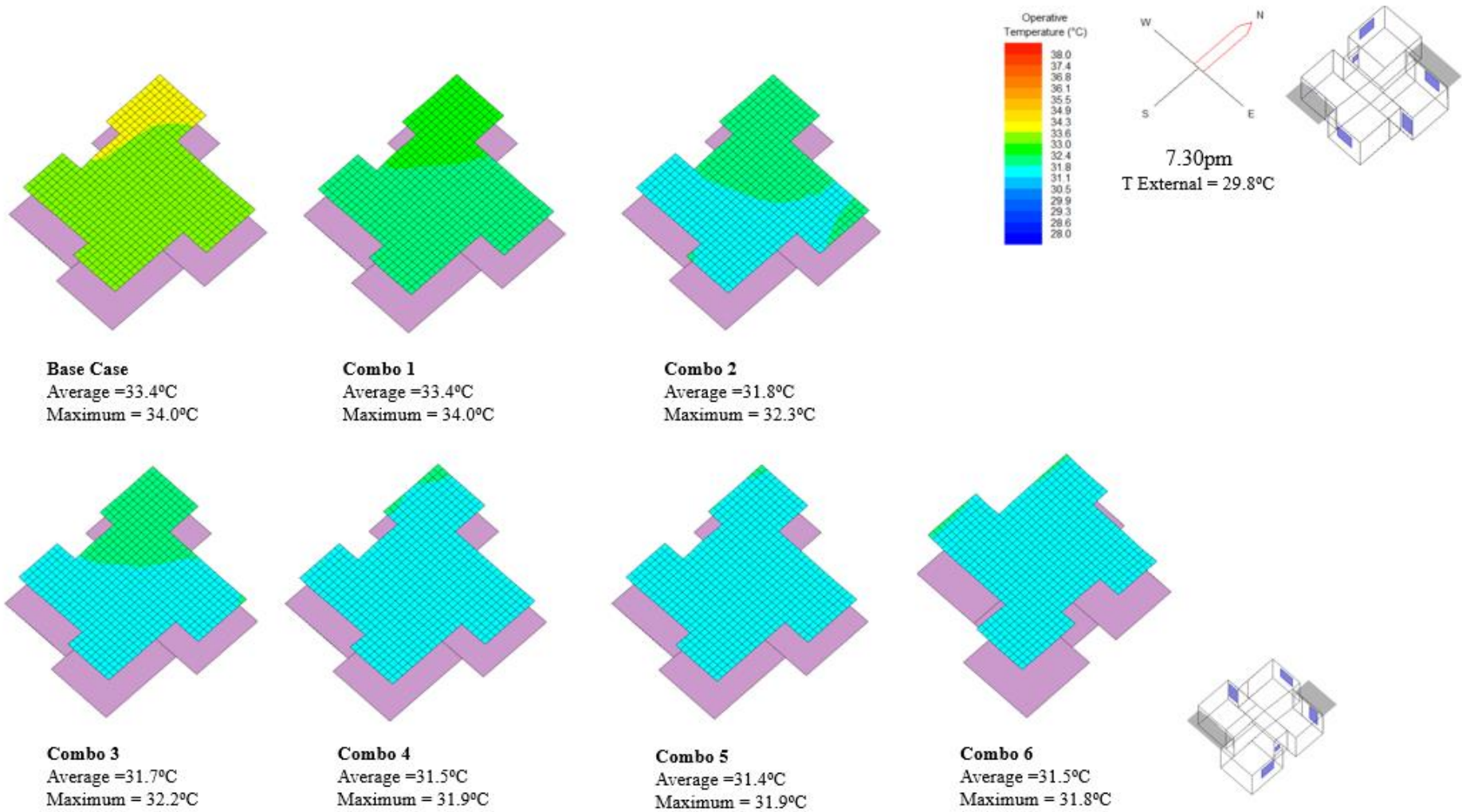


Figure 23: Spatial plots from combination of passive cooling strategy study at 7.30pm

Summary of Combinations

Study of Passive Cooling Strategies

Summary and Conclusions

Figure 24 summarises the combination results. The relative heights represent improvements in average internal operative temperatures at 3.30pm, which is around the time the maximum temperatures throughout the day occur.

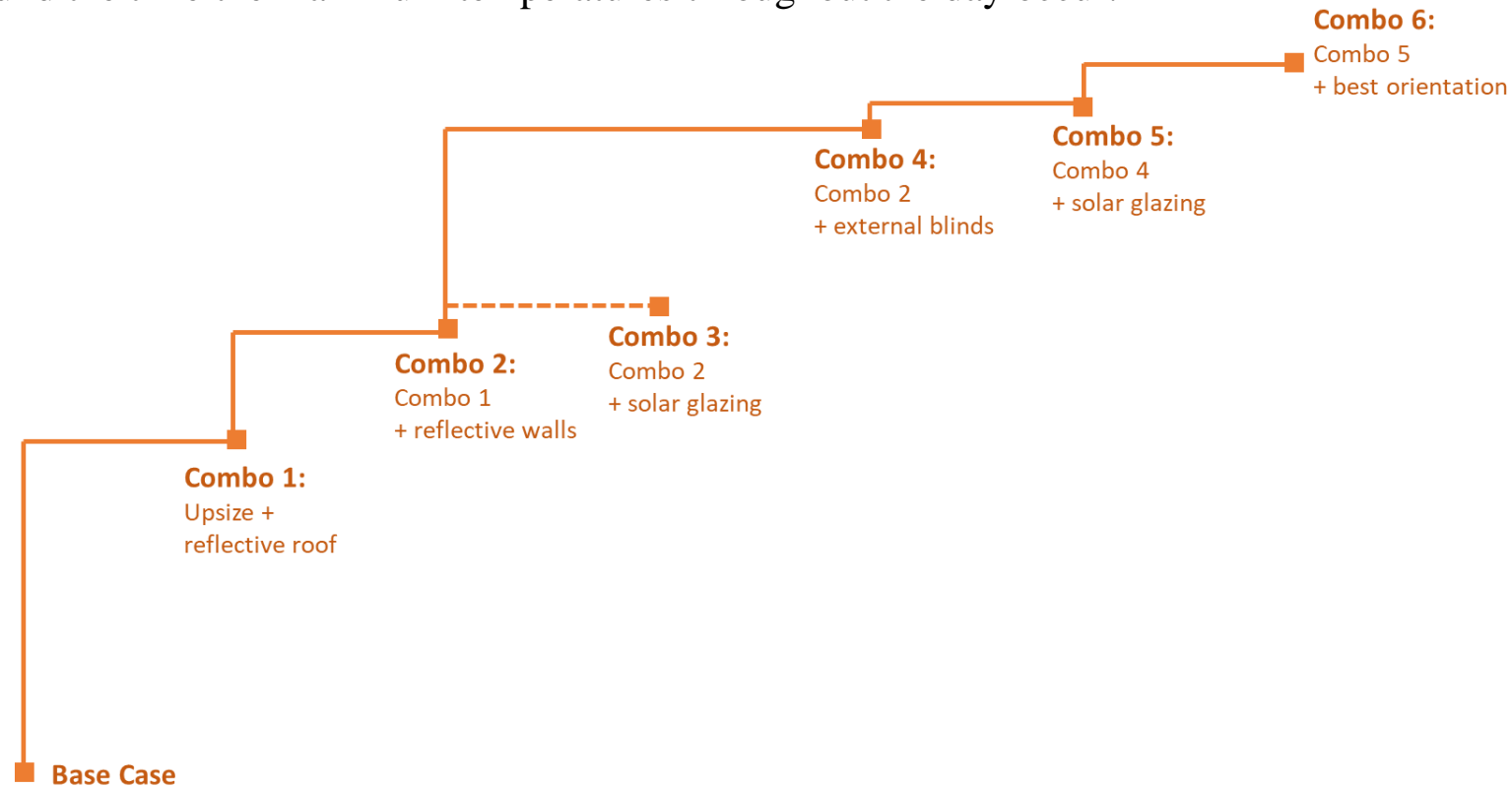


Figure 24: Combination summary results (3.30pm on 15th August – spatial average operative temperatures)

Additional Analysis

February Study

A study on Combo 5 was conducted in February, to ensure comfortable temperatures in the cooler months and test that the passive cooling strategies would not cause uncomfortably low temperatures. Figure 25 below show temperatures for the 15th February. (Note: the latitude, longitude used in this study is 17.98,-92.93). Generally, external temperatures are still fairly warm, between 20-35°C, thus passive cooling provides benefits all year round.

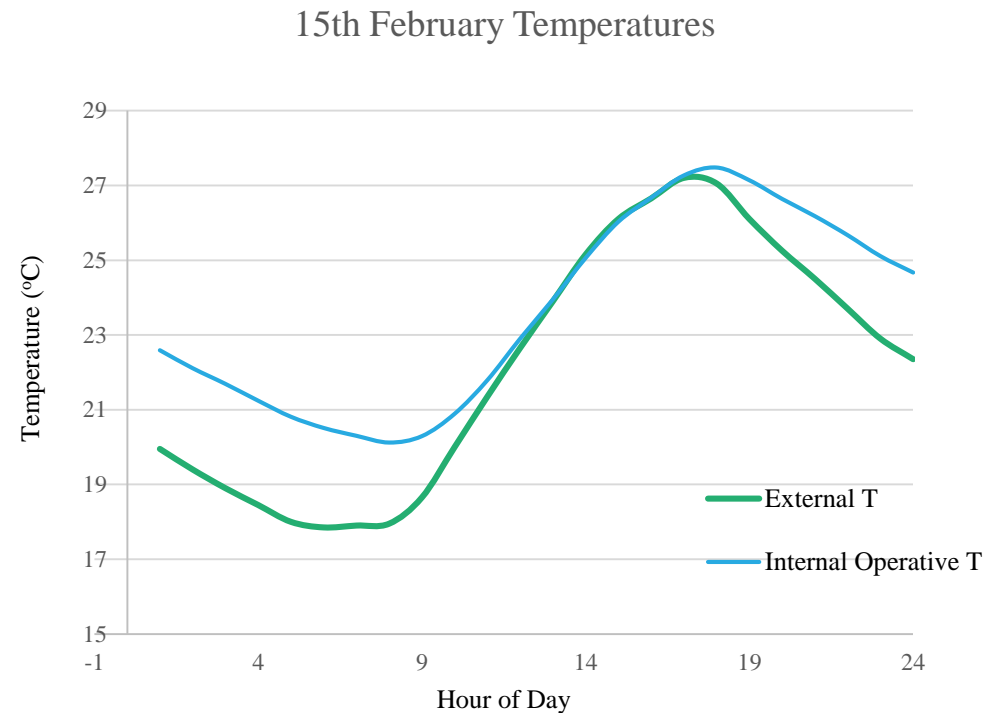


Figure 25: Internal Operative Temperatures in February with Combination 5 of the passive strategies

ARUP