CHAPTER 6

PARAMETRIC ANALYSIS OF AN ATRIUM BUILDING IN A MEDITERRANEAN CLIMATIC CONTEXT

6.1 Introduction

The previous two chapters concentrated on the thermal performance and thermal comfort survey of an atrium building in the Mediterranean climatic context. It consisted of an analysis of the thermal performance of the case study building and the comparison of the results predicted by a dynamic thermal simulation programme. This method was used in order to validate the programme so that it would be used in the analysis of the of the impact of selected design alternatives such as the roof glazing materials, ventilation modes, building type, etc on the thermal performance of the atrium building and the occupants' thermal comfort. It was decided to employ a dynamic thermal model to predict conditions throughout the occupied period and the space, by performing a parametric analysis of building performance. This is aimed to lead to the identification of effective energy saving measures and formulate guidelines for climatic responsive atrium design and optimum occupant comfort, in Greece.

The main aims of this chapter is to give answers to various critical issues raised in the introductory chapter:

- To further examine why the atrium space performs as it does.

- To further examine whether the atrium would have provided higher thermal comfort conditions if different geometry, ventilation mode, roof shape and glazing material were different.
- To examine which strategies would give best comfort if no HVAC is used.
- To examine whether there are elements of the atrium design connected with local discomfort (to examine the variation in comfort in various spots and heights within an atrium).
- To establish which are the optimum design-options in terms of comfort for atrium buildings in a Mediterranean climatic context.

Simulations were performed for one typical day for each of the two seasons. The results of each design alternative are analysed, and tabulated summaries of the results for each type are presented and discussed at the end of the chapter.

6.2 Parametric Study

Parametric analysis has been used in previous studies Kolokotroni (1989) in the same climatic context, and Ho (1996) and Wall (1996) for the same type of buildings (glazed spaces). It involves varying one element in the model while all the other elements are constant. Therefore, the change in results is solely due to the change of that element. In the current study, and since the main aim is to provide comfort, the comfort results along with air temperature in the atrium space will be used as the main measures of effectiveness and a benchmark against which all the results will be evaluated.

The use of the thermal comfort model and the resultant presentations will also serve as a guideline for analysing those specific conditions critical in the atrium design. However, the results should be carefully investigated and related to the simulated air and surface temperatures. Energy is also considered, but in the current study the main aim is to achieve comfort, not necessarily to reduce energy consumption.

6.2.1 Setting the acceptable thermal comfort limits

Before embarking on the parametric analysis, the first step is to set the criteria by which to evaluate the thermal comfort results; that is to set the acceptable thermal comfort limits for the atrium space. That is essential since the atrium space cannot be rigidly classified under a specific category of spaces for human occupancy. The analysis carried out in the previous two chapters will be used at this stage to set the thermal comfort limits.

Table 6. 1 Neutral temperature and comfort zone for both seasons

	Neutral temperature	Acceptable Condition (75%)	Acceptable Condition (90%)
Cool Season	14.98 ^{0}C	11.98-17.98	13.47 – 16.49
Warm Season	24.22 ^{0}C	21.22-27.22	22.71-25.73

Table 6. 2: Minimum atrium temperature requirements based on its use, according to Hastings

Use	Description	Minimum Temperature (^{0}C)
Communication	The users do not stay in the atrium but use it to move from one place to another or to get fresh air	10-14
Active use	Functions where the users move around like in a lobby, sports hall or an exhibition centre	12-18
Relaxing, sedentary activity	The users are sitting down for long periods	20
Plant growing	Greenhouse or park, minimum temperature depends on the plants	5

Table 6.1 was analysed in chapter 5 (Table 5.5) and shows the calculated neutral temperature, the acceptable conditions for 75% of the occupants and the acceptable conditions for 90% of the occupants for both the cooling and heating seasons.

In addition to that, research by Hastings argues that the use of the atrium decides its thermal climate. Table 6.2 shows a classification based on Hastings (1992).

As it can be seen from the two tables, the acceptable conditions that satisfy 75% of the occupants in the atrium in the cool season as calculated from the analysis of the results in chapter 5, is similar to the temperature range suggested by Hastings for an active use of the atrium space. The atrium space of the case study is mainly used as a communication space and therefore even temperatures as low as 10^0C can be accepted. There are no suggestions as far as an upper comfort limit is concerned for the warm season.

To create the link between 75% acceptability and measured thermal sensation, it is accepted that a group mean thermal sensation (PMV) between the limits of ± 1 corresponds with 25% of the occupants being dissatisfied (PPD). The 25% general dissatisfaction accounts for a 10% criterion for the body as a whole, corresponding to tests performed in the laboratory under uniformed conditions. Additional average 10% dissatisfaction might occur because of local thermal discomfort. Since the adaptive model is based on field measurements, where people are naturally integrating whole body plus local sensations, field votes already account for both sources of discomfort. A final 5% is added because of the greater than normal thermal asymmetries in the atrium space.

The adaptive model of thermal comfort is essential to account for additional contextual factors and individual experiences that appear to modify people's expectations in naturally ventilated buildings. The mean expectation vote for the cool season was "slightly cool" (-0.51) whereas the largest percentage of the subjects (37%) expected to feel neutral (Figure 5.12). For the warm season, the mean expectation vote was –0.39, indicating that the majority of the population expected to feel "slightly cool" inside the atrium space. In total

66.5% of the population votes were amongst the three central categories, 24.5% of the votes for the cooler side of the scale and only 9% expected to feel "warm" or "hot" inside the atrium space.

6.2.2 The Parametric Study Scenario

The second step is to set the scenario of the parametric study: an outline of the expected sequence of actions. This is determined by the evaluation of the research outcomes of the previous chapters that function as the base on which the parametric analysis depends on:

- The main atrium building types identified in the Mediterranean climate
- The thermal processes that occur in an atrium building, and the design factors that influence it's performance
- The response of the design factors to the Mediterranean climatic context
- The application of the thermal comfort standards as set by the occupants' survey and the case study thermal performance analysis.

Figure 6.1 shows the main scenario for the parametric study. The thermal simulations will be performed for the cool and the warm season as performed for the analysis of the case study building. The models will focus on the atrium space as a free running space, assuming a constant indoor temperature of the neighbouring blocks for both seasons.

The objective of the parametric study is to look into the effect of different parameters on thermal comfort conditions inside the atrium. The results of the thermal comfort analysis will be compared to those derived from the analysis of the two previous chapters as indicators of the occupants' preference. There will be a comparative analysis of the various results aiming to identify the design that reflects the most the occupants' thermal comfort preference.

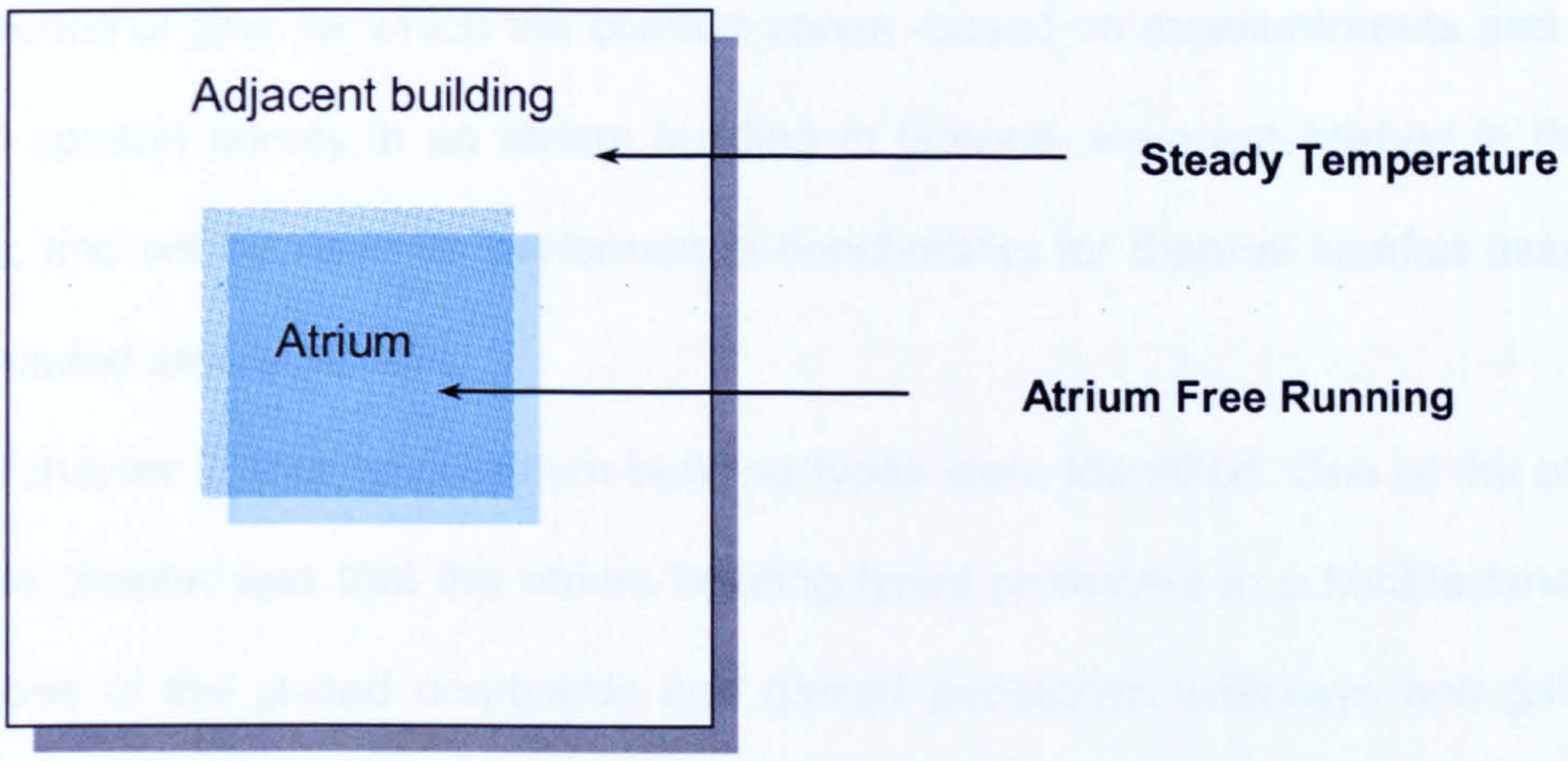


Figure 6. 1: The figure shows the main scenario for the parametric study: the adjacent building has a steady temperature for each of the two seasons whereas the atrium building is free running

The case study building in Ioannina provided guidance for a basic geometrical model for the parametric study. The assumed values have been chosen to correspond to the following criteria:

- The building is non-domestic and occupied during normal working hours for all days of the week.
- The base case has a plan of 32x32m square plot in a suburban plot, free from external obstruction.
- The main building envelope has a base temperature of 20^0C.
- Independent ventilation for the main building is assumed whereas the atrium space is naturally ventilated.
- The default climate is that for Athens as it is a more typical example of a city in the Mediterranean region and expressed some of the more worrying aspects of the climate, i.e. high summer temperatures. The weather file was already in the CLIDAT component and represents annual weather data. APPENDIX E includes a psychometric chart for the climate

of Athens. The sequential analysis performed by the simulation programme also required specific day of the year and iterations were run for the months of December for the cool season and June for the warm season and the 22nd day. These dates correspond to the same period of time for which the comfort zones -based on measurements and occupants' thermal comfort survey in an atrium building in Greece- were established in the previous chapter, and will be used as performance benchmarks for thermal comfort assessment of the simulated atrium models.

In chapter 2, four basic atrium-building types were identified. One of the outcomes of the same chapter was that the atrium building types prominent in a Mediterranean climate were those of the glazed courtyards and glazed pedestrian walkways and gallerias. The attached type (e.g. greenhouse) is rarely found in the Mediterranean climatic context.

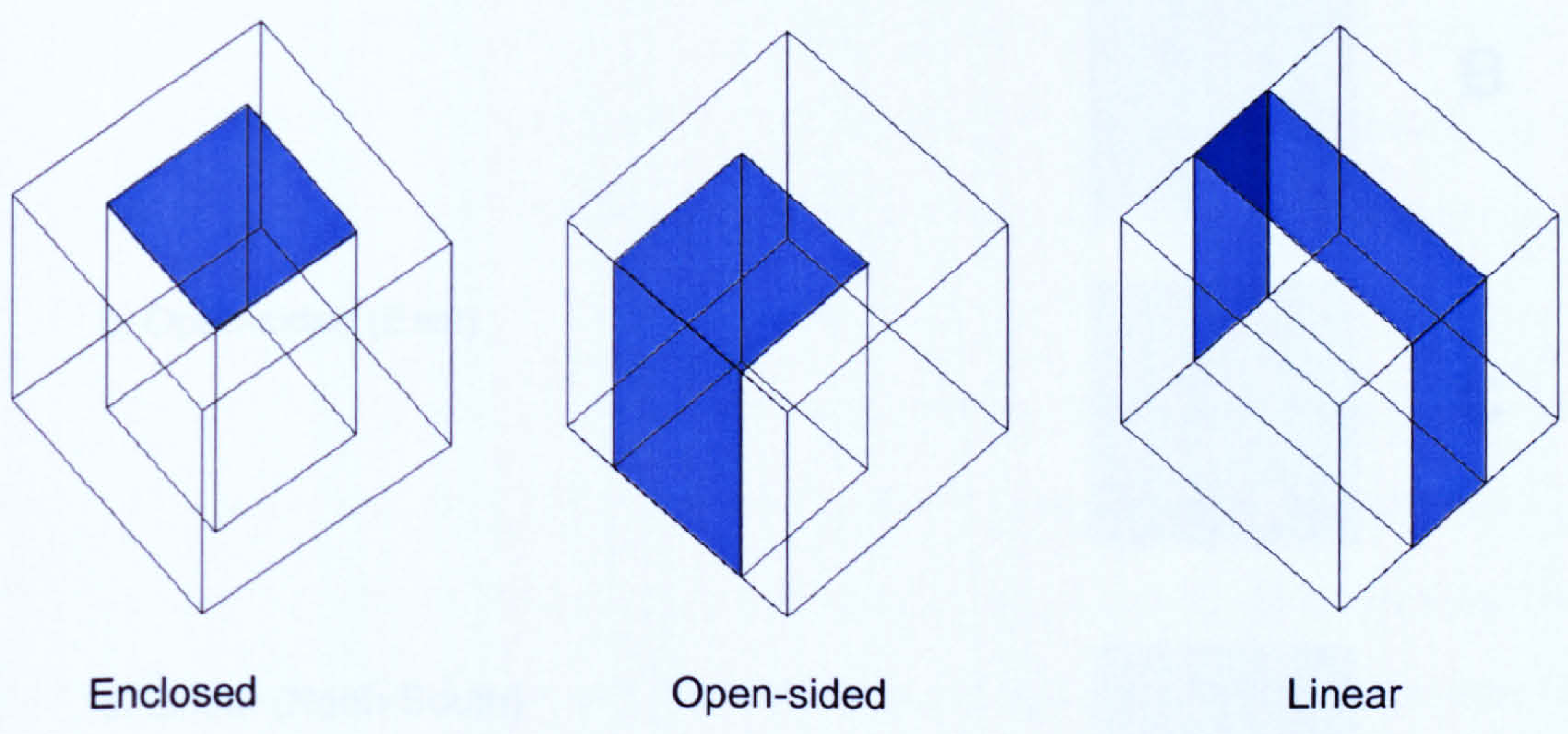


Figure 6. 2: The atrium building types to be analysed in the parametric study.

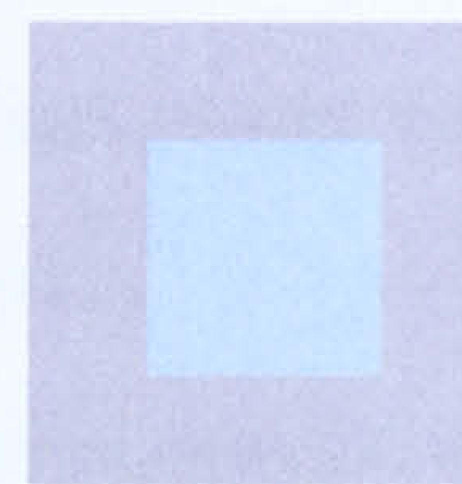
The thermal mass of the adjacent building is set to the one assimilating the case study building, which is typical construction in the Mediterranean region. The atrium floor to building floor ratio is set: AF/BF = 1:3. The three main types of buildings to be analysed are shown in Figure 6.2. The parameters selected and investigated in the current study are categorised into the following:

1. BUILDING TYPE AND GLAZING ORIENTATION

Variations of the glazing proportion and orientation of the three generic atrium types, as identified above, will be examined. The options selected for the current parametric study are shown below.

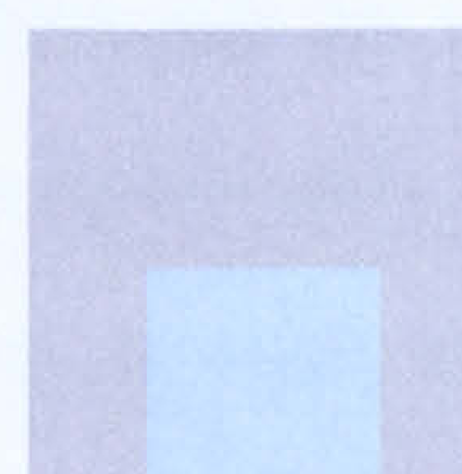
Atrium   Adjacent Building

a. Enclosed



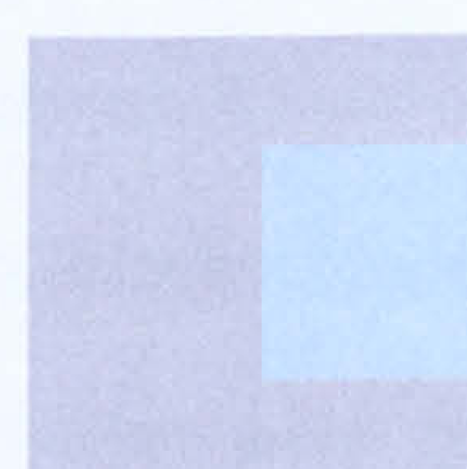
A

b. Open-sided (South)



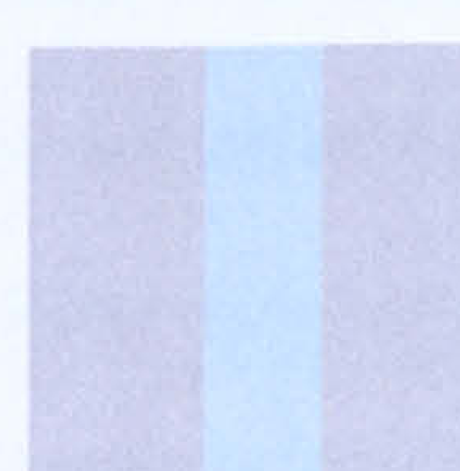
B

c. Open-sided (East)



C

d. Linear (North-South)



D

e. Linear (East-West)

E

All the possible different options of the atrium building types and glazing orientation were considered. The selection – as stated before- was based on the evaluation of previous related research. Some of the issues leading to these choices are explained in the following paragraphs.

Building orientation affects the indoor climate of a space in two main respects; a) solar radiation from different orientations through the facades has a substantial effect on the internal environment and b) the relationship between the direction of the prevailing winds and the orientation of the building will influence natural ventilation within the building (Olgyay, 1992). Assuming that ventilation takes place under natural buoyancy, it becomes the primary factor that the analyses are most concerned with.

In terms of comfort, as well as energy efficiency, orientation for atria depends on the heating requirements and the occupancy periods combined with the solar gains from the atrium's glazed surfaces. The graph in APPENDIX G shows the solar radiation for a given surface depending on its orientation and slope: a) horizontal, b) south, c) east/west, d) north. As it can be seen from the graph, during heating season, when maximum heat gain is required, the external atrium glazing should preferably be southeast orientated if morning heating is required. Atria facing south can receive maximum solar gains in early spring and autumn and could contribute to the heating loads, and less solar gain during summer, helping reduce the cooling loads. Atria facing west may receive excessive solar gain in the afternoon, and particularly in summer, when the buildings are already heated and ambient temperatures are high; that can lead to highly uncomfortable conditions, as seen from the analysis of the previous chapter. Atria with their facades facing north require higher energy loads due to lack of solar gain. Therefore, for the current study, South and East orientations are considered. The option of the horizontal glazing surface is discussed below.

2. Aspect ratio

a. 3 Floors

b. 6 Floors

In passive atrium building design, the shape and proportion of the atria primarily influence the amount of heat transfer between the atria and the ambient environment. The parametric analysis can give an insight to amount of heat gain and heat loss of the atrium related to building form (surface area to volume ratio).

3. Roof shape

a. Flat Roof

b. Vault Roof

c. Saw tooth Roof

In the Mediterranean climate where the sun angle is relatively high, horizontal glazing will receive more solar radiation in summer than an inclined roof. Previous related research claims that that the saw tooth roof shape is the most appropriate for a climate like the Mediterranean. From the parametric analysis the results of all the different roof shapes could actually be compared, combined with the use of different glazing material as well as the option of using shading. Flat roof is included in the options, as it will provide a base case for comparison.

4. Atrium glazing type

a. Clear glass

b. Reflective glass

c. Low-E glass

As seen in a previous chapter, the challenge of designing an atrium building for the Mediterranean climate is to cope with the large diurnal and seasonal variations; while heat build up might feel good on a cold winter afternoon, it presents problems for the designer trying to control cooling loads during warmer months. One of the options is to reduce heat gain through proper glass selection: glass that provides a comfortable environment for occupants by keeping buildings cool in the summer and warm in the winter (solar control) or prevents heat escape from the buildings (thermal insulation).

Three things happen to solar energy when it strikes the surface of glass: it is reflected, absorbed, and transmitted through the glass. Different glass types, such as

Reflective, or Low-E glass can be used to reduce the solar heat gain. Reflective glass absorbs and reflects a major proportion of the sun's direct energy, whereas Low-E glass allows most natural light to enter freely, but reflects a significant portion of long and short wave heat energy. Clear glass will be also examined as it provides a base case for comparison.

<u>**5. Ventilation rate**</u> a. 5ac/h

b. 10 ac/h

From ventilation viewpoint, as seen in a previous chapter, the atrium is designed to capture solar gains and create a column of warm air in the space to enhance the ventilating flow. Naturally ventilated atrium buildings rely primarily on wind pressure blowing in one side and out the other. Wind can create a negative pressure along the roof to "suck" air out while letting air in the same vent or in the side vents. Natural buoyancy is another effect, which predominates especially on hot, low, wind days.

Different modes of ventilation coupling between the atrium and the main building may be used to optimise the thermal buffering of the atrium. To select an appropriate ventilation mode for the different seasons, one needs to consider the climate of the site, and the environmental criteria of the atrium and the main building (Baker, 1988). Ho also adds that is equally important that the openings be adjustable so that the airflow patterns and ventilation rates are according to the comfort criteria. In the current study, the atrium is treated as a naturally ventilated space and ventilation rates of 5ac/h for winter and 5 and 10 ac/h for summer will be examined.

In the current study, thermal stratification in the atrium is the driving force. Infiltration is presented by a constant air exchange rate. The radiation model uses air-based view factors and assumes a high long-wave emission of all surfaces.

<u>**6. Glazing ratio facing the atrium space**</u> a. 0%

b.30%

c. 60%

The atrium space was designed to serve as the major circulation area for the new building. In the daytime, the atrium cavity provides useful light to adjacent blocks and also keeps plants at the lower levels healthy. In the current study, the analyses focus on the glazed areas in the internal atrium facades that affect heat and light transmission between the main building and the atrium. The size of the windows of the adjacent building facing the atrium space will vary between 0%, 30% and 60%.

7. Shading

The primary reason for solar shading is to provide thermal comfort by reducing unnecessary solar gain. In general, the most effective way to reduce solar gain in the atrium is to provide external shading to the atrium roof glazing and external atrium glazing. As a consequence, the overall daylight levels in the atrium and the main building are substantially reduced. The options of the roof shape and different glazing materials will give an insight of how much, if at all, shading is needed and suggestions will be made according to the results of the parametric analysis. However, a series of 108 iterations were completed with the option of constant shading for all the types of atrium buildings, for 30% of glazing ration facing the atrium space and for all types of glazing.

Another parameter such as the building's thermal mass is not examined with the same amount of detail in the current study. Generally, the construction materials used in the Mediterranean region (e.g. concrete and brick) resolve in heavyweight structures. Also in cases of retrofitting, the glazing of existing courtyards or walkways won't influence the thermal mass of the surrounding buildings. Therefore it was decided to use the thermal mass as a steady parameter in the current study. Reference to previous related studies provides adequate information and feedback. Another reason is that, in the current study, the main focus is the atrium space whereas the influence of thermal mass can only be examined in relation to the adjacent building. However, the investigation of the glazing ratio of the wall separating the atrium from the main building will provide some indication on the amount of heat exchange between the atrium space and its adjacent building.

Having discussed all the above set of parameters, in the next paragraph the basic models used for the iterations in the parametric study are described. Following that is the presentation, analysis and discussion of the results.

6.2.3 Modelling and Simulation

In the previous paragraph the design alternatives chosen for the parametric analysis were described. Some choices were obvious; other choices were made only after qualitative and quantitative study of design options. There is a combination of 5 building types, 2 building heights, 3 roof shapes and 3 glazing ratios, which respond to 90 basic models. Appendix C shows the table of the various parameters for each of the 90 models. Each of the 90 models was analysed varying 6 more parameters (3 glazing materials and 2 ventilation rates), for both heating and cooling season. The 90 models are graphically presented in APPENDIX F. All the various parameters opted for 540 iterations for summer and 90 for winter. Further 108 iterations were performed for shading summing up for a total of 738 iterations for both seasons.

The required input for the comfort analysis includes the position of the subject, which is set to 1.5m and the activity level, which is set to activity level 3 "walking slowly". The clothing insulation is 1 clo for winter and 0.4 clo for summer. Also, the plant type is used to give a typical air velocity, which is used in calculating the convective heat loss of occupants. The default values are: Natural Ventilation, Summer - (0.3 m/s)

Natural Ventilation, Winter - (0.08 m/s)

In the following paragraphs, the impact of variations of all the above parameters on the thermal and comfort conditions of an atrium building in a Mediterranean climate is investigated. The results are analysed in a sequence of stages. In the final stage conclusions are drawn with a summary and evaluation of the findings. Optimum choices in the form of design guidelines are discussed in the next and final chapter.

6.3 Parametric Analysis Results

As stated before, the main measure of effectiveness in the parametric study will be the PPD (Percentage of People Dissatisfied) in relation to the air temperature. The calculation programme used for the thermal study output the Dry Bulb Temperature (^{0}C) in the occupied region. There is an apparent interface in the effect of all the different parameters in occupants' comfort. However, there will be an attempt to analyse the results under the title of all selected alternatives.

Most of the analysis concerns the summer results as this the time when possible overheating can cause highest discomfort. The results of the iterations for the winter period are discussed in a following paragraph.

6.3.1 Building type, proportion and glazing orientation

The analysis of the results for the various atrium building types, proportion and glazing orientation is-at this stage- only for the flat roof with clear double-glazing fenestration, with 30% of windows in the wall separating the main structure from the atrium and no shading.

Figure 6.3 shows the Percentage of People Dissatisfied in the five different atrium-building types and Figure 6.4 show the Dry Bulb temperatures (^{0}C) in the occupied region that result in them, as predicted by ROOM. The highest percentage of dissatisfied people and for most hours of the day occurs in the open-sided atrium with the east orientation. However, what is of greater importance is the PPD between 14:00 to 16:00 hours when the highest ambient temperatures occur. As it can be seen from the graph, between 11:00 hours and 17:00 hours it reaches 100% of dissatisfaction for all types. The influence of orientation in comfort is more obvious in the open-sided and linear type. The eastern orientation propagates discomfort conditions, from the early morning hours until early evening.

The air temperature results presented in Figure 6.4 are used as an indicator of the thermal conditions inside the atrium during summer. There is a large temperature fluctuation in all the different types of atrium. The lowest temperature occurs in the linear type with the north-south orientation. Between 9:00 and 19:00 hours, the temperature exceeds the established thermal comfort limits for summer.

The above are compared with the corresponding results in Figure 6.5 and Figure 6.6 for the same type of buildings in winter. As it can be seen from the two graphs, although there is small temperature variation between the different atrium types, there are notable higher percentages of people dissatisfied between 12:00 and 16:00 hours for the enclosed type with south orientation. This type also experiences the highest internal air temperature. The graphs also indicate that there are acceptable internal conditions for all types, within and above the comfort limits.

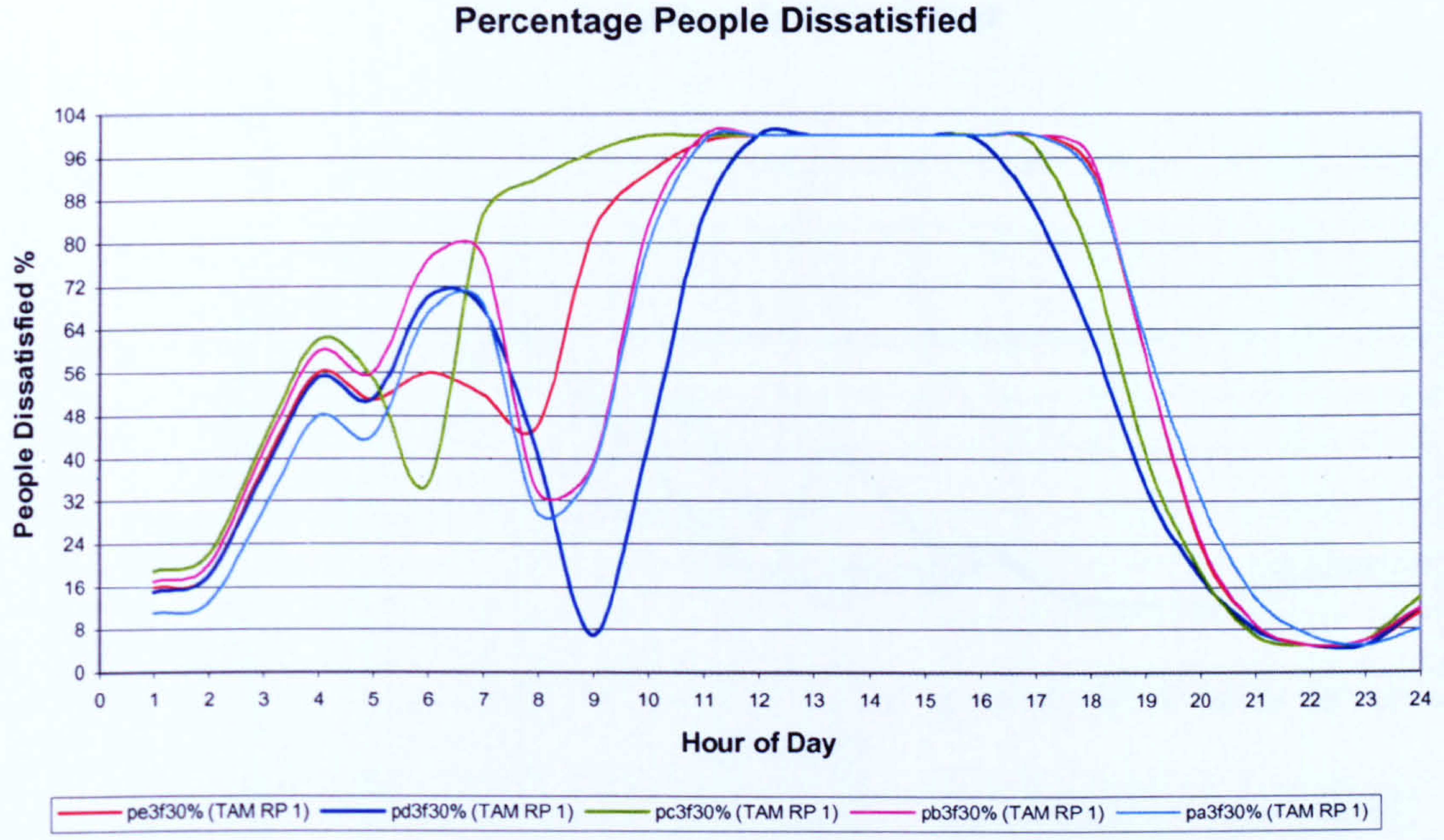


Figure 6. 3: Percentage of People Dissatisfied in the five different atrium-building orientations as predicted by ROOM during summer.

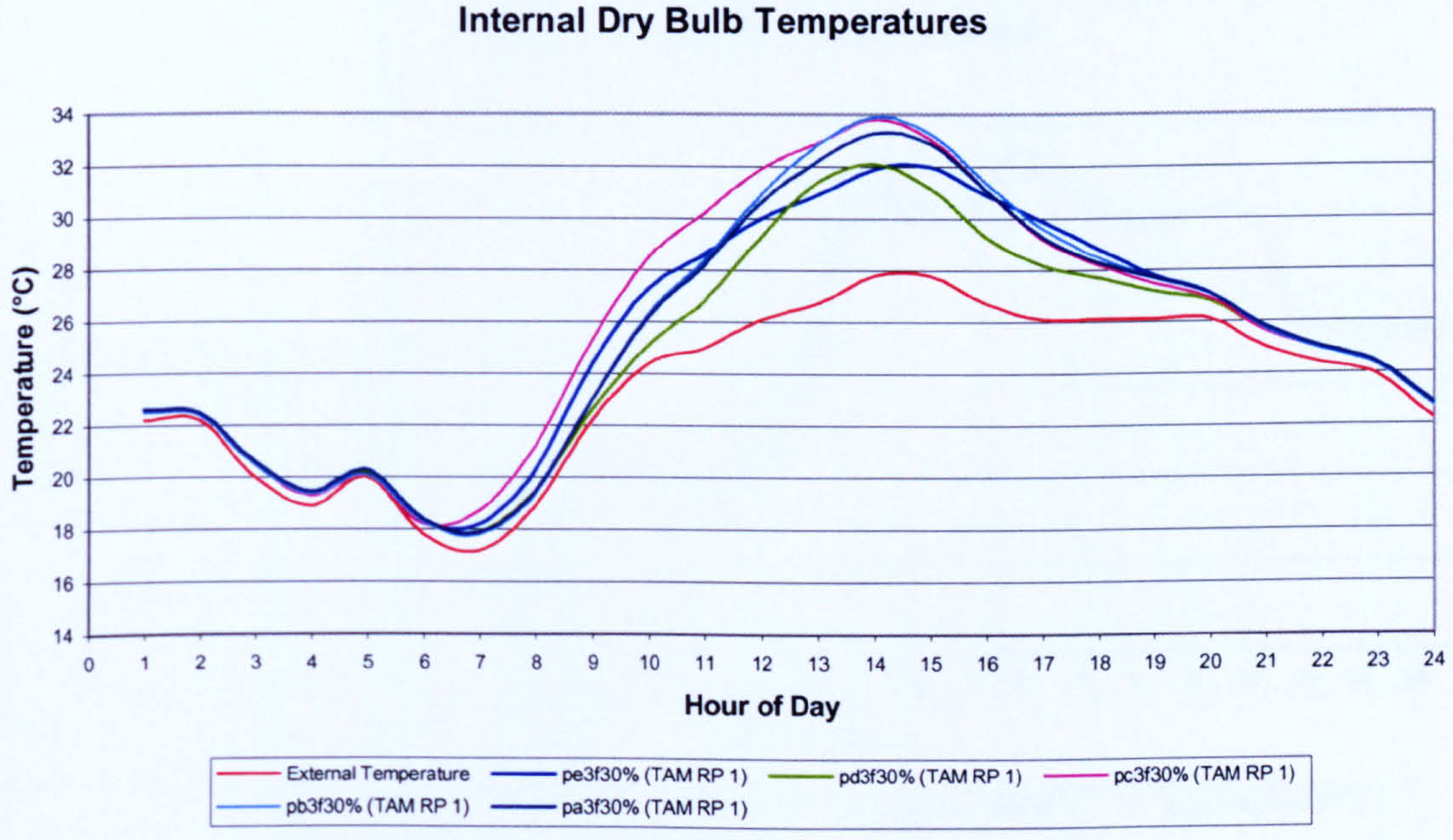


Figure 6. 4: Internal dry bulb temperatures in the occupied region in the five different atrium-building orientations as predicted by ROOM during summer

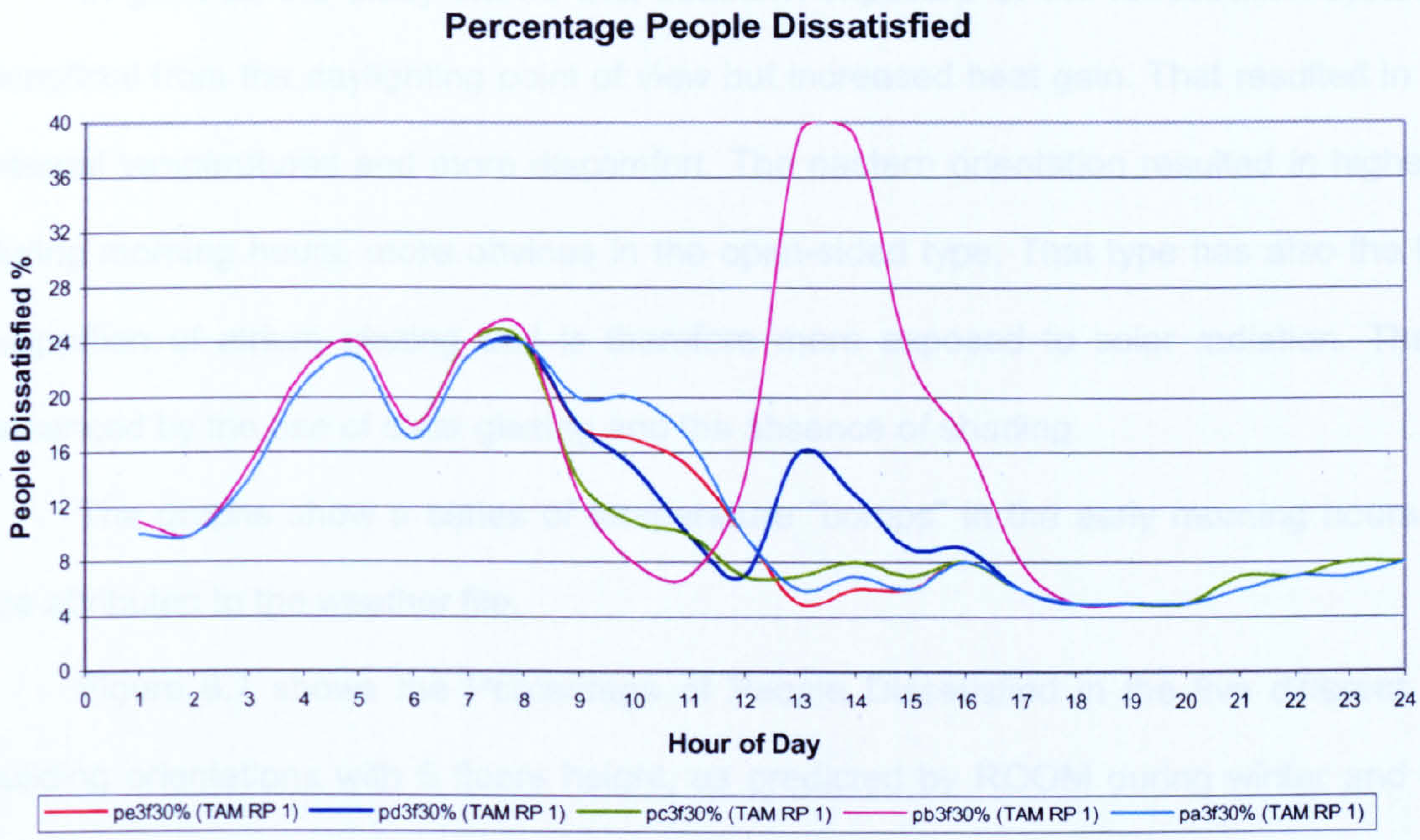


Figure 6. 5: Percentage of People Dissatisfied in the five different atrium-building orientations as predicted by ROOM during winter

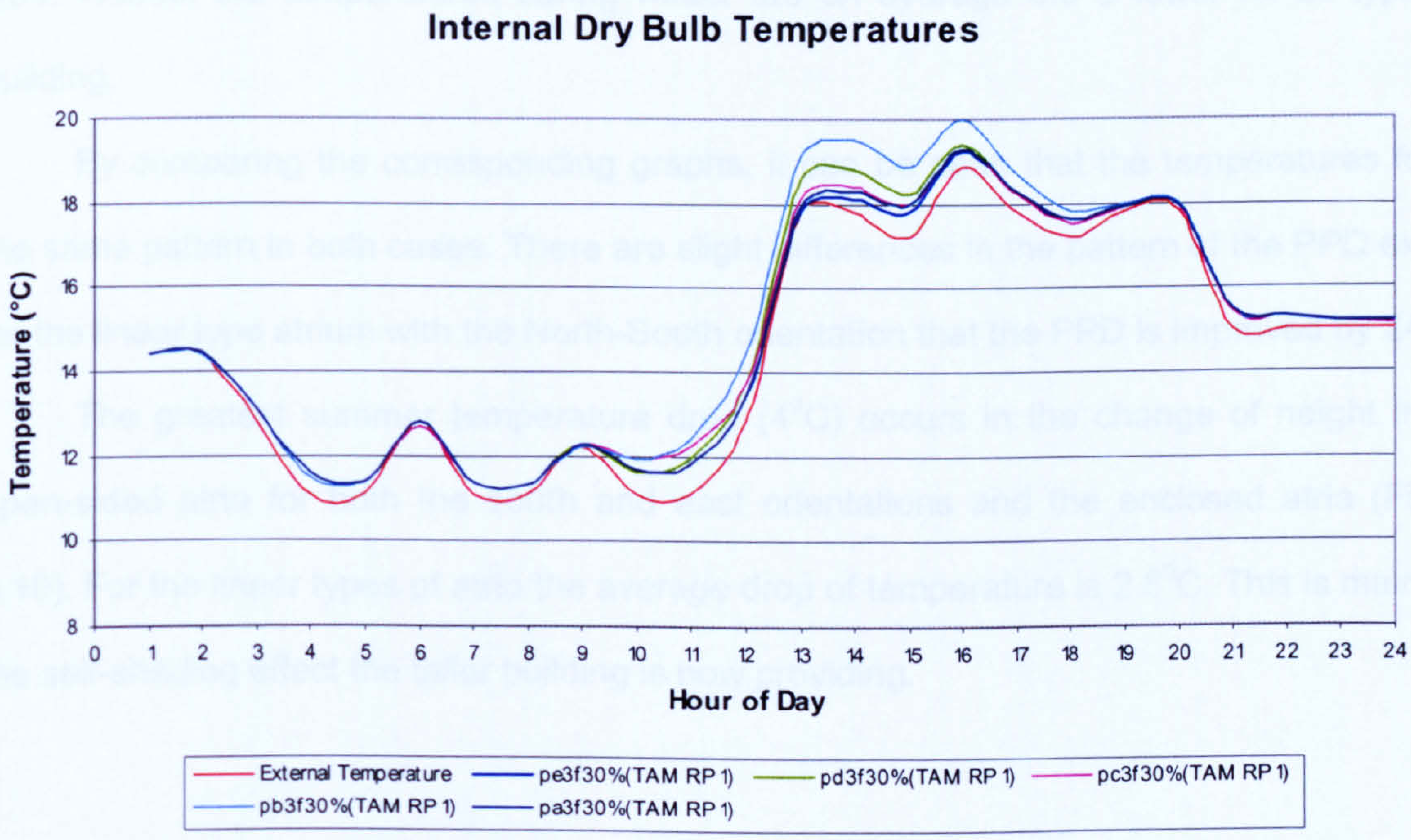


Figure 6. 6: Internal dry bulb temperatures in the occupied region in the five different atrium-building orientations as predicted by ROOM during winter

In general, the study shows that southern exposure of the fenestration system was beneficial from the daylighting point of view but increased heat gain. That resulted in higher internal temperatures and more discomfort. The eastern orientation resulted in higher PPD during morning hours, more obvious in the open-sided type. That type has also the largest proportion of atrium glazing and is therefore more exposed to solar radiation. That was enhanced by the use of clear glazing and the absence of shading.

The graphs show a series of temperature "bumps" in the early morning hours which are attributed to the weather file.

Figure 6.7 shows the Percentage of People Dissatisfied in the five different atrium building orientations with 6 floors height, as predicted by ROOM during winter and Figure 6.8 their internal temperatures for the same period. It is interesting to discover that by doubling the height of the atrium building, the average winter effects in all the selected atrium types are low, while the summer atrium temperatures drop depending on the atrium type. Indeed, the temperatures during winter are on average 0.5^{0}C lower for all types of building.

By comparing the corresponding graphs, it can be seen that the temperatures follow the same pattern in both cases. There are slight differences in the pattern of the PPD except for the linear type atrium with the North-South orientation that the PPD is improved by 24%.

The greatest summer temperature drop (4^{0}C) occurs in the change of height in the open-sided atria for both the south and east orientations and the enclosed atria (Figure 6.10). For the linear types of atria the average drop of temperature is 2.8^{0}C. This is mainly to the self-shading effect the taller building is now providing.

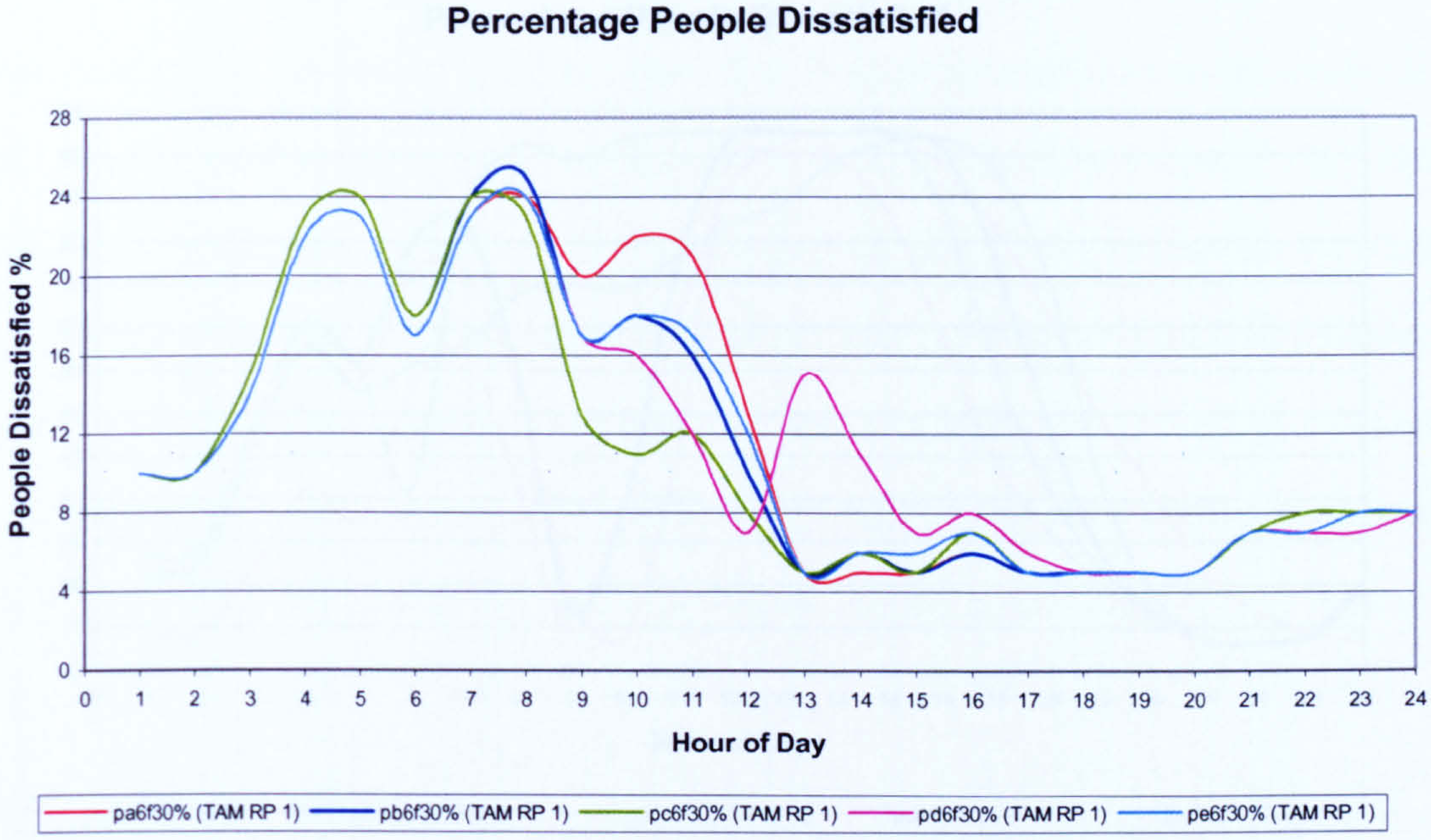


Figure 6. 7: Percentage of People Dissatisfied in the five different atrium building orientations and 6 floors height, as predicted by ROOM during winter

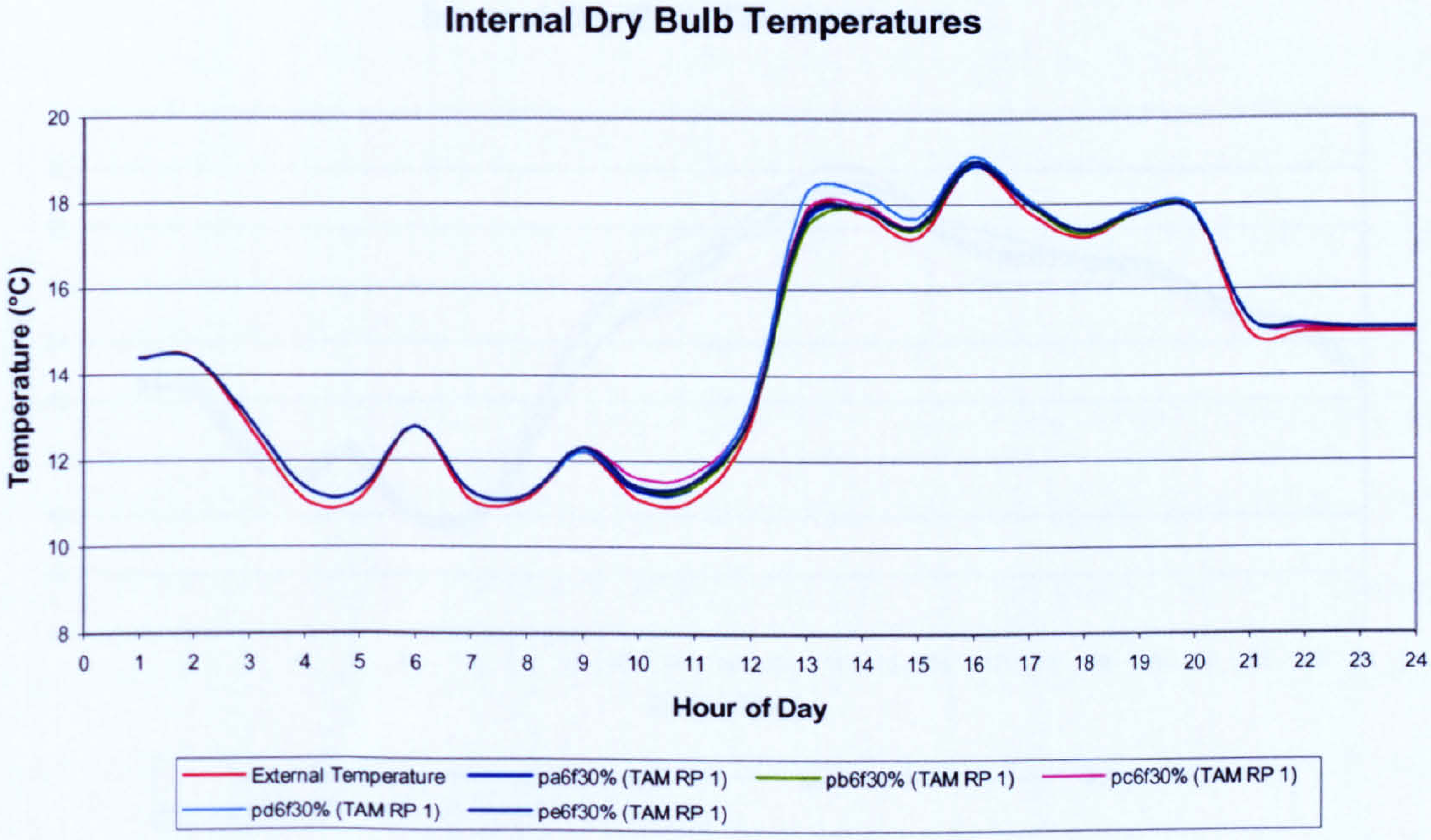


Figure 6. 8: Internal dry bulb temperatures in the occupied region in the five different atrium building orientations with 6 floors height, as predicted by ROOM during winter

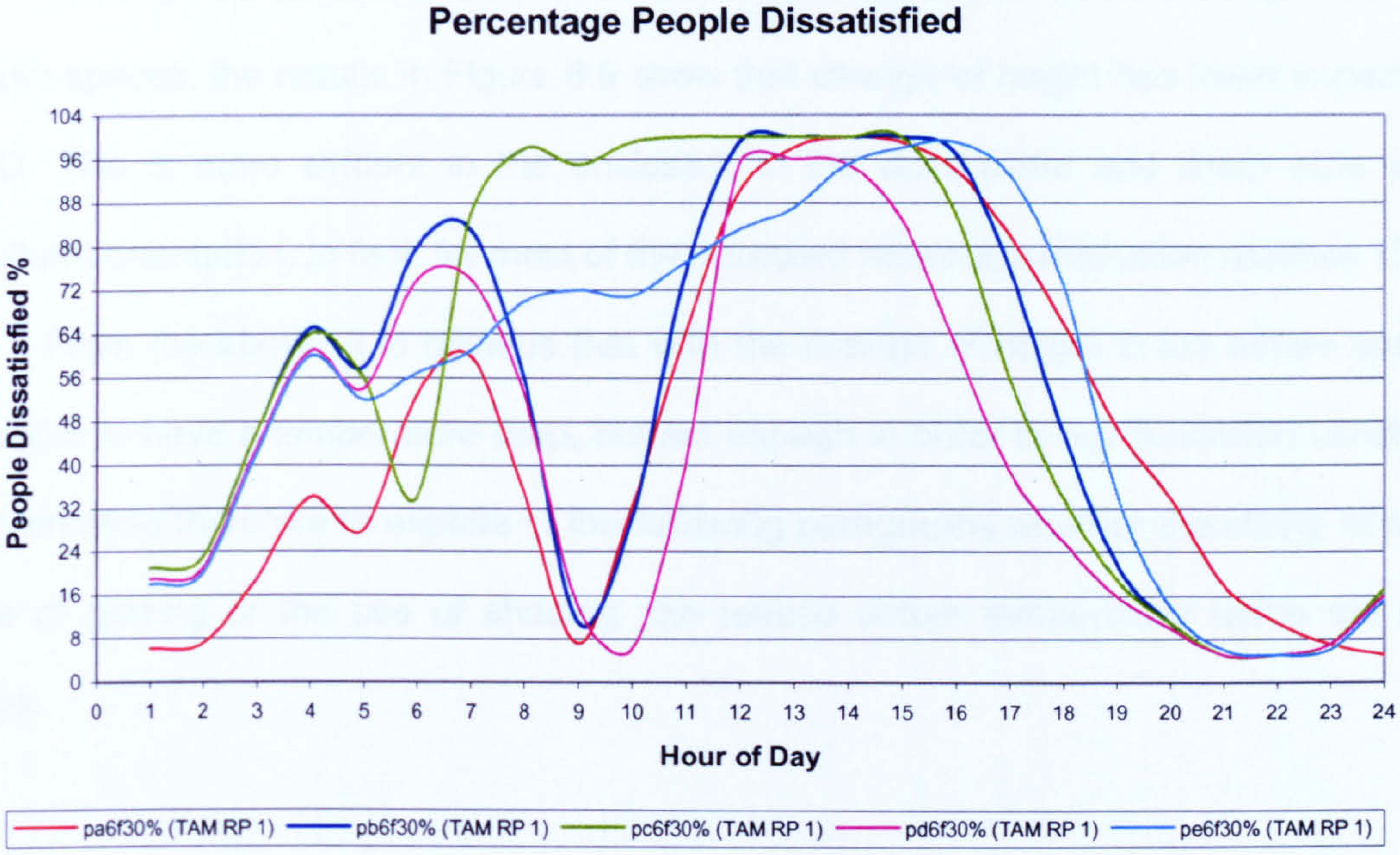


Figure 6. 9: Percentage of People Dissatisfied in the five different atrium building orientations and 6 floors height, as predicted by ROOM during summer

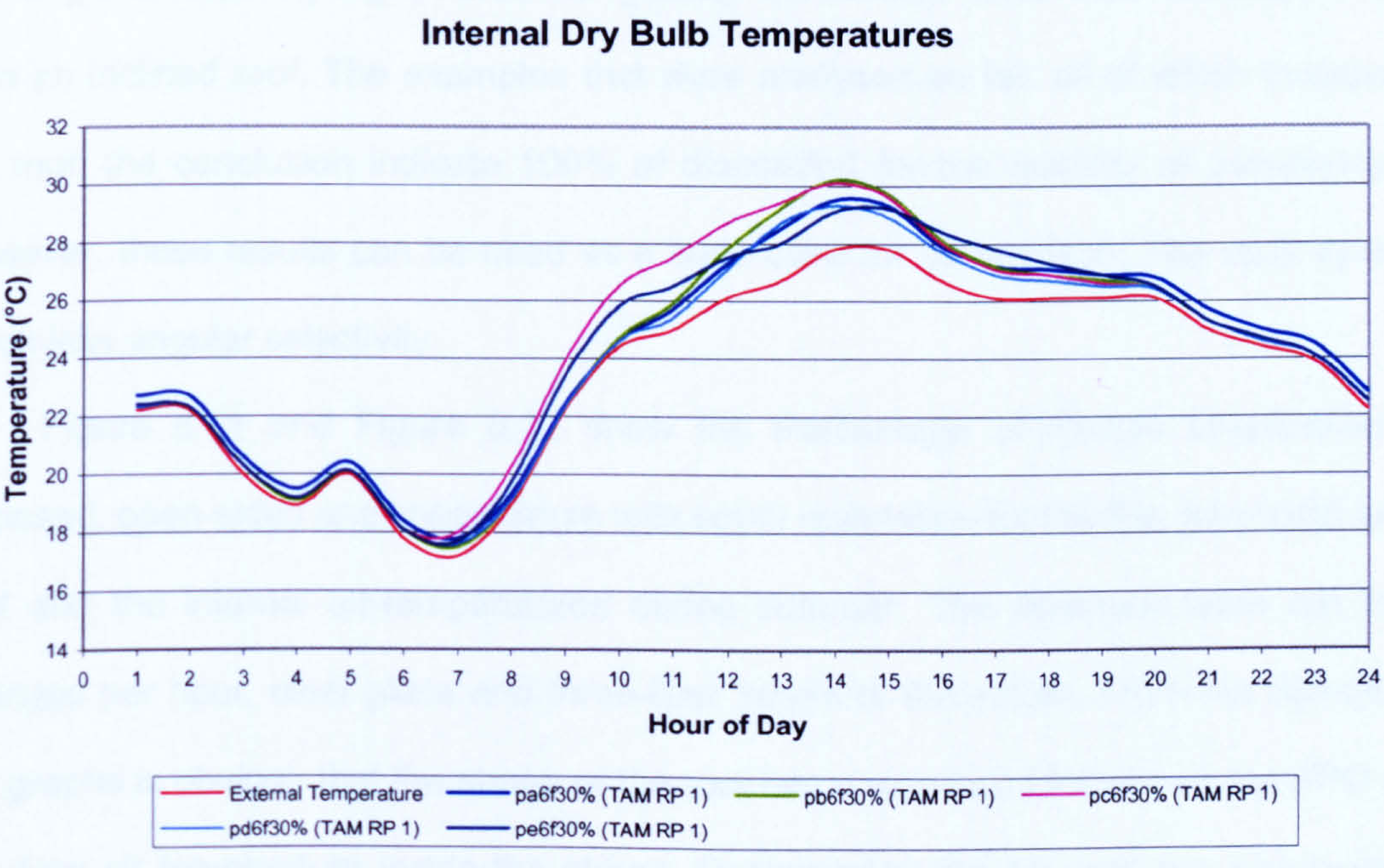


Figure 6. 10: Internal dry bulb temperatures in the occupied region in the five different atrium building orientations with 6 floors height, as predicted by ROOM during summer

Although compact and taller forms can reduce the overall summer temperature rise in atrium spaces, the results in Figure 6.9 show that change of height has lower impact on the PPD. This is more evident in the enclosed, in the open-sided and linear atria with the southern orientation. In fact, for most of the occupied hours dissatisfaction reaches 100%.

From the above, it is obvious that with the change of height in the atrium space it is possible to have a temperature drop, but not enough in order to reach comfort conditions. It is interesting therefore to explore in the following paragraphs weather the shape of roof, the type of glazing or the use of shading can reduce atrium temperature within the comfort limits.

6.3.2 Roof shape

As it was mentioned in a previous paragraph, in the Mediterranean climate where the sun angle is relatively high, horizontal glazing will receive more solar radiation in summer than an inclined roof. The examples that were analysed so far, all of which incorporated a flat roof, the conclusion indicate 100% of discomfort for the majority of occupancy hours. However, these results can be used as a base case for comparison. The vault system has much less angular selectivity.

Figure 6.11 and Figure 6.12 show the Percentage of People Dissatisfied in the enclosed, open-sided and linear atrium with south orientation for the flat, saw-tooth and vault roof and the internal air-temperatures during summer. The iterations were run for 5 air changes per hour, clear glass and three-floor height of the atrium. From the comparison of the graphs is obvious that the shape of the roof has a significant impact on the PPD and the resulting air temperature inside the atrium. Compared to the flat roof, the saw-tooth shape results in half of the population feeling discomfort, and a drop of temperature of almost 5^0C.

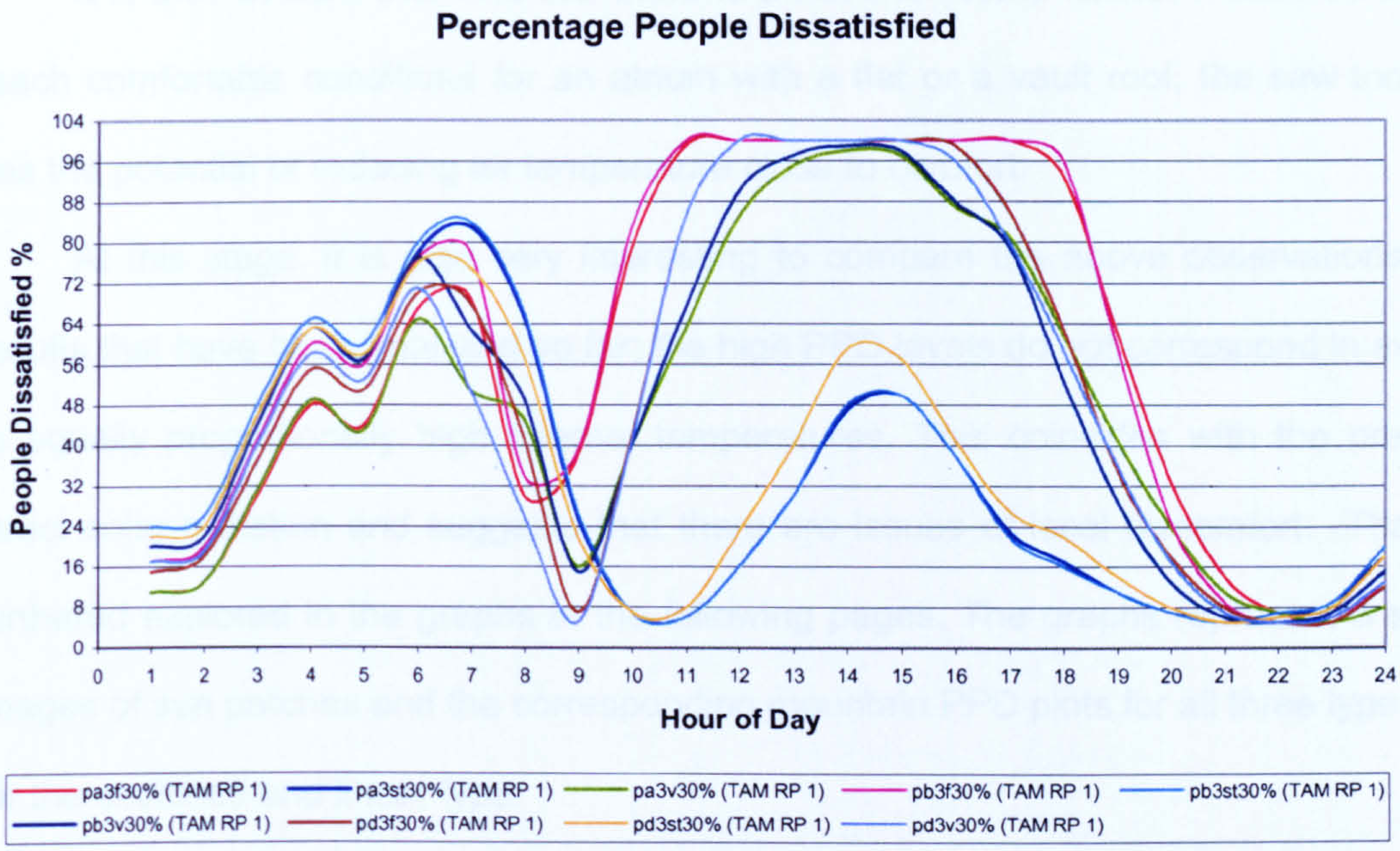


Figure 6. 11: Percentage of People Dissatisfied in the enclosed, open-sided and linear atrium with south orientation and 3 floors height, as predicted by ROOM during summer

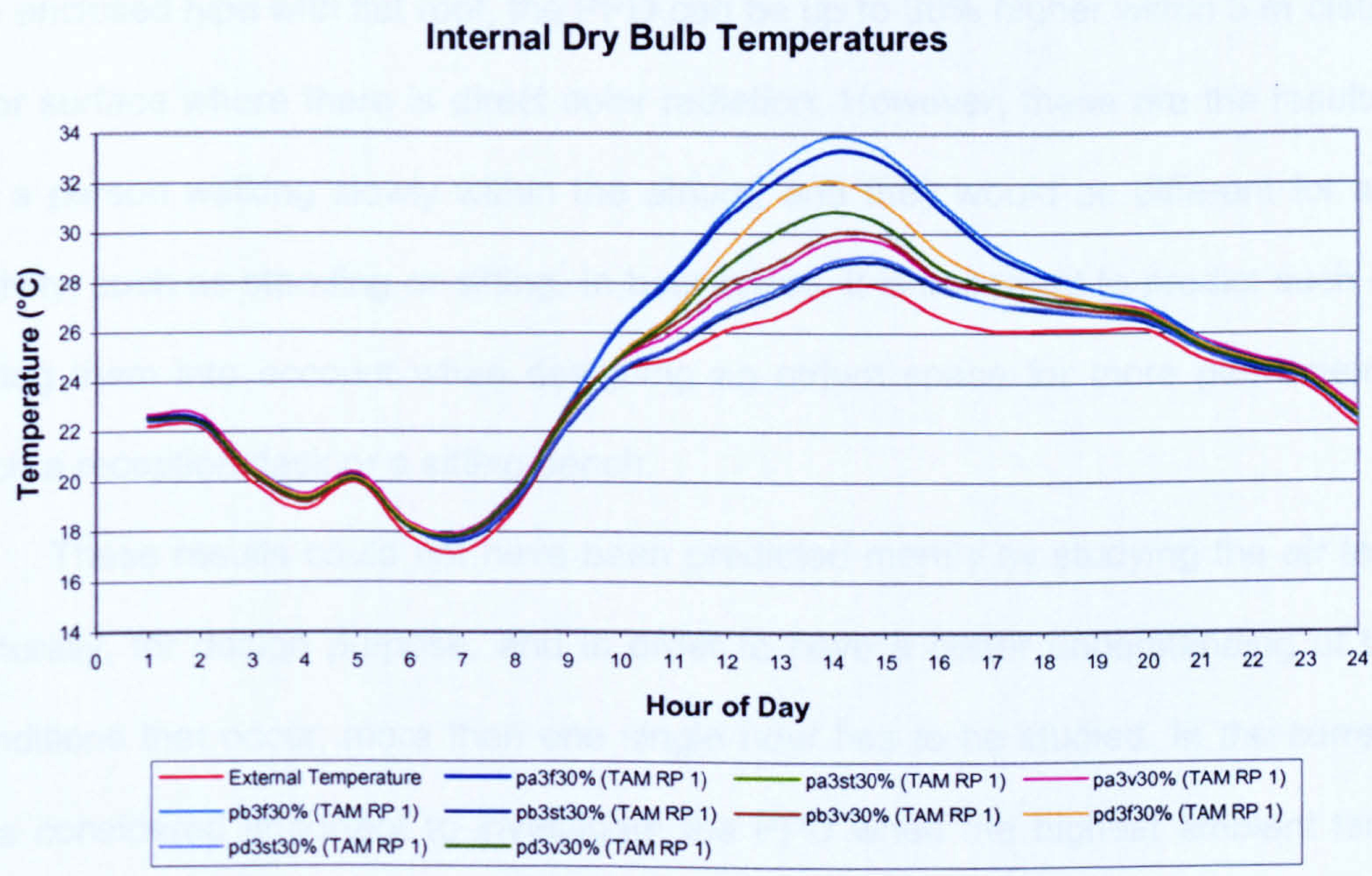


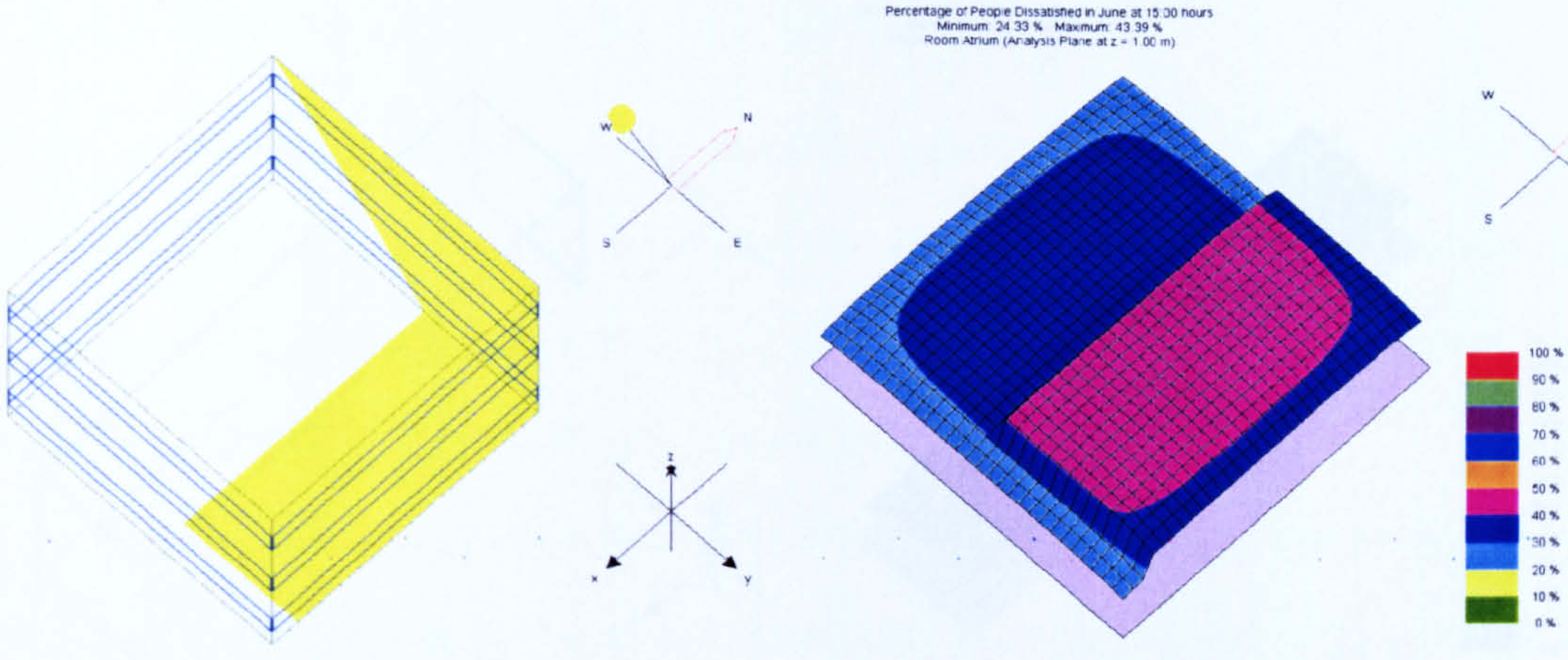
Figure 6. 12: Internal dry bulb temperatures in the occupied region in the enclosed, open-sided and linear atrium with south orientation and 3 floors height, as predicted by ROOM during summer

It is also evident that whereas there is a need for some radical measures in order to reach comfortable conditions for an atrium with a flat or a vault roof, the saw tooth shape has the potential of reducing air temperature close to comfort.

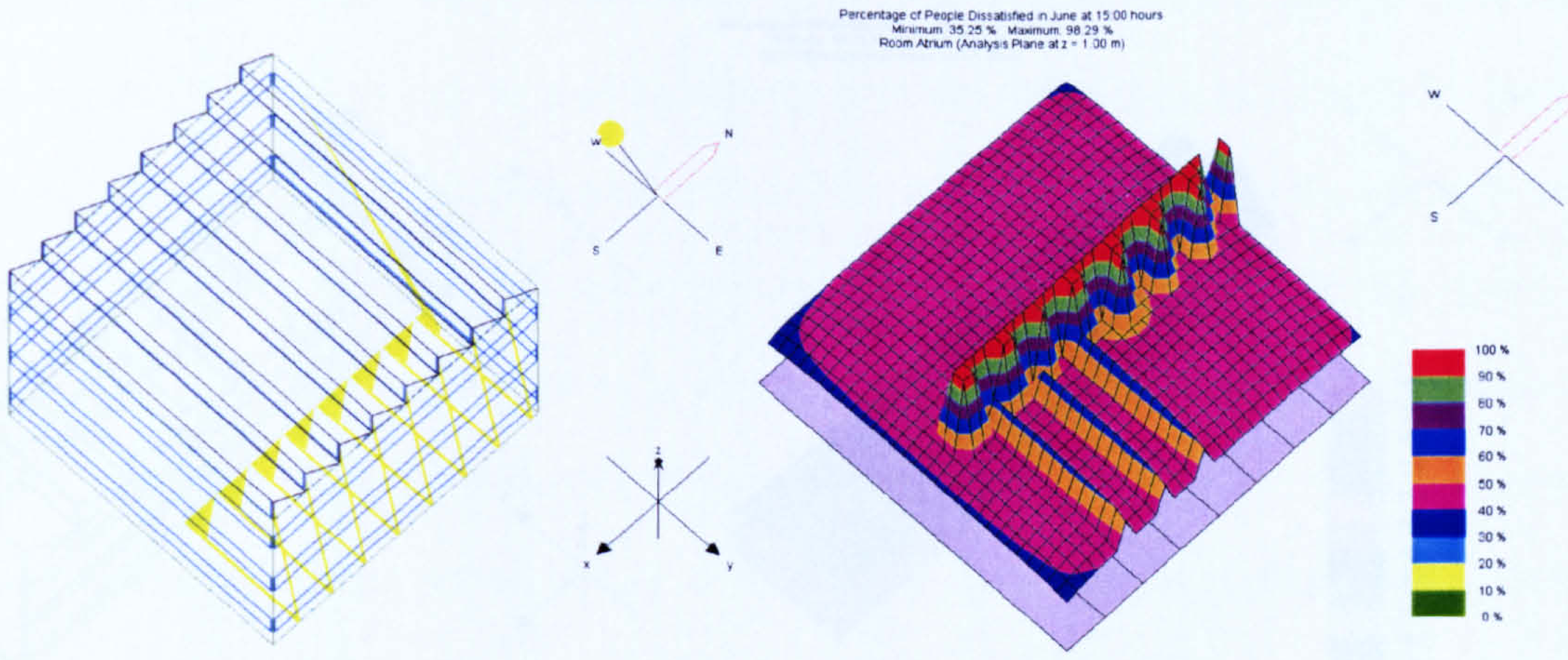
At this stage, it is also very interesting to compare the above observations with the results that have been analysed so far; the high PPD levels do not correspond in every case to equally proportionally high internal temperatures. This coincides with the presence of direct solar radiation and suggests that there are issues of local discomfort. That can be furthered explored in the graphs in the following pages. The graphs represent a sample of images of sun patches and the corresponding mountain PPD plots for all three types of roofs for the enclosed and linear type.

The graphs show that highest percentages of discomfort correspond to the presence of direct solar radiation. It is therefore evident that solar radiation can give rise to a different experience of the thermal environment in various spots of the same surface. For example, in the enclosed type with flat roof, the PPD can be up to 30% higher within 5 m distance of the floor surface where there is direct solar radiation. However, these are the results predicted for a person walking slowly within the atrium, and they would be different for a sedentary activity, such as standing or sitting. In both cases, it is important to predict such effects and taking them into account when designing an atrium space for more permanent activities, such a reception desk or a sitting bench.

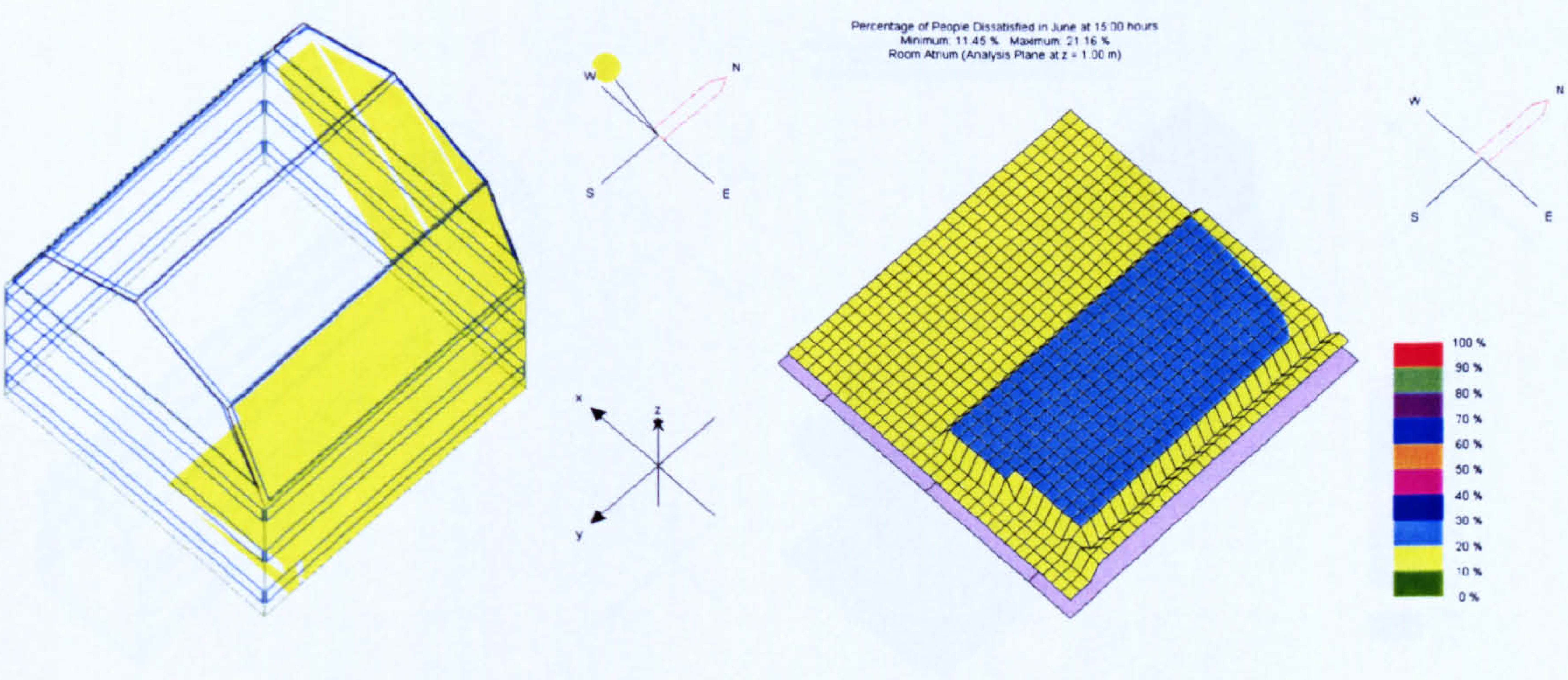
These results could not have been predicted merely by studying the air temperature. Naturally, for design purpose, and in order to have a better understanding of the thermal conditions that occur, more than one single hour has to be studied. In the current study, it was considered important to investigate the PPD when the highest ambient temperatures occur and therefore there is an increased chance for higher discomfort.



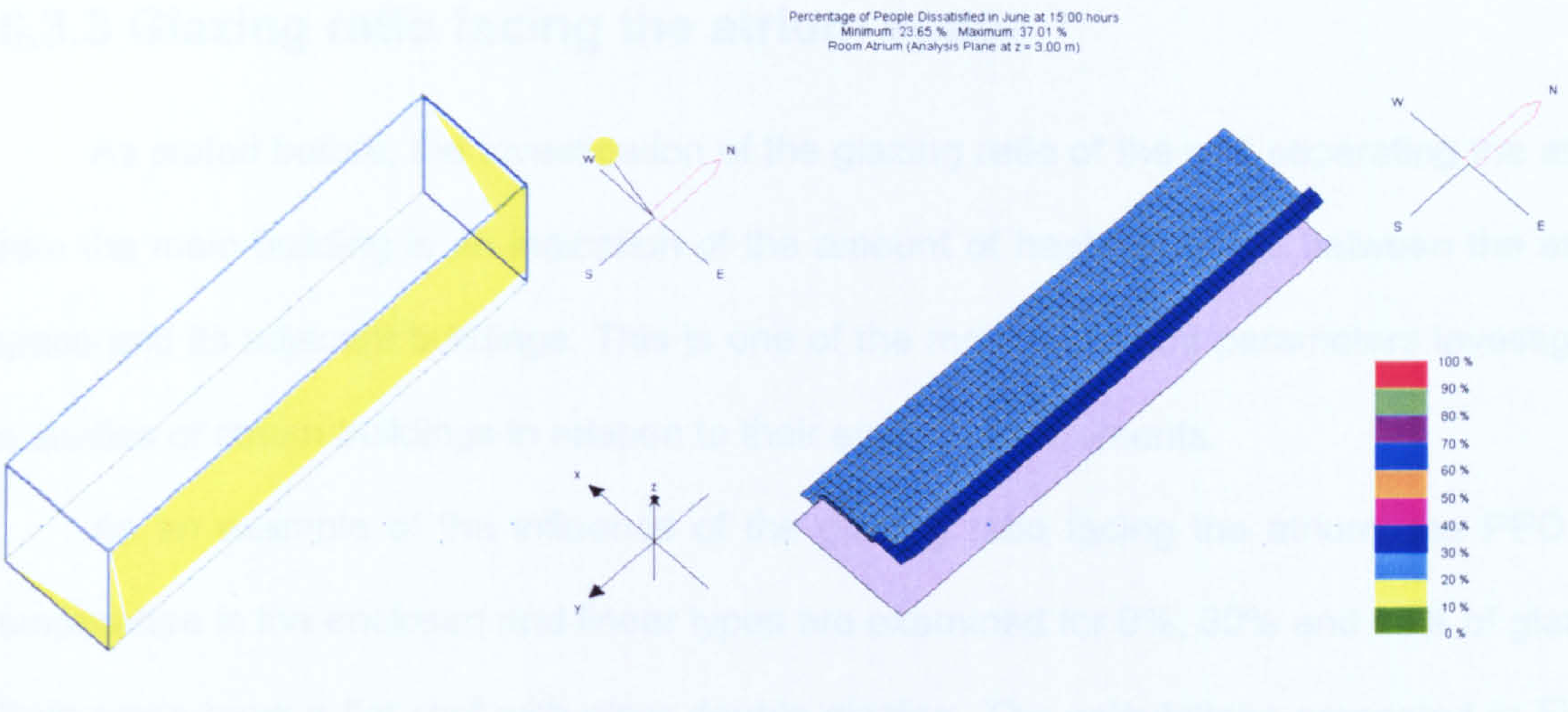
Sun patch and corresponding PPD for the enclosed type with flat roof



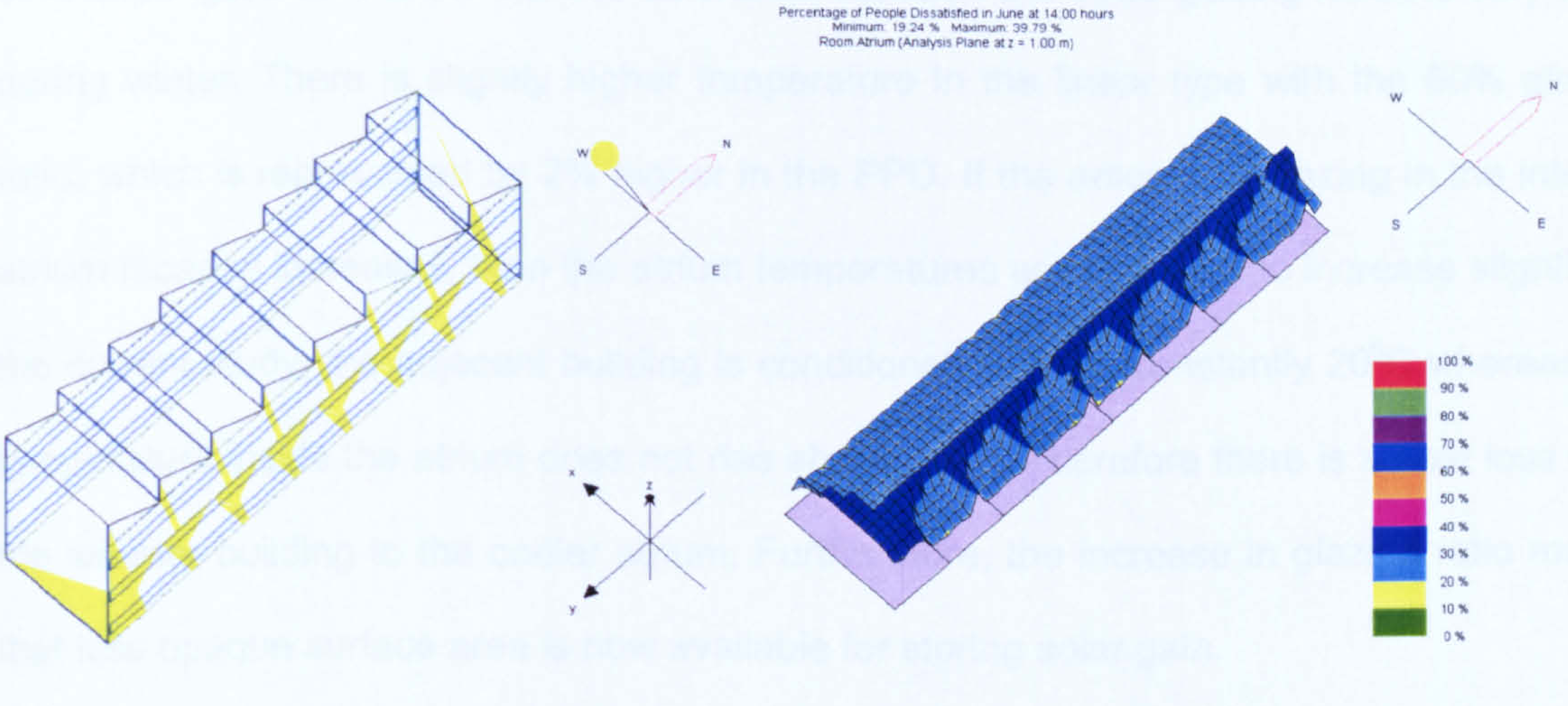
Sun patch and corresponding PPD for the enclosed type with saw-tooth roof



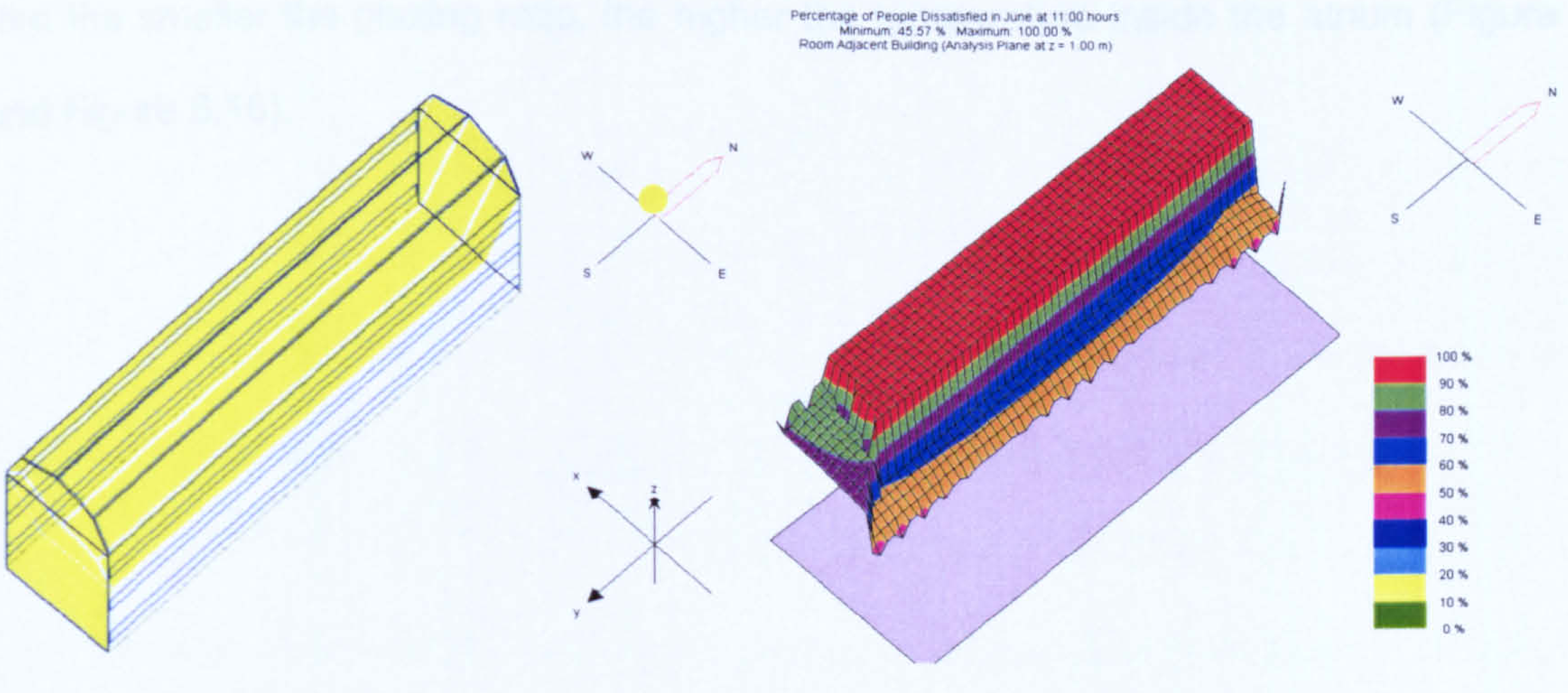
Sun patch and corresponding PPD for the enclosed type with vault roof



Sun patch and corresponding PPD for the linear type with flat roof



Sun patch and corresponding PPD for the linear type with saw-tooth roof



Sun patch and corresponding PPD for the linear type with vault roof

6.3.3 Glazing ratio facing the atrium space

As stated before, the investigation of the glazing ratio of the wall separating the atrium from the main building is an indication of the amount of heat exchange between the atrium space and its adjacent buildings. This is one of the most important parameters investigated in studies of atrium buildings in relation to their energy requirements.

As an example of the influence of the glazing ratio facing the atrium, the PPD and temperature in the enclosed and linear types are examined for 0%, 30% and 60% of glazing. Both types have a flat roof with clear double-glazing. The calculations presented in Figure 6.13 and Figure 6.14 show that the difference between the three glazing ratios is very small during winter. There is slightly higher temperature in the linear type with the 60% glazing ratio, which is represented by 2% higher in the PPD. If the amount of glazing in the internal atrium facades increases, then the atrium temperatures are expected to increase slightly. In the current study, the adjacent building is conditioned to have constantly 20^{0}C whereas the temperature inside the atrium does not rise above 19^{0}C. Therefore there is a heat loss from the warmer building to the cooler atrium. Furthermore, the increase in glazing ratio means that less opaque surface area is now available for storing solar gain.

In the summer, although there are no substantial differences in the PPD, it appears that the smaller the glazing ratio, the higher the temperature inside the atrium (Figure 6.15 and Figure 6.16).

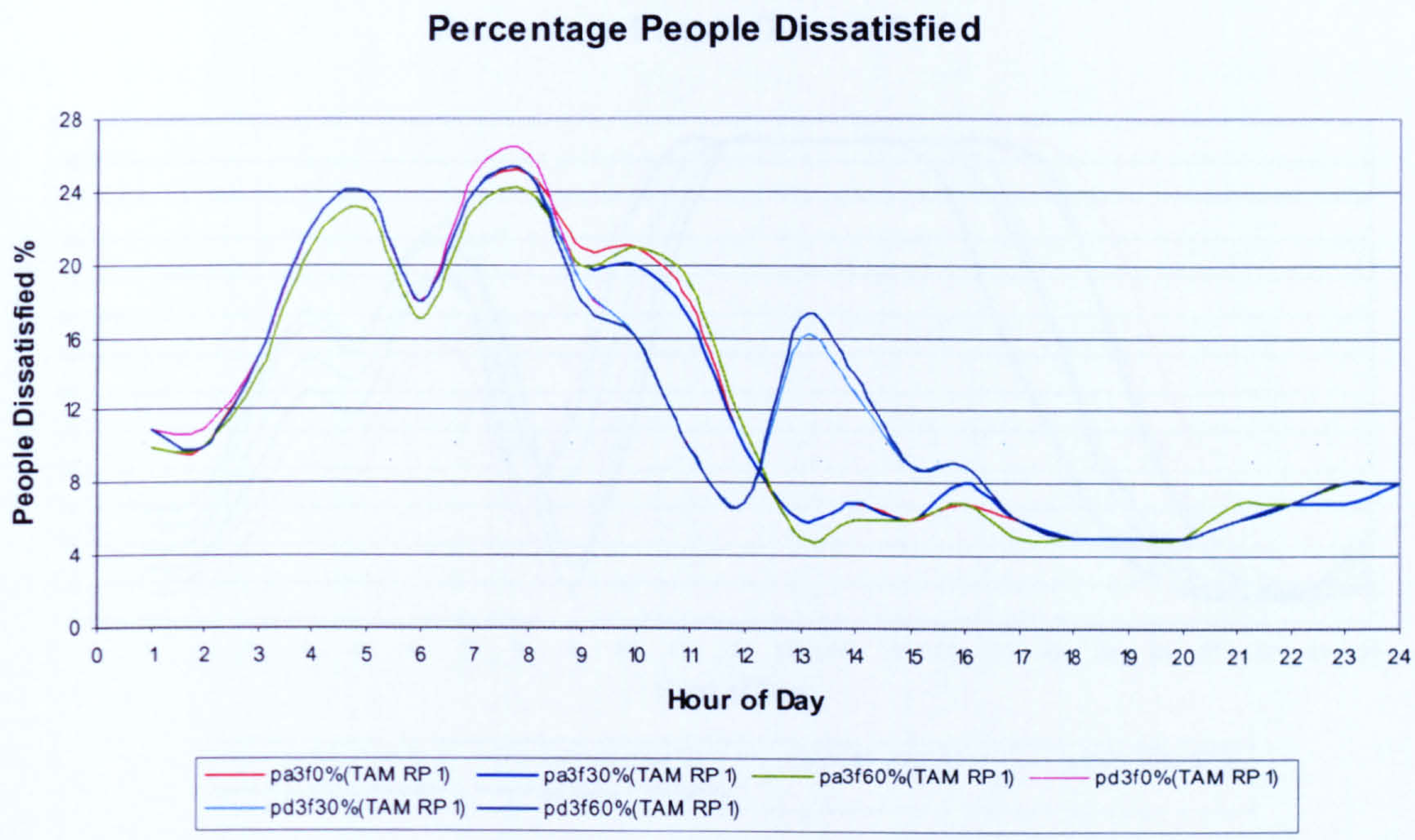


Figure 6. 13: Percentage of People Dissatisfied in the enclosed and linear type for various glazing ratio facing the atrium as predicted by ROOM during winter.

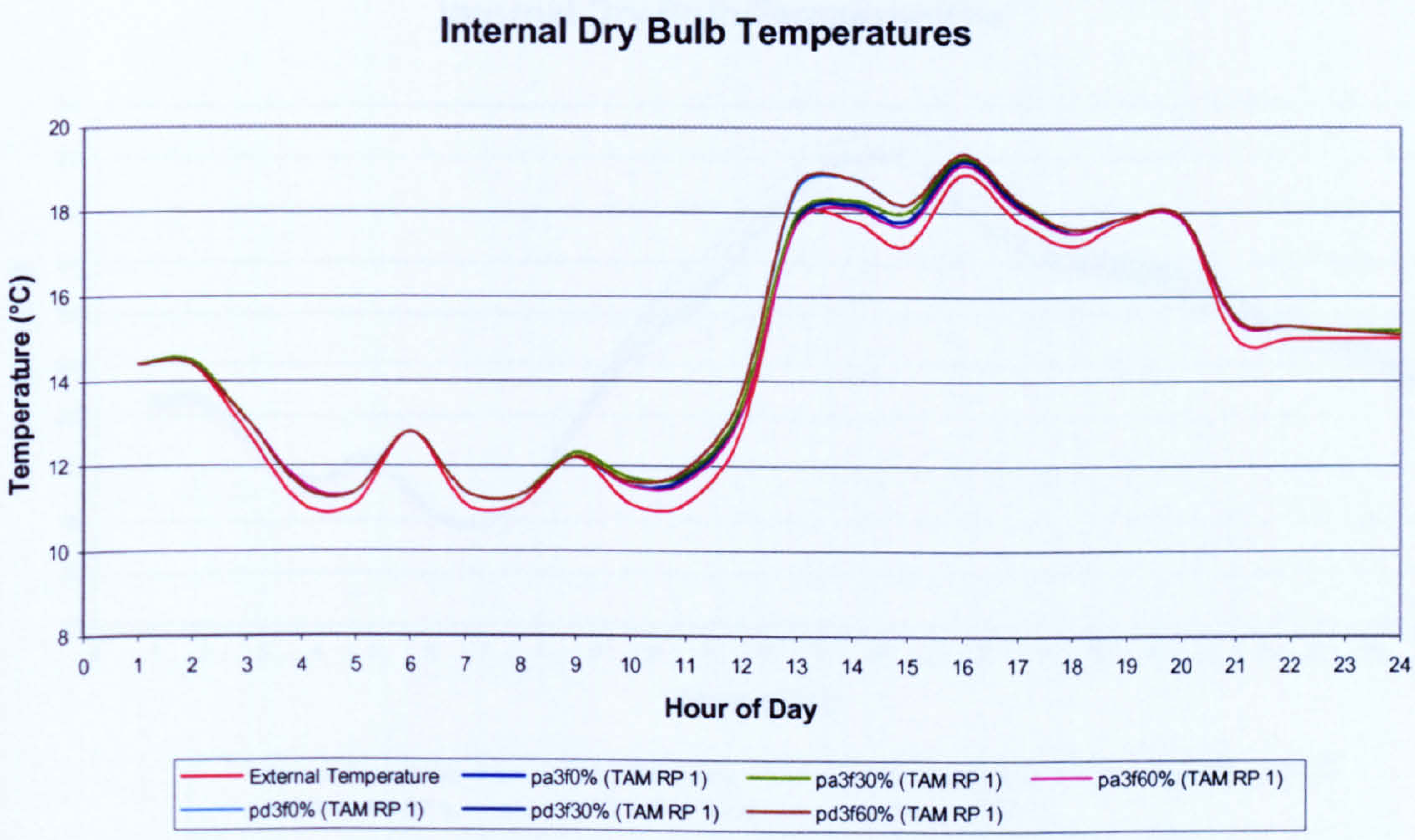


Figure 6. 14: Internal dry bulb temperatures in the enclosed and linear type for various glazing ratio facing the atrium as predicted by ROOM during winter.

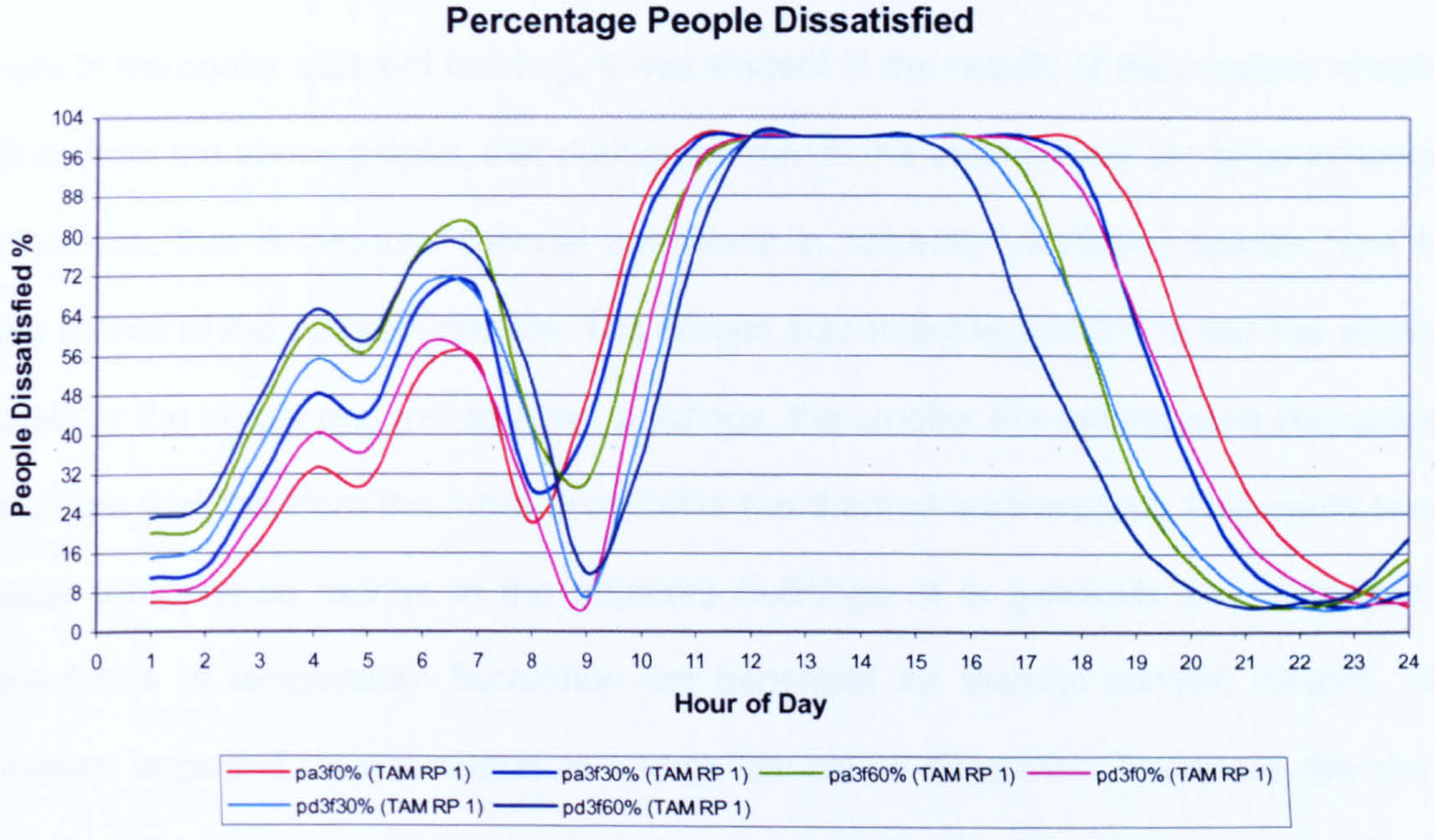


Figure 6. 15: Percentage of People Dissatisfied in the enclosed and linear type for various glazing ratio facing the atrium as predicted by ROOM during summer.

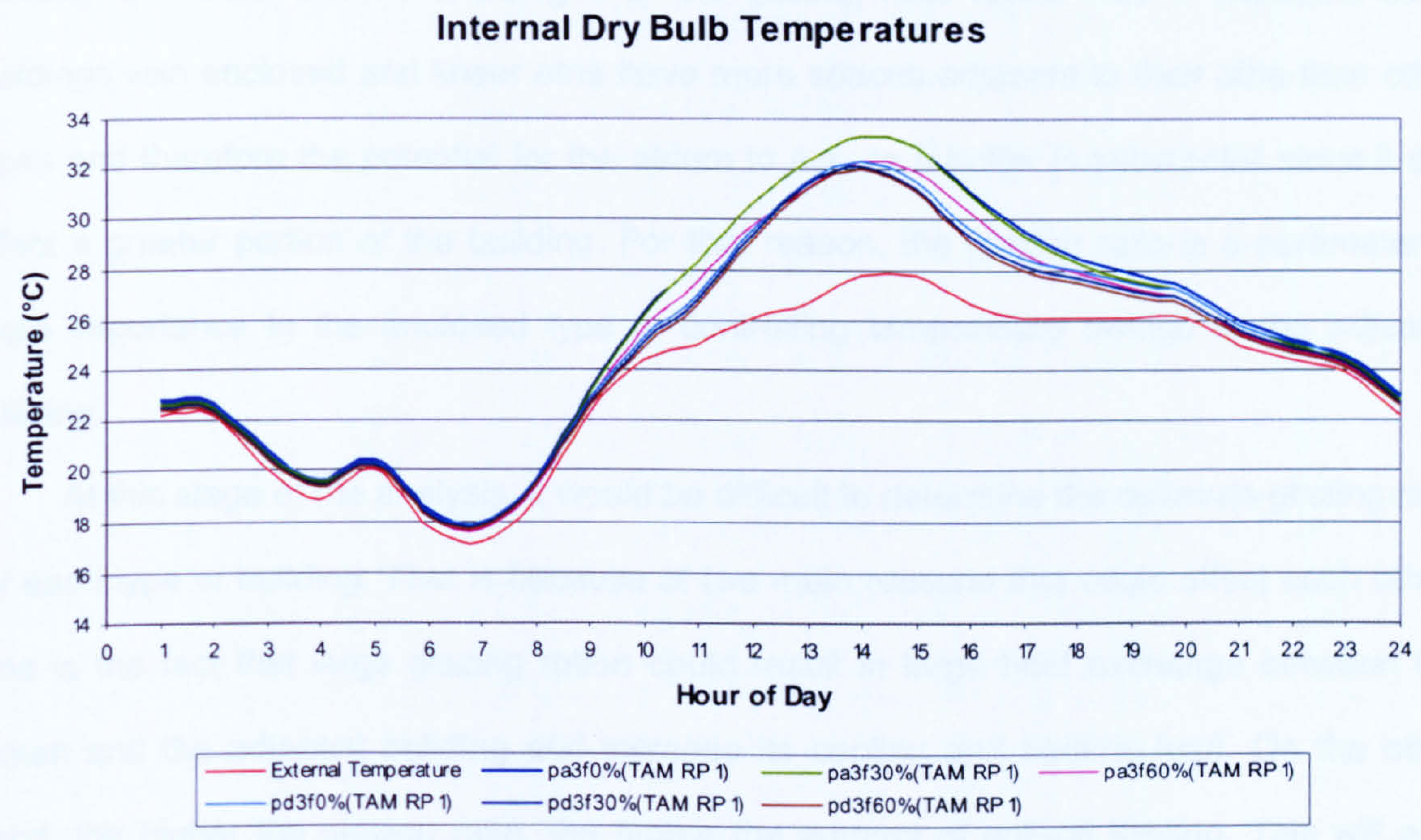


Figure 6. 16: Internal dry bulb temperatures in the enclosed and linear type for various glazing ratio facing the atrium as predicted by ROOM during summer.

That is the reverse of what occurs in winter: there is heat transfer from the warmer atrium to the cooler adjacent building. It was evident in the results of the previous chapter as well as from the above graphs, that during summer in the atrium there are large temperature fluctuations; that is because thermal conditions in naturally ventilated spaces tend to be close to that of the ambient climate. The results also indicate that the larger the amount of shared by the atrium and the adjacent buildings, the smaller the temperature fluctuations in the atrium and therefore the more acceptable the thermal environment. This could result in greater temperature swings in the adjacent buildings. It is generally acknowledged that some forms of temperature fluctuation are beneficial for thermal comfort (Givoni, 1976). However, large and rapid temperature swings can cause discomfort. Therefore, the aim is to design atria with temperature swings within acceptable limits. One way to achieve that is by having a well-insulated intermediate boundary.

The analyses showed that the more atrium surfaces connected to the adjacent building, the more effect the changes of the glazing ratio have. This is expected since buildings with enclosed and linear atria have more spaces adjacent to their atria than other types and therefore the potential for the atrium to act, as a buffer is substantial since it can affect a greater portion of the building. For that reason, the glazing ratio is a parameter of more importance in the enclosed type in controlling temperature swings in the adjacent building.

At this stage of the analysis, it would be difficult to determine the optimum-glazing ratio for each type of building. That is because of two main reasons that could offset each other: One is the fact that large glazing ration could result in large heat exchange between the atrium and the adjacent building and increase its cooling and heating load. On the other hand, the higher the glazing ratio, the higher the amount of natural lighting. This will also depend on the amount as well as the type of glazing. The latter is analysed in more detail in the following paragraph.

6.3.4 Glazing type

The thermal characteristics of glass used for the atrium fenestration obviously influence its thermal conditions and subsequently the occupants' comfort. The term thermal characteristics refer here to the U value of the glazed construction and the properties of the glass with regard to transmission, reflection and absorption of solar energy. The tables of these thermal characteristics of the glazing types used in the current study are presented in APPENDIX G.

There is a clear influence of the glass type on the internal conditions of the atrium space as shown in Figure 6.17 and Figure 6.18. The iterations are for the enclosed and the open-side types, for winter. The reduction of the air temperature in both types of buildings is slightly higher than 1^{0}C. In the case of a winter day, it is more important to look at the levels of the PPD during the first and last hours of the occupied period. The PPD in the open-side atrium type, during the first occupied hours is lower than that of for the enclosed type, for all three types of glazing. This is because the east-facing atrium fenestration receives intense morning sun and results in a warmer atrium environment.

It is also interesting to note here, that the incorporation of the low-e and reflective types glass with low admission of solar radiation can reduce the PPD by 6% and 18% respectively compared to the clear glazing for the open-side type. In the case of the courtyard type the results do not have large differences for each of the glazing types.

The same pattern of PPD in relation to different glazing types is found in the corresponding results for the summer (Figure 6.19 and Figure 6.20). The predicted results show that the use of the selected high performance glass has the potential of lowering the internal air temperature for atrium types of 1^{0}C. However the levels of dissatisfaction will still be very high (100% for all the occupancy hours).

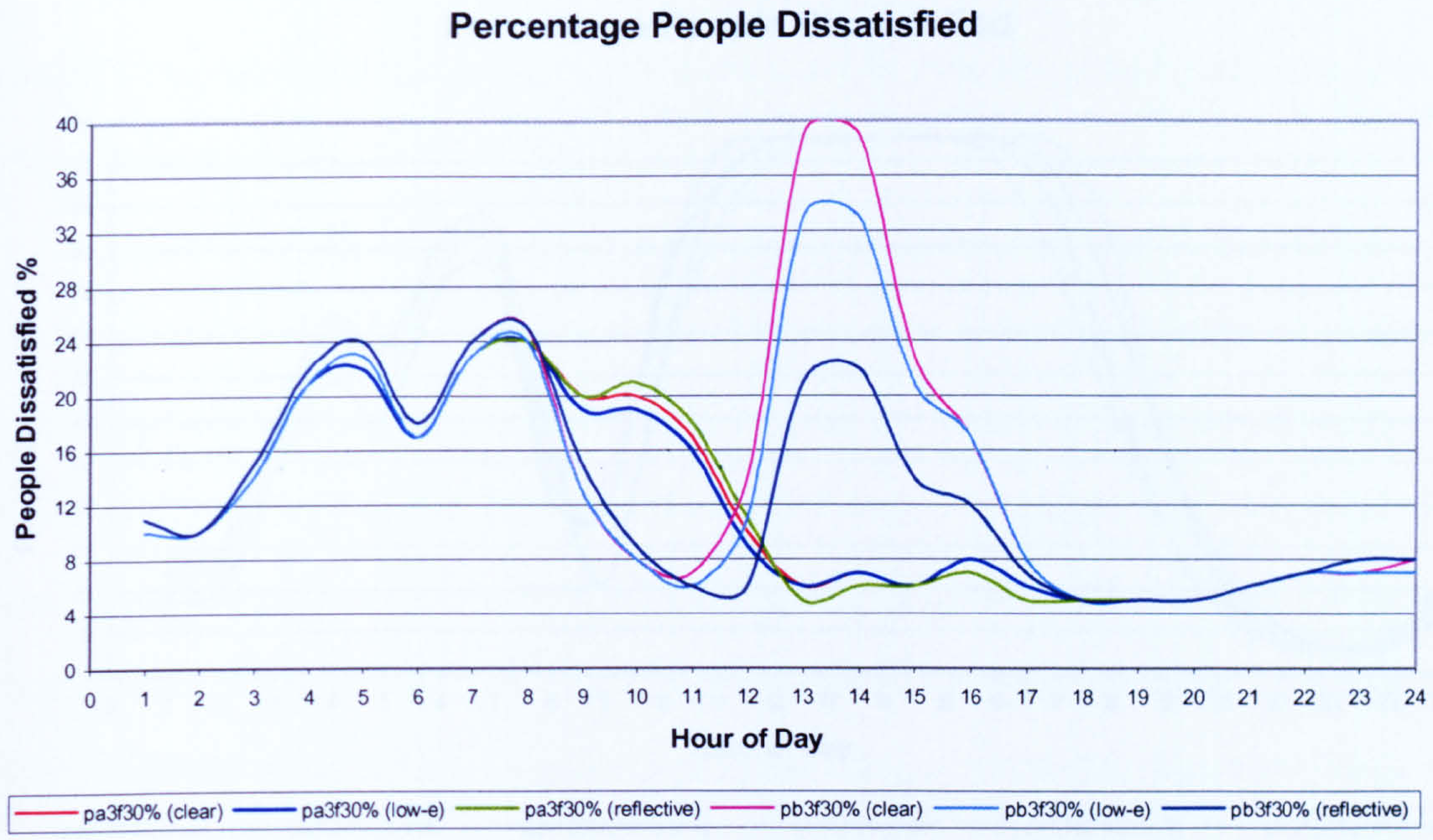


Figure 6. 17: Percentage of People Dissatisfied in the enclosed and open-side type for different glazing types as predicted by ROOM during winter

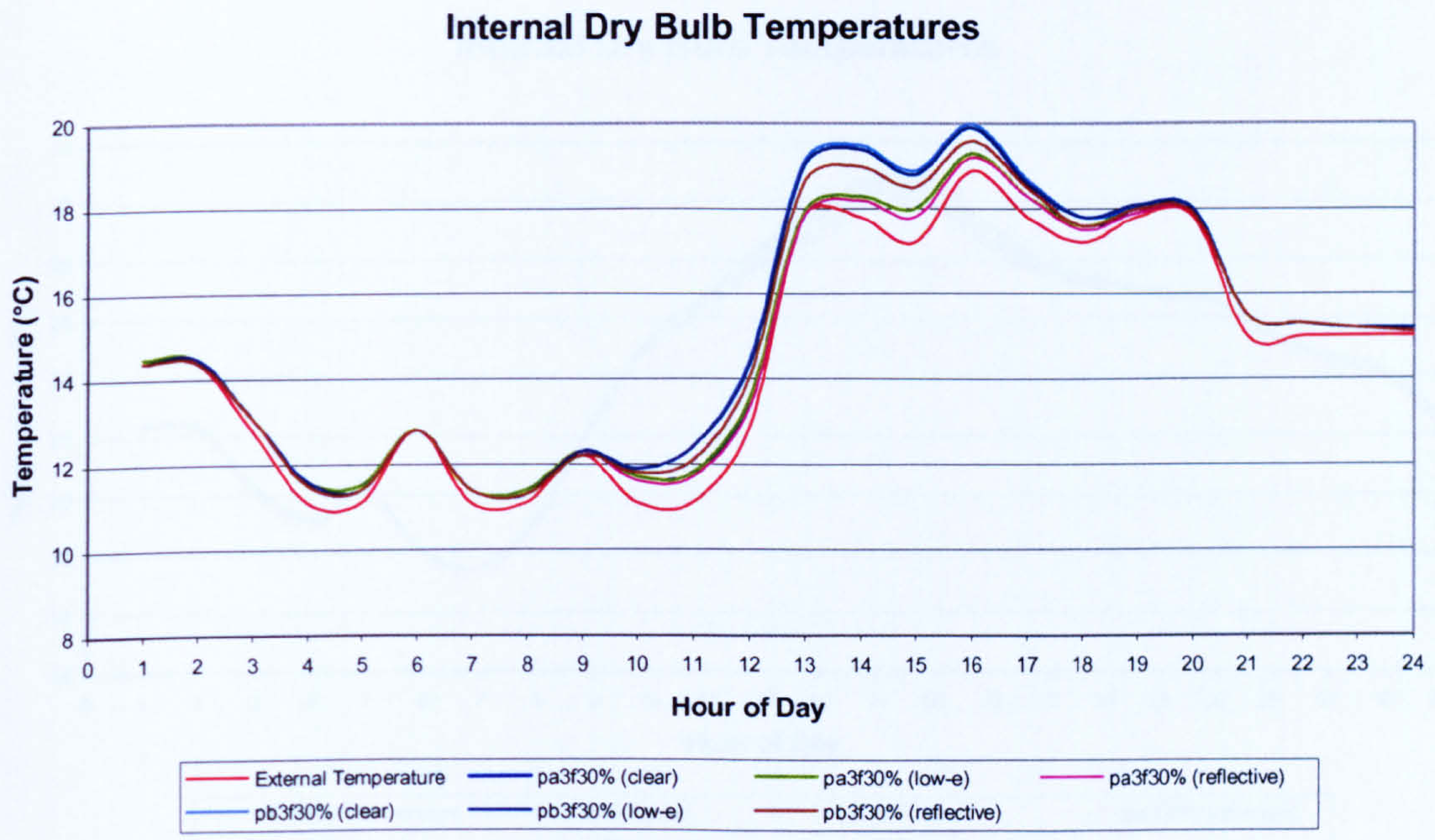


Figure 6. 18: Internal dry bulb temperatures in the enclosed and open-side type for different glazing types as predicted by ROOM during winter

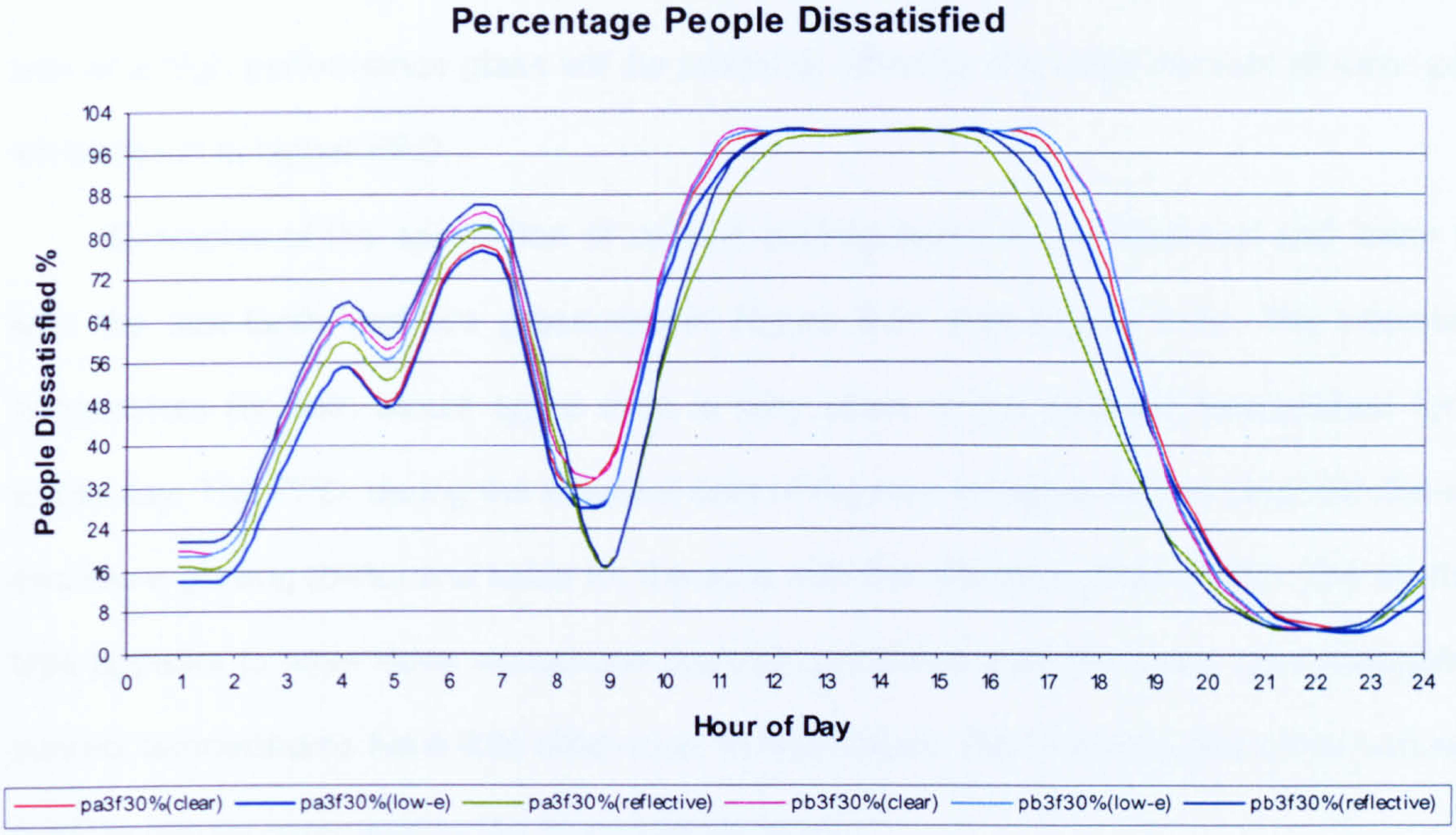


Figure 6. 19: Percentage of People Dissatisfied in the enclosed and open-side type for different glazing types as predicted by ROOM during summer

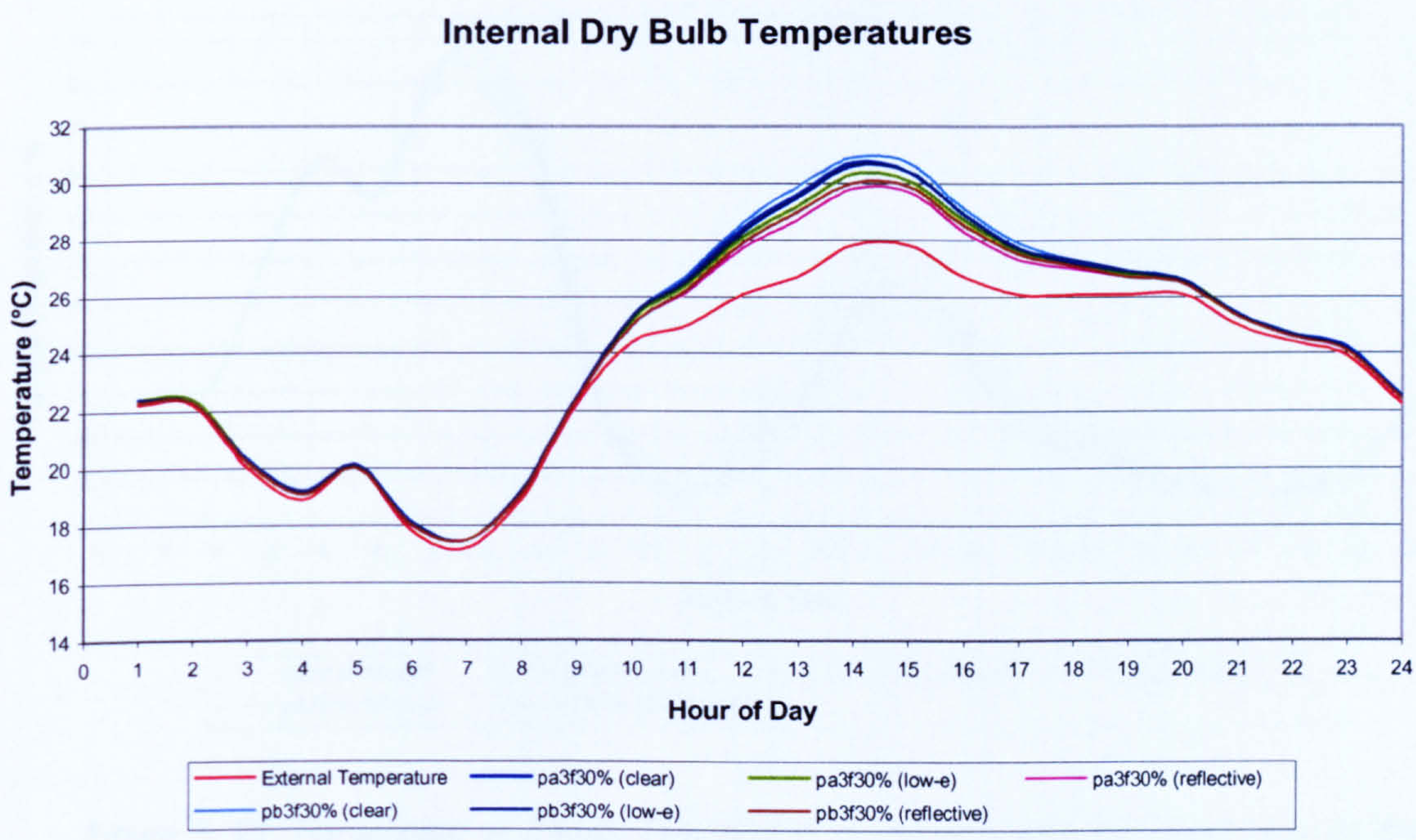


Figure 6. 20: Internal dry bulb temperatures in the enclosed and open-side type for different glazing types as predicted by ROOM during summer

The open-side type has larger surfaces exposed to solar radiation; therefore even the use of a high performance glass will be probably offset by the large amount of solar gains, which result in higher PPD.

Examples of the application of various glazing types in the enclosed and linear type with the saw-tooth roof are presented in Figure 6.21 and Figure 6.22. The internal air temperature for both atrium types drop is very close to the ambient temperature for the whole day. The PPD, during the warmest time of the day, is higher for the atria with the clear and low-e glazing (54%) and lower for the atria with the reflective glass (38%). The enclosed type appears to have more acceptable thermal conditions than the linear type although the internal temperatures have little difference. In both cases, the reflective glass has noticeable positive results compared to the low-emission glass.

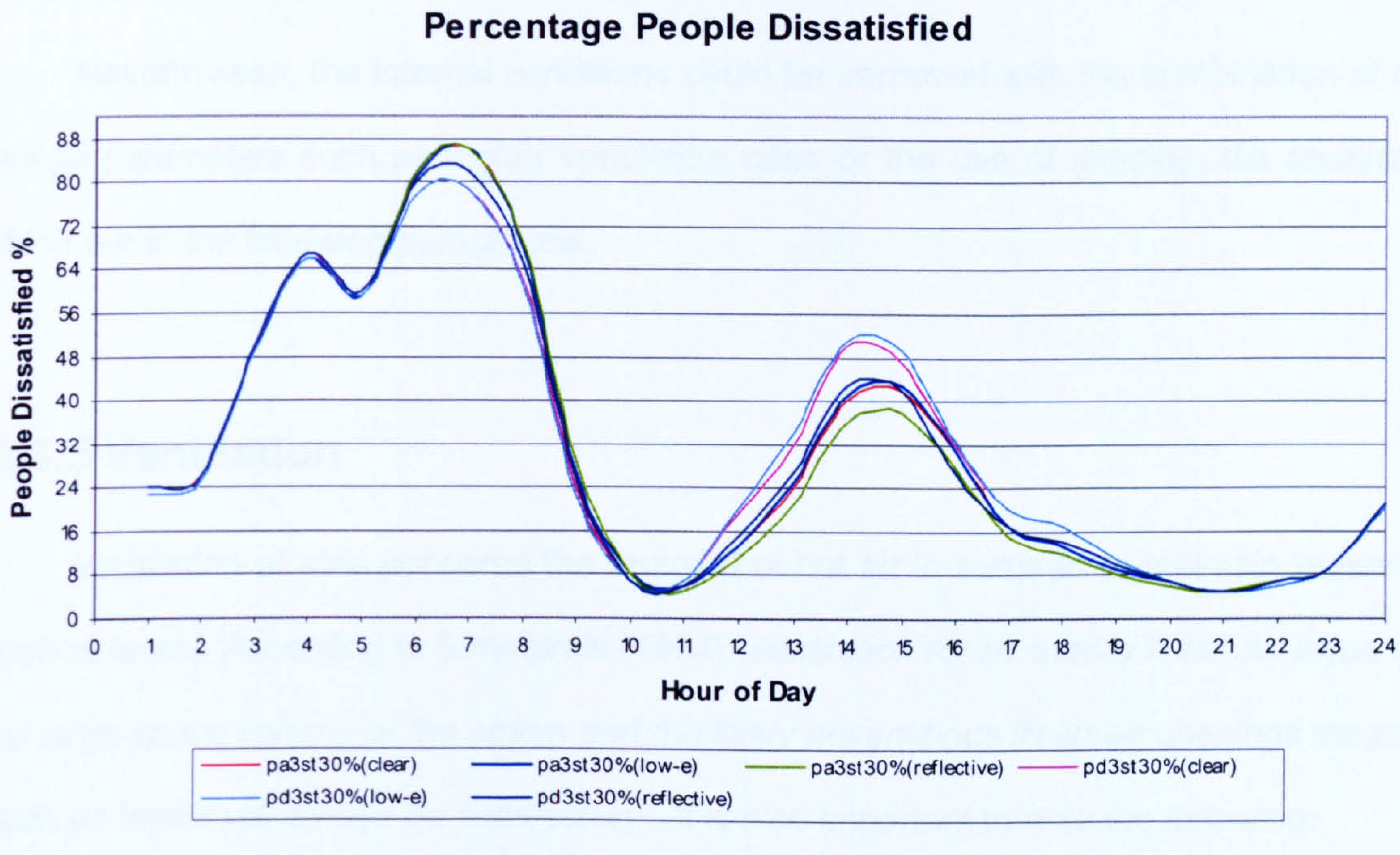


Figure 6. 21: Percentage of People Dissatisfied in the enclosed and linear type for different glazing types as predicted by ROOM during summer

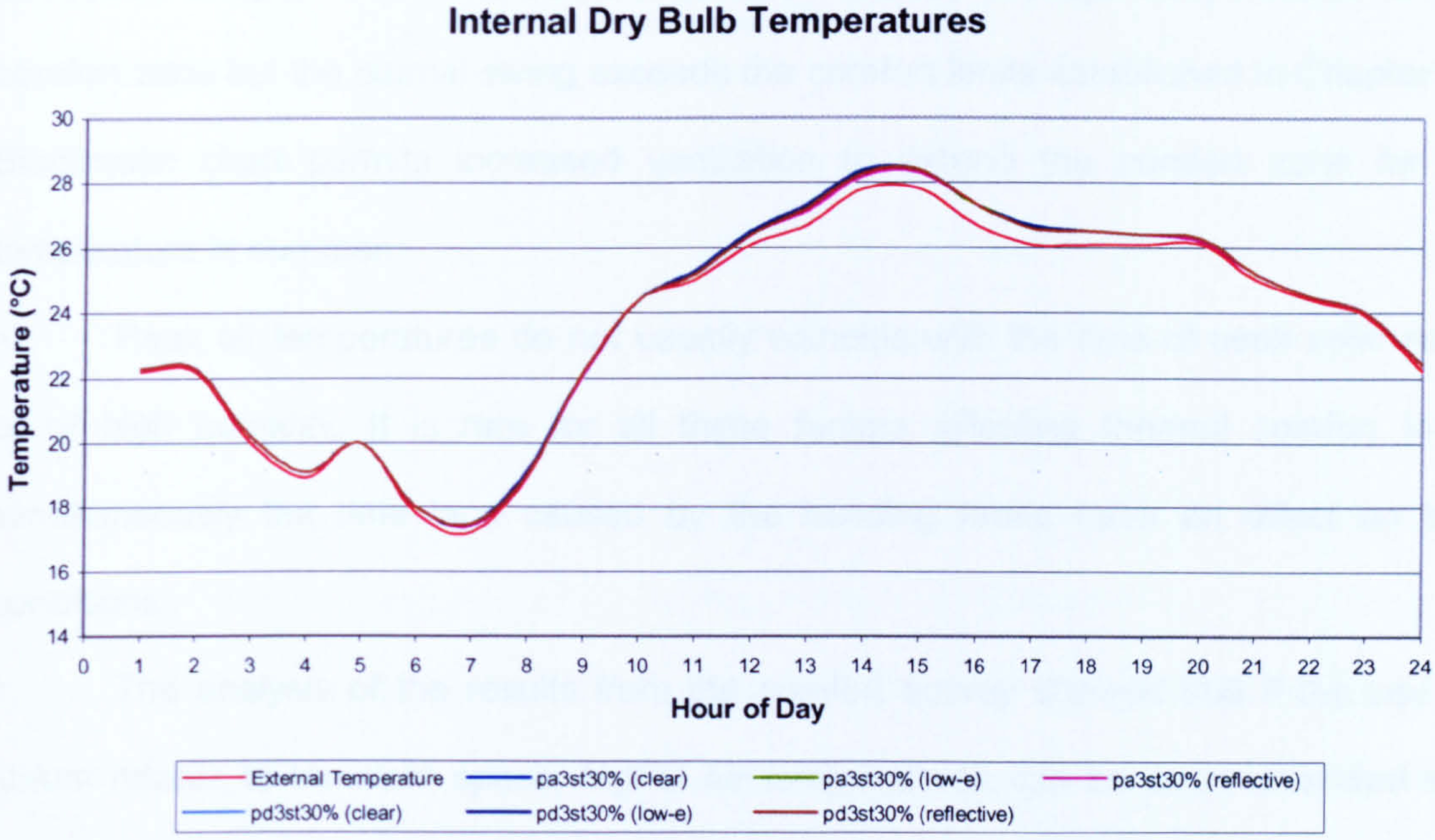


Figure 6. 22: Internal dry bulb temperatures in the enclosed and linear type for different glazing types as predicted by ROOM during summer

Nevertheless, the internal conditions could be improved with the combination of other design parameters such as higher ventilation rates or the use of shading, the analyses of which are in the following paragraphs.

6.3.5 Ventilation

Ventilation of atria concerns the removal of hot air in summer to maintain reasonable comfort levels. According to Simmonds (1994) "*ventilation for air quality is not an issue since the large space volume of the atrium and the likely adventitious fresh air openings mean that fresh air levels will always be satisfactory*". It is also important to note the following:

- Peak summertime conditions in a Mediterranean climate occur for relatively short periods. The traditional summer design outside temperature of 30^0C is exceeded for 15% of the time in the three-month summer period (June-September). Local climate data for

Greece in Chapter 3 indicate that the summer monthly average temperatures are within comfort zone but the diurnal swing exceeds the comfort limits established in Chapter 5. The Bioclimatic chart permits increased ventilation to extend the comfort zone for higher temperature in summer.

- Peak air temperatures do not usually coincide with the time of peak solar radiation or of high humidity. It is rare for all these factors affecting thermal comfort to occur simultaneously but time lags caused by the building fabric have an effect on internal conditions.
- The analysis of the results from the comfort survey showed that if the use of the atrium relates to transient space, higher air temperatures can be accommodated without compromising comfort standards.

It is very important to acknowledge that the indoor environment of an atrium space is strongly affected by solar radiation. It was also discussed in Chapter 2 that the combination of large glazed surfaces, the atrium height and the buoyancy force could cause air stratification. Figure 6.23 shows a 3-D visualization of air-temperature distribution in three different times in an enclosed atrium with a flat roof. When the temperature at the lower levels within the atrium is much lower than that at higher levels it results in an increase of the pressure difference, which in turn enhances the natural buoyancy effect for natural ventilation purposes.

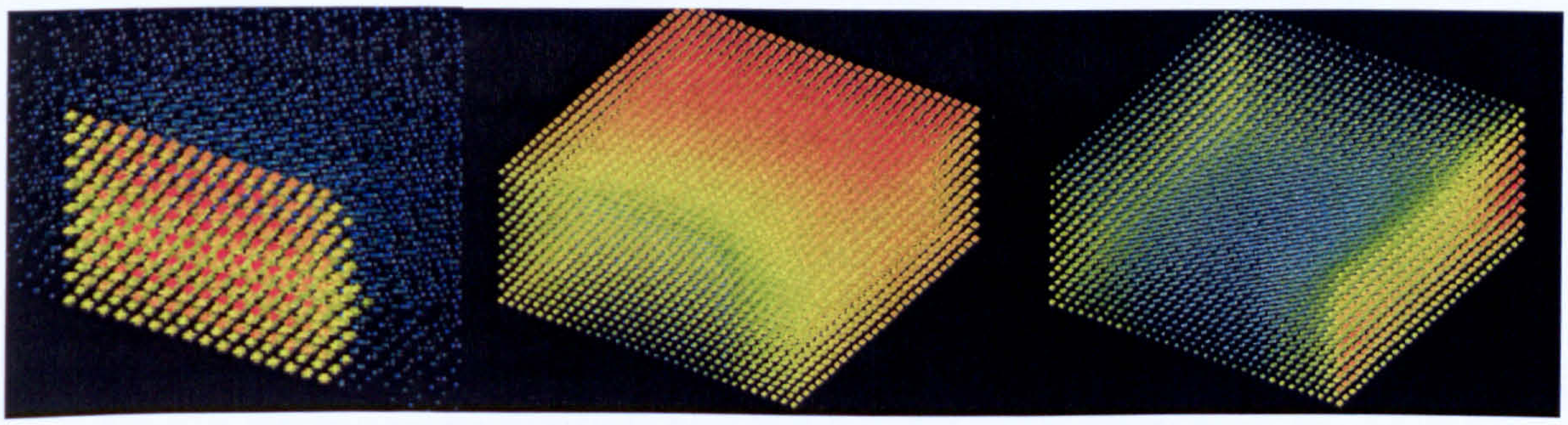


Figure 6. 23: 3-D visualization of air-temperature distribution in three different times in an enclosed atrium with a flat roof

The analyses of the results so far indicate that in the summer the atrium space can be very hot leading to high levels of discomfort. Iterations for two ventilation rates were performed only for the summer period. The influence of ventilation on comfort and temperature varies for different types of atrium spaces. Figure 6.24 and Figure 6.25 show the effect of 5ac/h and 10ac/h in the enclosed atrium with 3 and 6-floor height, for a flat roof and for two types of glazing.

In this set of results the three-floor height atrium with the clear glass and 5ac/h is the warmest (at occupied level) and the percentage of discomfort is still very high for most hours of the day. As it can be seen, higher ventilation rates improve thermal conditions in the atrium with the smaller height, regardless of the glazing type. This causes an average temperature drop of 2^0C.

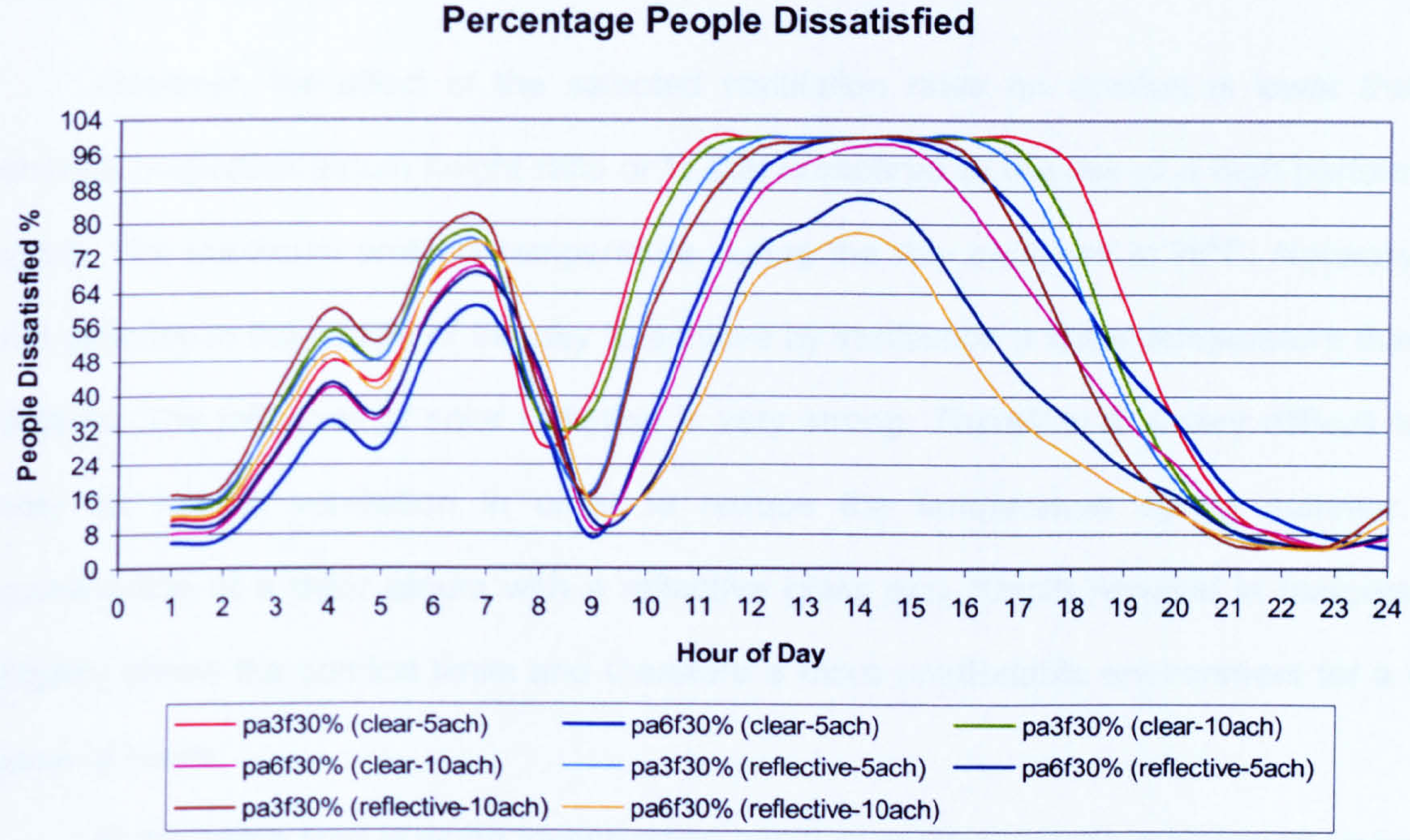


Figure 6. 24: Percentage of People Dissatisfied in the enclosed type for 5ac/h and 10ac/h as predicted by ROOM during summer

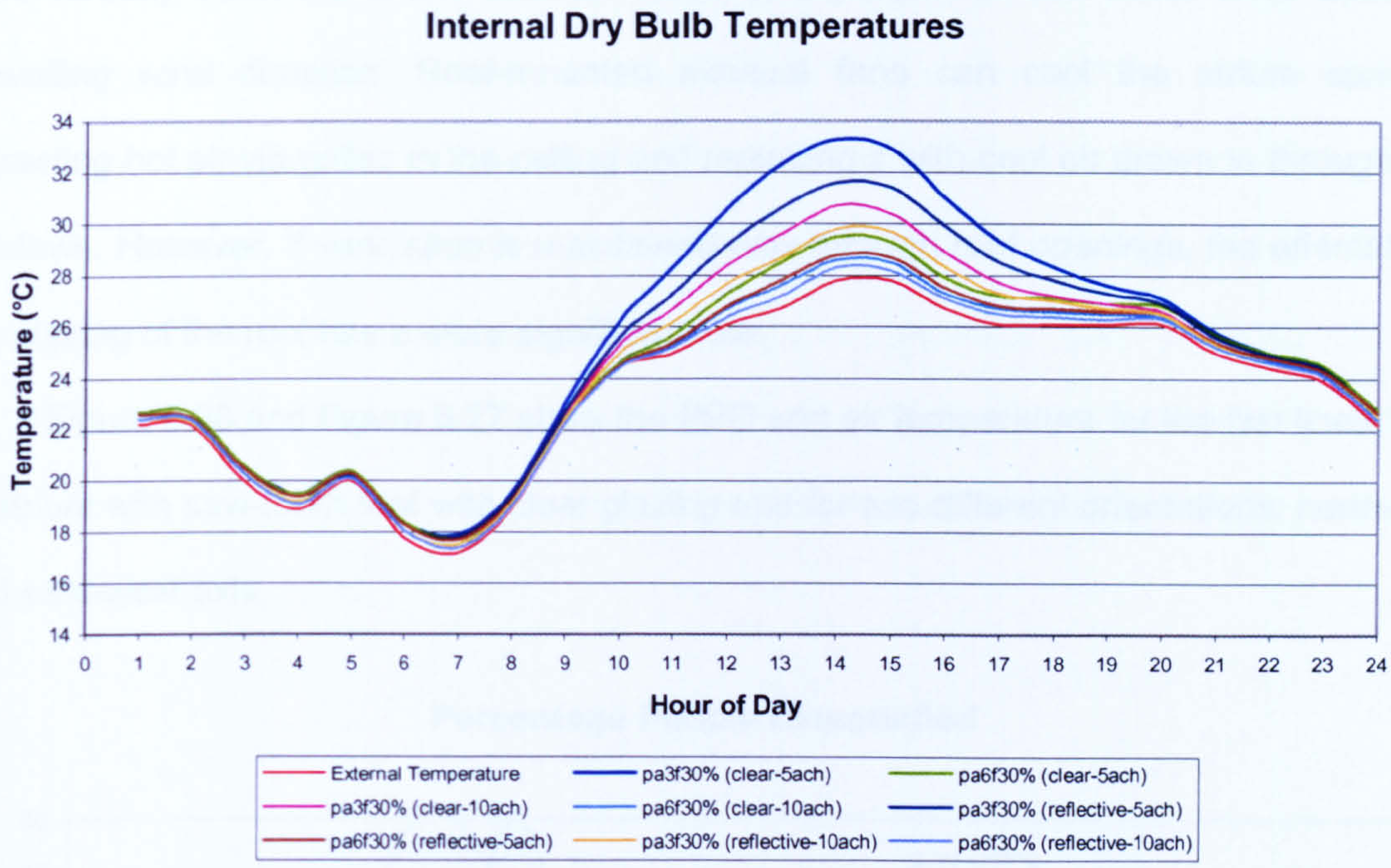


Figure 6. 25: Internal dry bulb temperatures in the enclosed type for 5ac/h and 10ac/h as predicted by ROOM during summer

However, the effect of the selected ventilation rates on comfort is lower than the change proportion atrium height ratio or to that compared to the use of a high performance glass. The maximum ambient temperature during the day analysed is 28^{0}C. Naturally, it is not possible in the middle of the day to achieve by ventilation a lower temperature than that outside. The influence of solar radiation is very strong. Therefore it is very difficult to rely only on natural ventilation in order to reduce the temperature during summer. The combination of a taller atrium with a reflective glass and 10ac/h resulted in temperatures slightly above the comfort limits and therefore a more comfortable environment for a wider span of hours.

At the same time is worth investigating whether comfort can be maintained by venting excess heat produced by solar radiation through a controlled opening of the atrium fenestration for the rest of the day (except for the night time and the peak day hours that have already been discussed above). What is important in this case, is to check the prevailing wind direction. Roof-mounted exhaust fans can cool the atrium space by extracting hot air via grilles in the ceiling and replacing it with cool air drawn in through open windows. However, if ventilation is maintained only through roof openings, the orientation of the glazing of the roof has a more significant role.

Figure 6.26 and Figure 6.27 show the PPD and air temperature for the two linear types of atrium with saw-tooth roof with clear glazing and for two different orientations: north-south and east-west axis.

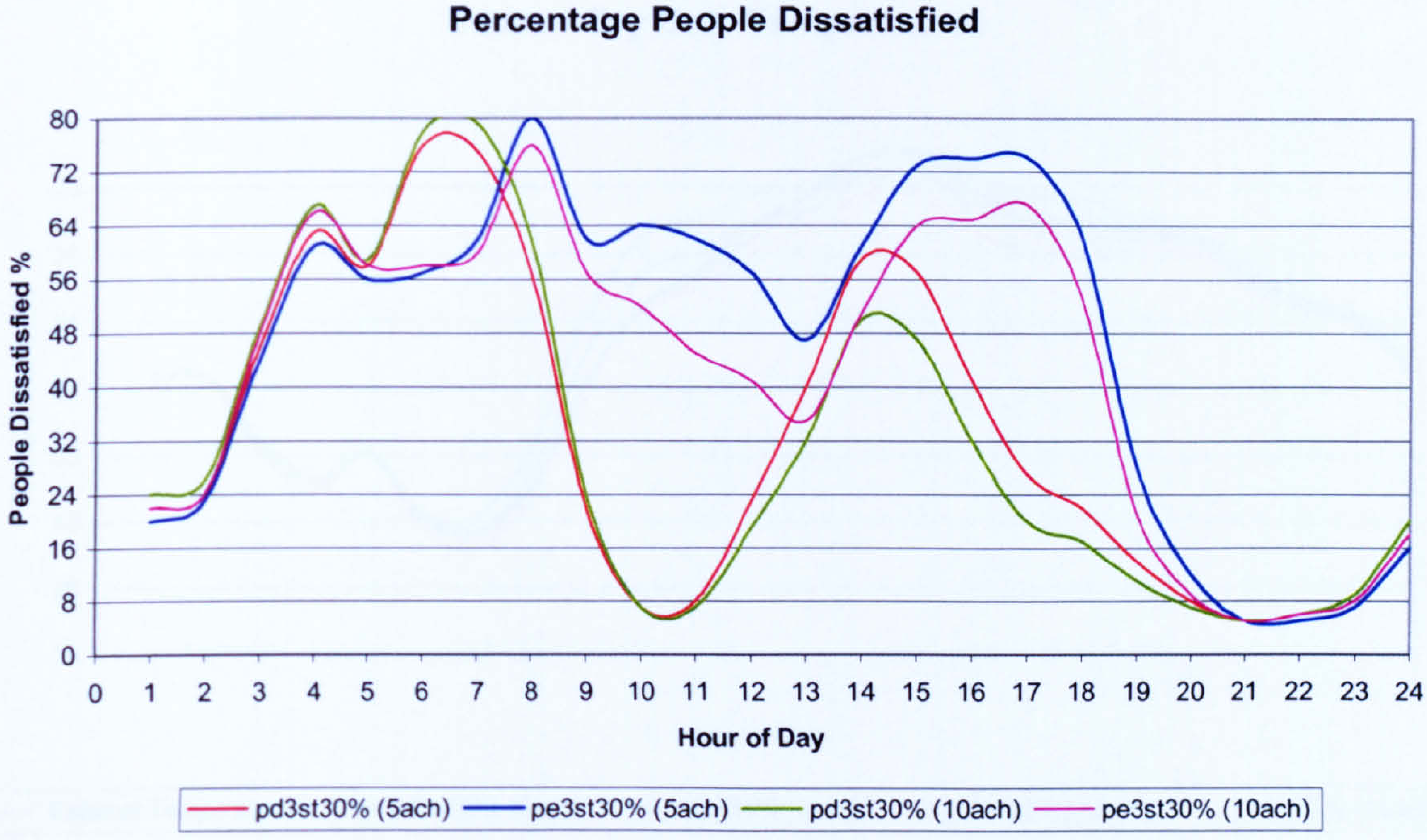


Figure 6. 26: Percentage of People Dissatisfied in the linear type for different orientations and for 5ac/h and 10ac/h as predicted by ROOM during summer

The external temperature ranges from 17^{0}C to 28^{0}C. The temperatures in all four types of atria analysed follow closely this pattern with maximum 2^{0}C above the ambient temperature in the atrium with the east-west axis during morning and late afternoon hours. The PPD however, follows a pattern with much greater swings. Acceptable comfort levels are achieved between 9:00 and 12:00 hours in the atrium with the north-south axis. When the ventilation rate is 5ac/h, the PPD falls below 25% after 18:00 hours. This can be achieved an hour earlier by raising the ventilation rate to 10 ac/h.

As expected, the linear atrium with the east-west axis has high levels of discomfort during early morning hours and late afternoon; this is caused by direct solar radiation since the sun has a lower angle at these hours. The increase of ventilation rates from 5 ac/h to 10 ac/h can lower the PPD by maximum 10%, but it won't be effective enough to create a comfortable environment.

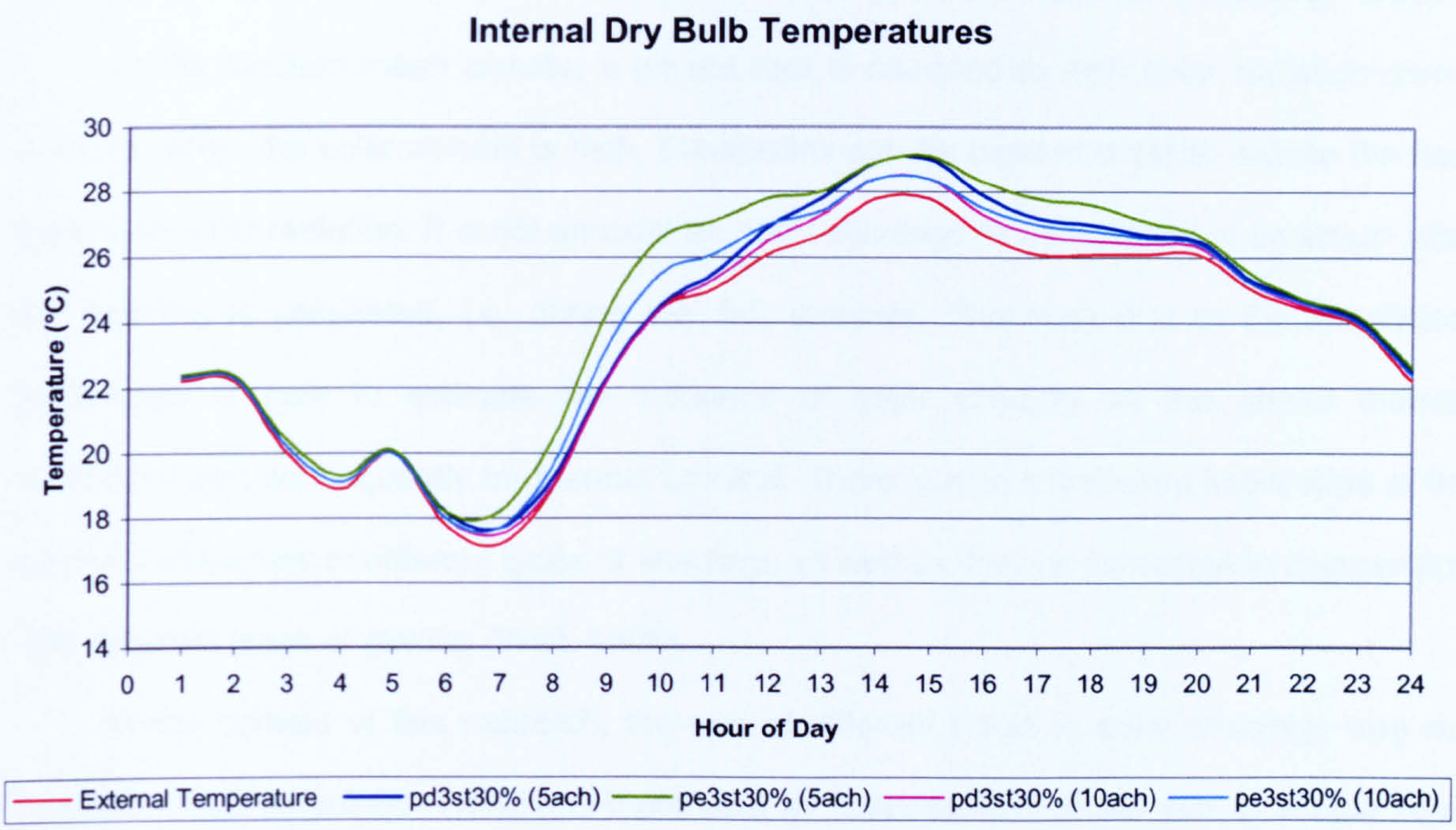


Figure 6. 27: Internal dry bulb temperatures in the linear type for different orientations and for 5ac/h and 10ac/h as predicted by ROOM during summer

In the case of a retrofitting of a galleria or a walkway in an east-west axis, where not much can be done to alter the orientation of the building, appropriate shading should be applied in the access of the airflow that ventilates the space.

The application of shading in the atrium fenestration in the summer and the results of that parametric study are discussed in detail in the next paragraph.

6.3.6 Shading

The primary reason for solar shading is to provide thermal comfort by reducing unnecessary solar gain. Design parameters include orientation, sun path, sun angle, daylight transmission, ventilation, user control, maintenance and cost. All these parameters vary according to climatic characteristics and the functions of the spaces (Goulding, 1992).

In the Mediterranean climate, a glazed roof is exposed to high solar radiation during summer when the solar altitude is high. Sunshades can be used in order to reduce the heat gain from solar radiation. It is not unusual for solar shadings to be installed in an atrium after the building is completed, i.e. during the first summer. This may due to the insufficient knowledge of how to estimate the influence of solar shading on the atrium thermal conditions and consequently on thermal comfort. There is also insufficient knowledge of the physical properties of different types of shadings as well as their performance in combination with different types of glazing (Wall, 1996).

In the context of this research, the use of different types of solar shadings was not possible to be examined. However, there was an investigation of the use of simple solar shading in the selected atrium types in combination with various roof shapes, two ventilation rates and different types of glazing.

The predictions shown in Figure 6.28 and Figure 6.29 are for the enclosed type with 30% glazing ration and flat roof.

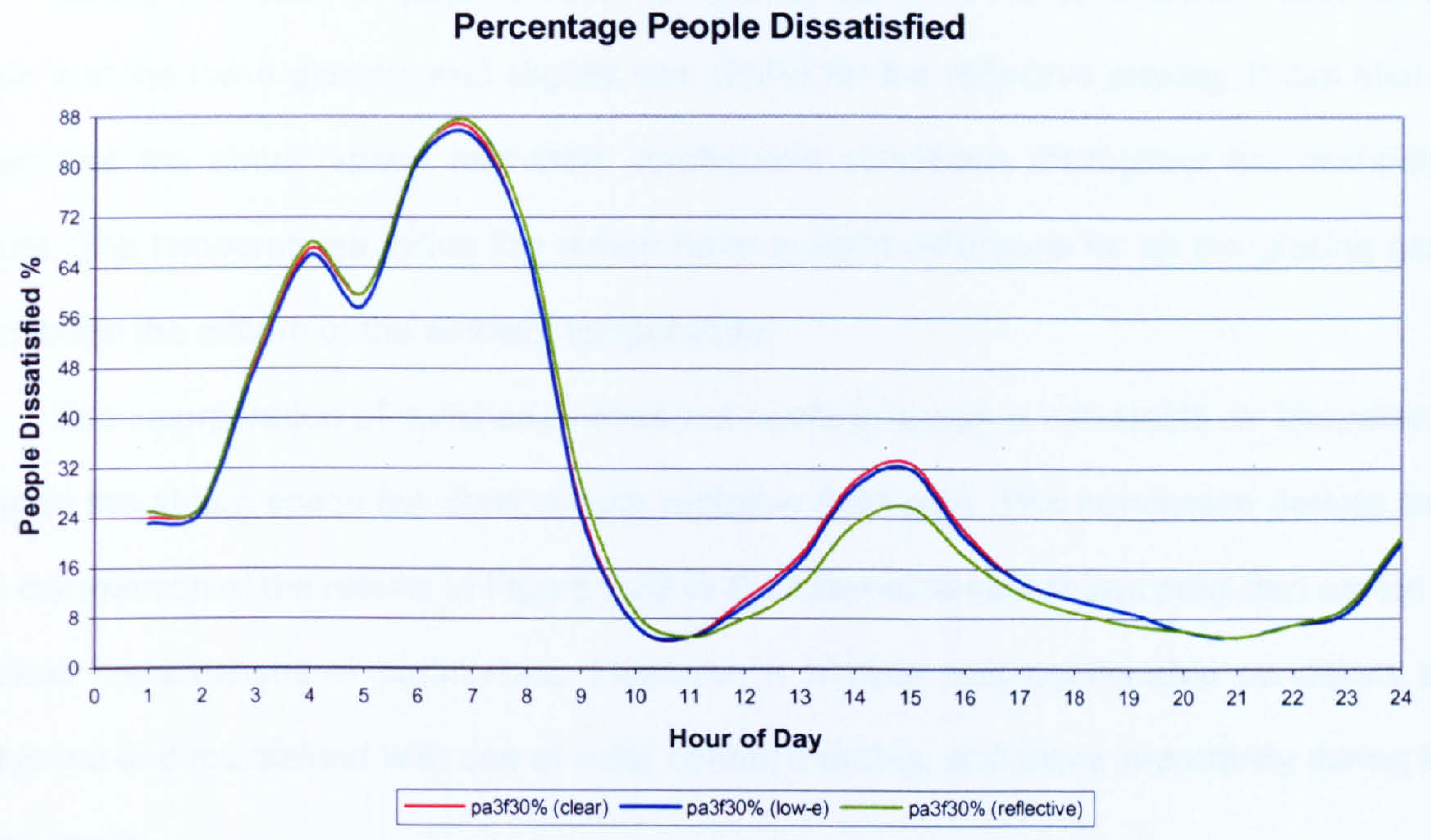


Figure 6. 28: Percentage of People Dissatisfied in the enclosed type with shading and 10ac/h as predicted by ROOM during summer

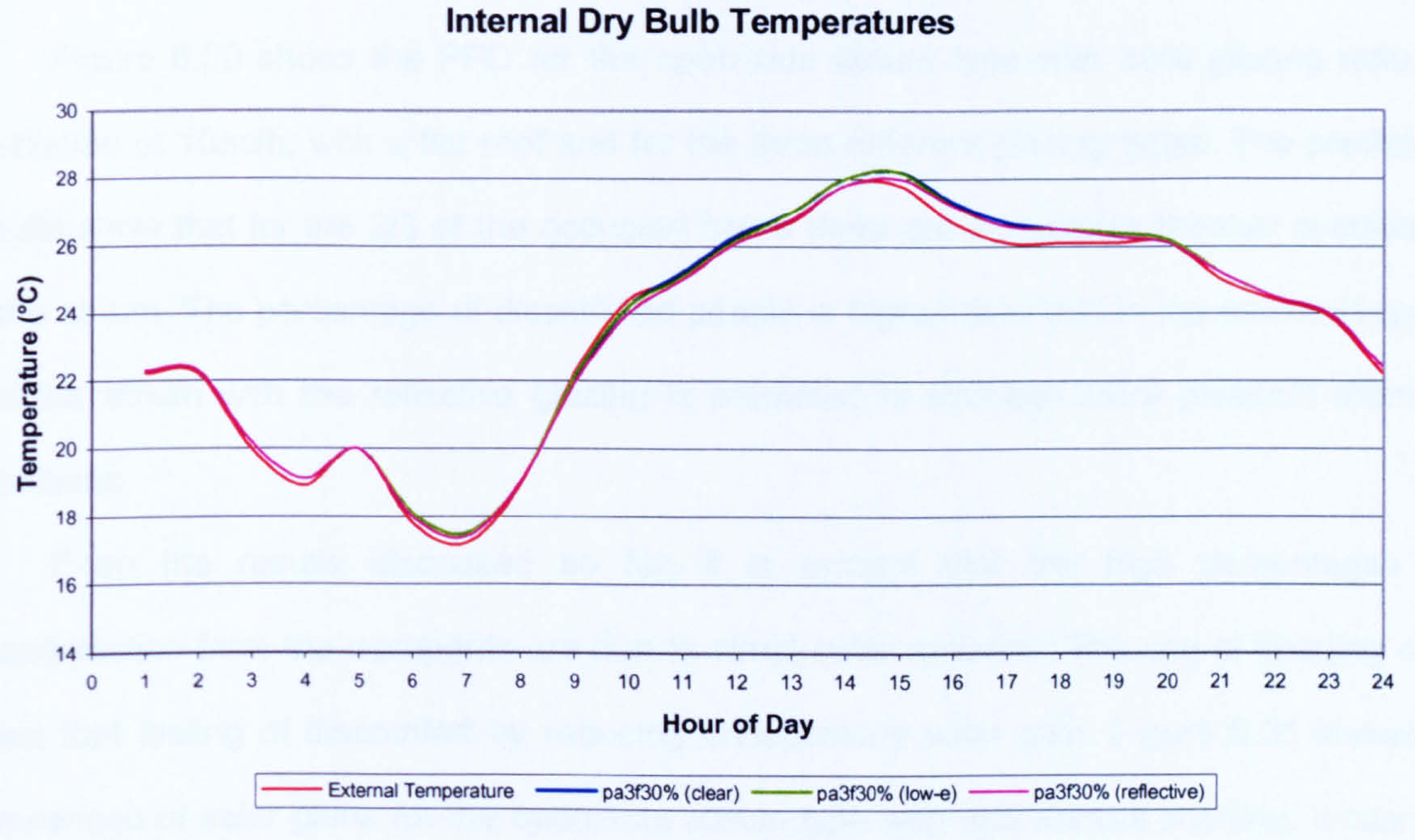


Figure 6. 29: Internal dry bulb temperatures in the enclosed type with shading and 10ac/h as predicted by ROOM during summer

During the hours of peak ambient temperatures, the PPD is less than 33% for the clear and the low-e glazing, and slightly less (25%) for the reflective glazing. It can also be seen that the atrium space maintains comfortable conditions throughout the occupancy hours. The temperatures inside the atrium have a slight difference for all the glazing types and follow the pattern of the ambient temperature.

The incorporation of sunshades does not seem to cause a noticeable air temperature drop in the atrium space but does reduce radiative heat gain. This conclusion derives from the comparison of the results in Figure 6.29 to the internal temperatures predicted earlier for various combinations of parameters. However, it is clear that comfortable conditions are achieved and maintained with use of solar control shading, and more importantly during the peak hours.

The above results apply to the enclosed atrium type, where shading is applied on the atrium glazed roof to protect it from the high angle summer sun. It is therefore interesting to investigate how effective is shading in an atrium type with different orientation.

Figure 6.30 shoes the PPD for the open-side atrium type with 30% glazing ratio, a ventilation of 10ac/h, with a flat roof and for the three different glazing types. The predicted results show that for the 2/3 of the occupied hours there are acceptable thermal conditions in the atrium. The percentage of dissatisfied people is higher than that in the enclosed type, and the atrium with the reflective glazing is predicted to maintain more pleasant thermal conditions.

From the results discussed so far, it is evident that the high percentages of dissatisfaction from the occupants are due to direct solar radiation. The use of shading can affect that feeling of discomfort by reducing unnecessary solar gain. Figure 6.31 shows a comparison of solar gains for the open-side atrium type with and without shading. It can be seen from the graph that the incorporation of shading, the solar gains in the atrium reduce dramatically.

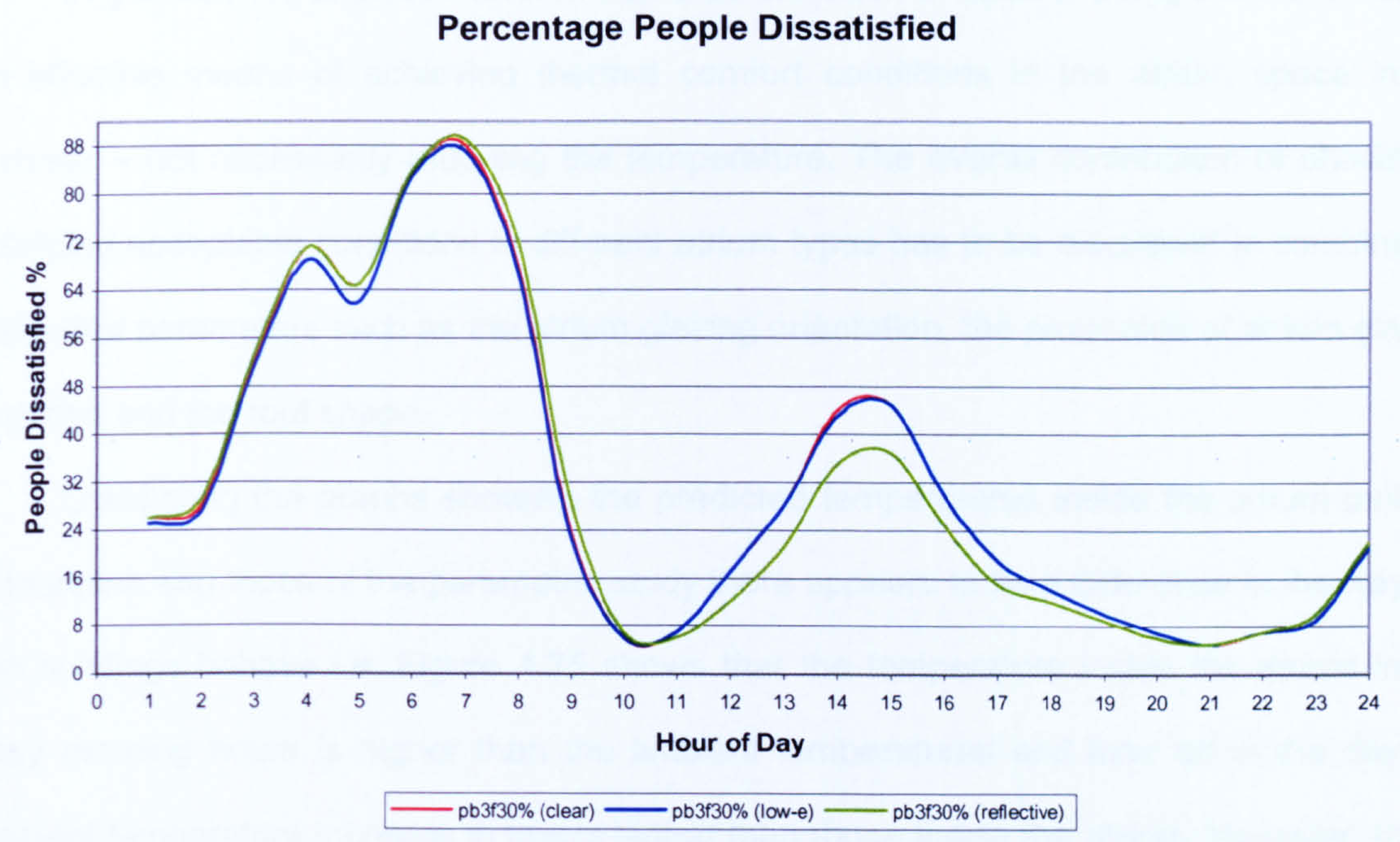


Figure 6. 30: Percentage of People Dissatisfied in the open-side type with shading and 10ac/h as predicted by ROOM during summer

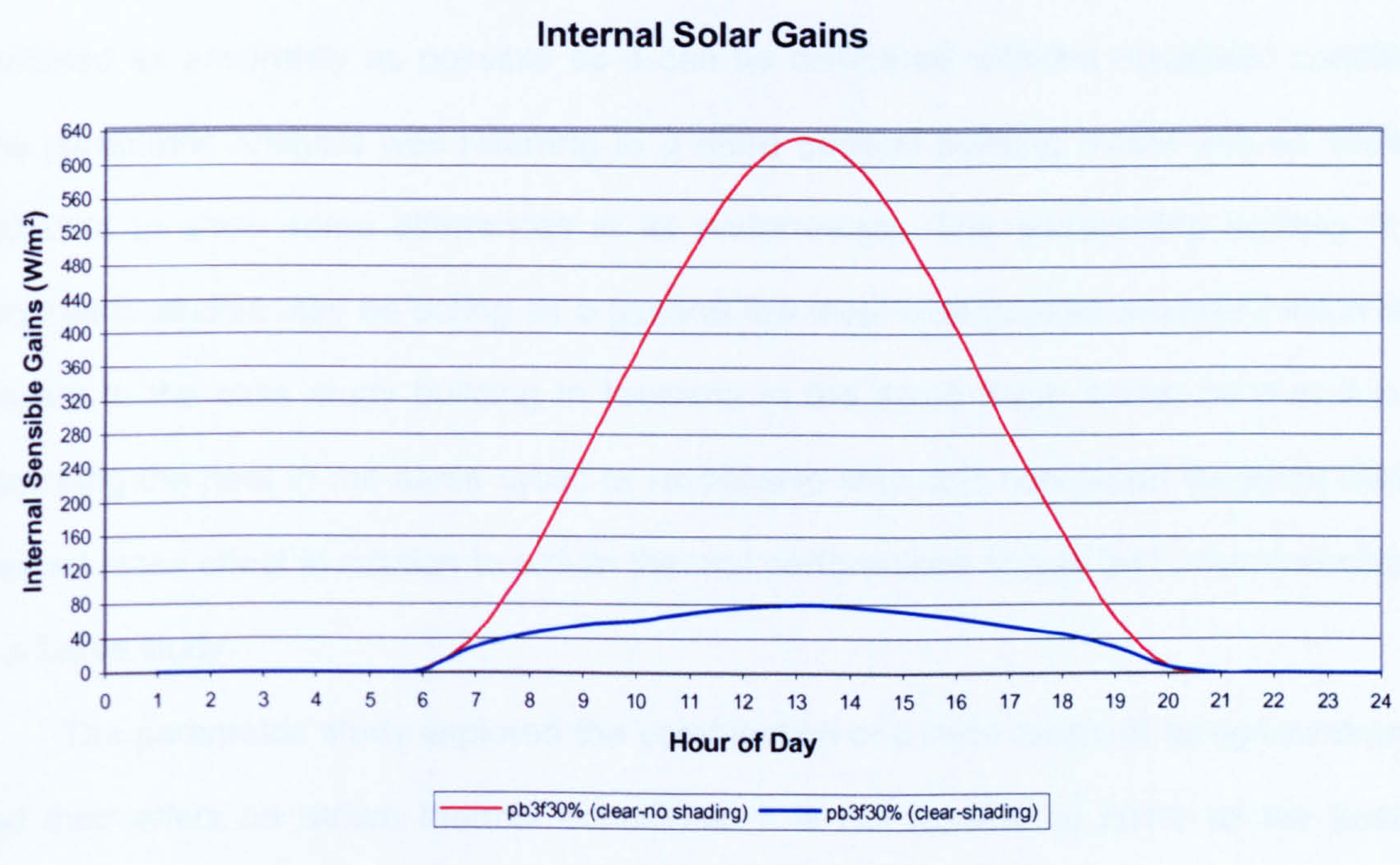


Figure 6. 31: Comparison of solar gains for the open-side atrium with clear glass with and without shading as predicted by ROOM during summer

In general, the analyses confirm that a combination of solar shading and ventilation is an effective means of achieving thermal comfort conditions in the atrium space in the summer – not necessarily reducing the temperature. The overall contribution of shading in providing acceptable conditions in different atrium types has to be discussed in combination with other parameters such as the atrium glazing orientation, the proportion of atrium glazing exposed and the roof shape.

Comparing the graphs showing the predicted temperatures inside the atrium building in Ioannina and those of the parametric study there appears to be a difference in the way the two buildings behave i.e. Figure 4.35 shows that the temperature inside the atrium in the early morning hours is higher than the ambient temperatures and later on in the day the ambient temperature increase to levels higher than those inside the atrium. However, this is not apparent in the results presented in the parametric analysis. This could be attributed to the thermal mass effect, as this was an area difficult to deal with and its worthy of more investigation. The building in Ioannina was obviously a special case-it was designed and modelled as accurately as possible so it can be compared with the measured conditions. The parametric analysis was referring to a more general building model and so could be expected to show some differences in its performance. The surrounding building in the parametric studies may be acting as a general low level heat transfer modifier (which is not present in the case study building in Ioannina in the same way); it may be that it is not absorbing the heat in the same cyclic or responsive way. It is concluded therefore that the thermal mass effect in relation to atrium thermal performance should be further investigated in a future study.

The parametric study explored the combination of a wide range of design parameters and their effect on atrium thermal conditions. It is not feasible to cover all the possible alternatives, however, for the purposes of this study the range was considered suitable, as the main aim was to explore the general trend of behaviour of an atrium space in the Mediterranean climatic context.

There was however the need for understanding the relative effectiveness of each element and their combination, in the atrium environment. The method devised to evaluate the influence of all the selected parameters is described in the following paragraph.

6.4 Summary of performance evaluation

Since the objective of this research is to achieve comfort or reduce discomfort, it was decided to use the level of discomfort as a measure of effectiveness of the design alternatives. In practice it is necessary to examine all months and hours of the day to arrive at a statistical description of comfort within the atrium space. The analyses produced a large amount of results. The approach taken was to assess the percentages of discomfort between 900 and 1800 hours. These were added in a cumulative way and summarised in a table. The values are "Percentage Discomfort Hours" per day and are referred to as "dissatisfaction scores".

If the research was concentrated in energy performance then other factors should be considered. For the current study, the aim is to achieve occupants' comfort and therefore only the hours of occupancy were taken into consideration. 900 to 1800 hours is a typical span of a building's occupied hours in the Mediterranean climatic context. Additionally, by choosing this period of time, the bumps in the ambient air temperature in the early morning hours, and consequently in the air temperature inside the atrium space, do not affect the results.

The "dissatisfaction scores" (ds) for all the design parameters are summarised for each atrium type in two tables. The first table represents the dissatisfaction score for the 10-

hour span. The second table shows the percentage of the effect on comfort of each factor; as the general trend for each type of building The design options that result in equal or less than 250 discomfort hours is considered acceptable.

The advantages of presenting the results for each type of building separately are: a) a less complicated and more comprehensive comparison of the impact of the selected design parameters on the atrium thermal conditions and b) an easier application of the results by the designers that are restricted in shape and type of the atrium, i.e. in the case of retrofitting. General conclusions from the comparison of all the results above are drawn at the end of the chapter.

Building type A (Glazed Courtyard Type)

Table 6.3 and Table 6.4 show the results for the enclosed type (PA). The results for winter are calculated for one glazing ratio facing the atrium, ventilation rate of 5ac/h and for three types of glazing. It can be seen that the differences of the dissatisfaction scores are low; such is the case that no design parameter has a prominent impact on the atrium's thermal conditions. That was also confirmed by the analyses of the graphs: the atrium temperature followed the pattern of ambient temperature and the excess heating gains from the exposed glazing in the roof seem to result in an acceptable environment.

The results for the summer season are discussed in more detail since there is a significant difference between the various scores predicted, i.e. the worse case scenario (ds= 932) for the enclosed type is three floor height, flat roof with clear glazing, 0% glazing ratio and 5ac/h. The best-case scenario results to dissatisfaction score of 99 and applies to the atrium with the saw-tooth roof with reflective glass, 0%glazing ratio and 5ac/h. The tabulated summarised results are very beneficial in that it is possible to see the effect that a contiguous design parameter has on comfort

Table 6.4 summarises the relative improvement that can be obtained by varying certain design parameters for the A atrium type. On average, by incorporating a vault roof in an enclosed atrium there is a reduction of 29.7% in dissatisfaction and with a saw-tooth roof shape a reduction of 75.4% in dissatisfaction compared to the flat roof. This is due to the fact that the flat roof collects and transmits more solar radiation at high altitudes (summer time) than the other two types of roof. Compared to the base case design (clear glazing), the low-e glazing and the reflective glazing reduce the seasonal percentage of occupants' dissatisfaction by 5.6% and 20.5% respectively. The change in height from three floors to six floors results in 39.3% of people less dissatisfied more likely due to the self-shading effect of the enclosed atrium. The change in glazing ratio of the adjacent building walls facing the atrium space from 0% to 30% and 60% resulted in 6.3% and 18.5% more acceptable conditions for the occupants as predicted by the programme. As discussed earlier, that is due to the fact that the airflow from the atrium to the adjacent spaces (which were conditioned at 20 ^{0}C) contributed to lower the atrium temperature, especially that of the ground floor and, therefore, resulted in more acceptable conditions.

It can also be seen from the tabulated results that the increase of ventilation rates from 5ac/h to 10 ac/h has a reduction of 8.8% in dissatisfaction. In the case of the saw-tooth roof, the increase of ventilation rates actually increases the dissatisfaction score or has no effect at all. Finally, by shading the atrium roof fenestration, a reduction of 72.1% in occupants' dissatisfaction can be achieved. Especially in the case of the glazed courtyard, the source of solar radiation inside the atrium, and as it was concluded from the previous paragraph a main cause of users' dissatisfaction, is the glazed atrium roof. By providing adequate shading during the summer period, acceptable thermal conditions can be achieved.

Type Code		SUMMER												WINTER		
		vent 5			vent 10			Vent5/Shading			vent10/Shading			vent5		
		glazing type			glazing type			glazing type			glazing type			glazing type		
		clear	lowe	reflective	clear	lowe	reflective	clear	lowe	reflective	clear	lowe	reflective	clear	lowe	reflective
pa3	f0	932.0	923.0	866.0	891.0	891.0	818.0							107.0		
	f30	909.0	850.0	828.0	878.0	855.0	773.0	192.0	191.0	165.0	177.0	171.0	153.0	105.0	101.0	104.0
	f60	843.0	819.0	740.0	798.0	767.0	678.0							105.0		
	st0	265.0	269.0	239.0	221.0	224.0	202.0									
	st30	260.0	265.0	247.0	225.0	224.0	203.0	165.0	161.0	153.0	153.0	146.0	143.0	231.0	265.0	237.0
	st60	263.0	268.0	242.0	222.0	229.0	206.0									
	v0	789.0	759.0	595.0	718.0	673.0	521.0									
	v30	724.0	682.0	524.0	654.0	606.0	462.0	105.0	101.0	98.0	106.0	102.0	98.0	103.0	102.0	105.0
	v60	669.0	627.0	475.0	603.0	555.0	423.0									
pa6	f0	775.0	702.0	559.0	698.0	631.0	491.0									
	f30	732.0	675.0	531.0	675.0	604.0	469.0	90.0	89.0	99.0	94.0	91.0	95.0	107.0	105.0	109.0
	f60	511.0	442.0	337.0	469.0	403.0	310.0									
	st0	103.0	103.0	99.0	104.0	104.0	101.0									
	st30	105.0	106.0	103.0	107.0	105.0	103.0	78.0	115.0	120.0	105.0	105.0	108.0	102.0	103.0	104.0
	st60	108.0	107.0	108.0	106.0	106.0	105.0									
	v0	499.0	459.0	362.0	442.0	402.0	321.0									
	v30	428.0	391.0	314.0	382.0	348.0	281.0	133.0	131.0	127.0	130.0	129.0	124.0	103.0	103.0	107.0
	v60	379.0	350.0	284.0	343.0	315.0	259.0									

Table 6.3: Percentage Discomfort Hours per day for atrium type A. The coloured boxes represent acceptable values of dissatisfaction scores (≤250)

PA							
glass type	**avg clear**	**avg low-e**	**avg ref**	**roof type**	**flat**	**sawtooth**	**vault**
Avg	495.3	467.8	393.9	**Avg**	696.5	171.0	489.4
diff	27.5	73.9	101.4	**diff**	525.4	318.4	207.1
diff %	5.6	15.8	20.5	**diff %**	75.4	65.1	29.7
glazing ratio	**0%**	**30%**	**60%**	**ventilation**	**5 ac/h**	**10 ac/h**	
Avg	493.1	461.9	401.9	**Avg**	473.0	431.6	
diff	31.2	60.0	91.2	**diff**	41.5		
diff %	6.3	13.0	18.5	**diff %**	8.8		
height	**3 floors**	**6 floors**		**shading**	**no**	**yes**	
Avg	562.8	341.8		Avg	452.3	126.2	
diff	221.0			diff	326.1		
diff %	39.3			diff %	72.1		

Table 6.4: Comparative results of Percentage Discomfort Hours per day for atrium type A

Building type B (Open side-south)

Table 6.5 and Table 6.6 show the results for the open-side type of atrium with the vertical fenestration facing south. As discussed previously in the chapter, that atrium type has a larger amount of glazing exposed to ambient climate compared to the courtyard type. This resulted in more seasonal temperature fluctuations and daily temperature fluctuations, higher solar gains for both seasons and therefore less percentage of dissatisfaction in winter and higher requirements for shading in summer.

For winter, there are no significant differences in the dissatisfaction scores from the courtyard type, except that the higher amount of solar radiation results in slightly more satisfying conditions.

During summer, more people are likely to feel uncomfortable (ds=931) in the atrium with three floors and a flat roof, clear glazing, 0% glazing ratio and 5ac/h. The six-floor, saw-tooth roof shape model with reflective glass, 60% glazing ratio and 10ac/h provides the most acceptable conditions (ds=129). Considering the dissatisfaction score for the atrium model with the flat roof and the clear glazing as the base case, there is a reduction of 59.2% and 39.3% by replacing the flat roof with a saw-tooth roof and a vault roof, respectively. The choice of a low-e type of glazing can have a positive effect on lowering the dissatisfaction score by 2.3% and the reflective type of glazing by 13.6% compared to the clear glazing. The statistic results show that the increase of the glazing ratio in the walls shared by the adjacent building and the atrium from 0% to 30% and from 30% to 60%, results in the same effect, an average reduction in the dissatisfaction score of 6.5%.

		SUMMER						WINTER		
		vent 5			vent 10			vent5		
		glazing type			glazing type			glazing type		
		clear	lowe	reflective	clear	lowe	reflective	clear	lowe	reflective
pc3	f0	991.0	993.0	962.0	970.0	970.0	918.0			
	f30	972.0	974.0	926.0	942.0	941.0	874.0	83.0	82.0	84.0
	f60	948.0	947.0	889.0	914.0	910.0	832.0			
	st0	387.0	373.0	281.0	299.0	285.0	221.0			
	st30	317.0	306.0	236.0	250.0	239.0	190.0	93.0	97.0	99.0
	st60	274.0	265.0	207.0	224.0	214.0	173.0			
	v0	756.0	736.0	631.0	701.0	677.0	572.0			
	v30	710.0	683.0	582.0	658.0	628.0	529.0	102.0	101.0	103.0
	v60	675.0	649.0	552.0	630.0	595.0	499.0			
pc6	f0	930.0	931.0	861.0	894.0	889.0	805.0			
	f30	870.0	864.0	780.0	835.0	820.0	721.0	77.0	80.0	85.0
	f60	817.0	801.0	703.0	783.0	759.0	644.0			
	st0	176.0	179.0	151.0	153.0	156.0	136.0			
	st30	143.0	147.0	128.0	132.0	133.0	121.0	101.0	102.0	103.0
	st60	125.0	129.0	115.0	120.0	123.0	111.0			
	v0	460.0	426.0	345.0	421.0	386.0	313.0			
	v30	405.0	372.0	303.0	374.0	342.0	279.0	103.0	102.0	105.0
	v60	371.0	336.0	276.0	345.0	311.0	257.0			

Table 6.5: Percentage Discomfort Hours per day for atrium type B. The coloured boxes represent acceptable values of dissatisfaction scores (≤250)

PB							
glass type	**avg clear**	**avg low-e**	**avg ref**	**roof type**	**flat**	**sawtooth**	**vault**
Avg	508.6	497.1	439.6	**Avg**	779.4	192.8	473.0
diff	11.5	57.5	69.0	**diff**	586.6	-280.2	306.4
diff %	2.3	11.6	13.6	**diff %**	75.3	59.2	39.3
glazing ratio	**0%**	**30%**	**60%**	**ventilation**	**5 ac/h**	**10 ac/h**	
Avg	514.7	481.4	449.1	**Avg**	500.0	463.4	
diff	33.3	32.4	65.6	**diff**	36.6		
diff %	6.5	6.7	12.8	**diff %**	7.3		
height	**3 floors**	**6 floors**		**shading**	**no**	**yes**	
Avg	585.7	377.7		Avg	481.7	162.1	
diff	208.0			diff	319.6		
diff %	35.5			diff %	66.3		
orientation	**PC**	**PB**					
Avg	523.9	481.7					
diff	42.2						
diff %	8.1						

Table: 6.6 Comparative results of Percentage Discomfort Hours per day for atrium type B

The increase of height of the building also results in 35.5% of reduction in the dissatisfaction score. It is also concluded that the effect of ventilation in achieving comfort is lower than that in the courtyard type. Cross ventilation would be more effective if the incoming air was from the lower vents of the vertical south facing fenestration is pre-cooled. That could be achieved by placing external shading in the atrium south facade or even by evaporative cooling from water-features outside the building. By shading the whole atrium fenestration thermal conditions inside the atrium improve for the occupants by 66.3%.

Building type C (Open side-east)

Tabulated results for the open-side type with the vertical façade facing east are shown in Table 6.7 and Table 6.8. In this set of results there is the highest and lowest of dissatisfaction scores amongst all the iterations for summer (excluding shading), which indicates that this type of atrium is more sensitive to the change of certain parameters.

According to the graph in Appendix D that shows the annual amount of solar irradiation available in Athens, surfaces facing east receive more solar radiation than those vertical surfaces orientated towards the south. The eastern exposure is very beneficial during winter, since it takes advantage of solar gains early in the morning when the building most needs them. However, during summer, it can build up high temperatures inside the atrium.

In winter the dissatisfaction scores are lower compared to the previous two types of buildings discussed above, nevertheless without significant fluctuations.

This is not the case for the summer however considering that the worse case scenario has a dissatisfaction score equal to 993 (3-floor height, 0% glazing ratio, flat roof with low-e glazing and 5ac/h) whereas the lower score is 111 (saw-tooth roof shape, 60% glazing ratio, reflective glass and 10ac/h). There are no iterations for shading.

		SUMMER						WINTER		
		vent 5			vent 10			vent5		
		glazing type			glazing type			glazing type		
		clear	lowe	reflective	clear	lowe	reflective	clear	lowe	reflective
pc3	f0	991.0	993.0	962.0	970.0	970.0	918.0			
	f30	972.0	974.0	926.0	942.0	941.0	874.0	83.0	82.0	84.0
	f60	948.0	947.0	889.0	914.0	910.0	832.0			
	st0	387.0	373.0	281.0	299.0	285.0	221.0			
	st30	317.0	306.0	236.0	251.0	239.0	190.0	93.0	97.0	99.0
	st60	274.0	265.0	207.0	224.0	214.0	173.0			
	v0	756.0	736.0	631.0	701.0	677.0	572.0			
	v30	710.0	683.0	582.0	658.0	628.0	529.0	102.0	101.0	103.0
	v60	675.0	649.0	552.0	630.0	595.0	499.0			
pc6	f0	930.0	931.0	861.0	894.0	889.0	805.0			
	f30	870.0	864.0	780.0	835.0	820.0	721.0	77.0	80.0	85.0
	f60	817.0	801.0	703.0	783.0	759.0	644.0			
	st0	176.0	179.0	151.0	153.0	156.0	136.0			
	st30	143.0	147.0	128.0	132.0	133.0	121.0	101.0	102.0	103.0
	st60	125.0	129.0	115.0	120.0	123.0	111.0			
	v0	460.0	426.0	345.0	421.0	386.0	313.0			
	v30	405.0	372.0	303.0	374.0	342.0	279.0	103.0	102.0	105.0
	v60	371.0	336.0	276.0	345.0	311.0	257.0			

Table 6.7: Percentage Discomfort Hours per day for atrium type C. The coloured boxes represent acceptable values of dissatisfaction scores (≤250)

PC							
glass type	**avg clear**	**avg low-e**	**avg ref**	**roof type**	**flat**	**sawtooth**	**vault**
Avg	554.8	541.4	475.6	**Avg**	877.2	200.6	494.0
diff	13.4	65.7	79.2	**diff**	676.7	-293.5	383.2
diff %	2.4	12.1	14.3	**diff %**	77.1	59.4	43.7
glazing ratio	**0%**	**30%**	**60%**	**ventilation**	**5 ac/h**	**10 ac/h**	
Avg	564.9	520.2	486.8	**Avg**	543.8	504.1	
diff	44.7	33.4	78.1	**diff**	39.8		
diff %	7.9	6.4	13.8	**diff %**	7.3		
height	**3 floors**	**6 floors**					
Avg	612.6	435.3					
diff	177.2						
diff %	28.9						

Table: 6.8: Comparative results of Percentage Discomfort Hours per day for atrium type C

The comparative results in Table 6.8 show a radical improvement in occupants' satisfaction by replacing the flat roof with a saw-tooth roof of 77.1% and 43.7% for the vault roof. The low-e glass affects the users' satisfaction overall by 2.4% whereas the reflective glass is much more effective, reducing the dissatisfaction score by 14.3%. The change in glazing ratio from 0% to 30% and 60% results in 7.9% and 13.8% less people dissatisfied respectively. More effective seems to be the change of the building height from 3 to 6 floors (28.9%). The south internal façade of the atrium will be shaded for most time of the day and will have an impact on the amount of daylighting available for the adjacent spaces. Increase ventilation rates from 5ac/h to 10ac/h will reduce the dissatisfaction score by 7.3%. In this case, as for the type of atrium discussed in the previous paragraph, pre-cooling the incoming air would have a more significant effect in comfort.

Building type D (linear north-south axis)

Type D, represents the linear atrium building with orientation in the north-south axis. This is the only atrium model that has a glazing fenestration facing north; in terms of passive solar heating that means that the north-facing glazing receives insignificant amount of solar radiation but a good energy value of natural lighting [Lewis, 1997]. Again, form the tabulated results presented in Table 6.9 and Table 6.10, it can be seen that there are low differences between the dissatisfaction scores for winter and a wider gap between the lowest (157 for the model with 6 floor height and 60% glazing ration, saw-tooth roof with reflective glass and 10ac/h) and the highest (842 for the model with 3 floor height and 0% glazing ration, flat roof with low-e glass and 5 ac/h) dissatisfaction score for summer.

In this atrium type, the difference of the effect between the flat roof and the vault roof in comfort is low (4%) whereas the saw-tooth roof can reduce the dissatisfaction score by 60.6%.

		SUMMER																		WINTER		
		vent 5			vent 10			Vent5/Shading			vent10/Shading			vent5		
		glazing type			glazing type			glazing type			glazing type			glazing type		
		clear	lowe	reflective	clear	lowe	reflective	clear	lowe	reflective	clear	lowe	reflective	clear	lowe	reflective
pd3	f0	842.0	839.0	771.0	803.0	793.0	711.0							110.0		
	f30	782.0	771.0	690.0	735.0	717.0	627.0	185.0	184.0	159.0	168.0	167.0	150.0	110.0	102.0	97.0
	f60	717.0	699.0	622.0	668.0	648.0	563.0							111.0		
	st0	368.0	412.0	316.0	299.0	308.0	252.0									
	st30	306.0	326.0	265.0	255.0	261.0	224.0	181.0	179.0	162.0	162.0	159.0	150.0	109.0	101.0	95.0
	st60	267.0	275.0	236.0	227.0	232.0	203.0									
	v0	841.0	834.0	747.0	795.0	781.0	680.0									
	v30	766.0	757.0	660.0	713.0	696.0	591.0	197.0	196.0	170.0	177.0	174.0	156.0	105.0	100.0	96.0
	v60	694.0	680.0	587.0	644.0	623.0	526.0									
pd6	f0	667.0	644.0	536.0	609.0	582.0	474.0									
	f30	558.0	532.0	436.0	512.0	483.0	391.0	137.0	135.0	125.0	135.0	132.0	125.0	104.0	99.0	93.0
	f60	481.0	451.0	371.0	446.0	412.0	338.0									
	st0	259.0	266.0	222.0	224.0	230.0	197.0									
	st30	211.0	214.0	188.0	190.0	193.0	171.0	142.0	136.0	131.0	136.0	134.0	128.0	102.0	98.0	93.0
	st60	182.0	186.0	167.0	169.0	170.0	157.0									
	v0	649.0	632.0	510.0	588.0	563.0	448.0									
	v30	532.0	507.0	406.0	479.0	457.0	361.0	147.0	143.0	132.0	143.0	139.0	129.0	102.0	97.0	93.0
	v60	444.0	422.0	339.0	407.0	383.0	308.0									

Table 6.9: Percentage Discomfort Hours per day for atrium type D. The coloured boxes represent acceptable values of dissatisfaction scores (≤250)

PD							
glass type	**avg clear**	**avg low-e**	**avg ref**	**roof type**	**flat**	**sawtooth**	**vault**
Avg	509.1	499.4	424.8	**Avg**	608.9	239.7	584.7
diff	9.7	74.7	84.4	**diff**	369.3	-345.1	24.2
diff %	1.9	15.0	16.6	**diff %**	60.6	59.0	4.0
glazing ratio	**0%**	**30%**	**60%**	**ventilation**	**5 ac/h**	**10 ac/h**	
Avg	547.0	471.2	415.1	**Avg**	501.5	454.0	
diff	75.8	56.1	131.9	**diff**	47.5		
diff %	13.9	11.9	24.1	**diff %**	9.5		
height	**3 floors**	**6 floors**		**shading**	**no**	**yes**	
Avg	567.5	388.0		Avg	477.8	152.9	
diff	179.5			diff	324.9		
diff %	31.6			diff %	68.0		
orientation	**PE**	**PD**					
Avg	709.1	477.8					
diff	231.4						
diff %	32.6						

Table: 6.10: Comparative results of Percentage Discomfort Hours per day for atrium type D

The south facing glazing orientation of the atrium will receive a beneficial amount of solar heat during winter when the sun is low for the maximum hours of the day, and will provide adequate shading during summer. Compared to clear glazing, the use of low-e and reflective glass in the atrium fenestration results in 1.9% and 16.6% reduction in the dissatisfaction score respectively. This is quite significant when having to make a cost effective choice between an expensive high performance glass such as the low-e and a clear double-glazing system. Compared to the previous types of atrium models analysed, the increase of the glazing ratio in the walls shared by the atrium and the adjacent buildings from 0% to 60% causes the highest reduction in the dissatisfaction score of 24.1%. In the case of building height, the 6-floor height atrium is reducing the dissatisfaction score by 31.6%. As the predicted results indicate ventilation can be more effective in this type of atrium building and the increase from 5ac/h to 10ac/h will reduce the dissatisfaction score by 9.5%. If the atrium fenestration is shaded there is a dramatic improvement in comfort of 68%. This is more effective for the buildings with flat and vault roof.

Building type E (linear east-west axis)

The results for the linear type with the east-west axis are summarised in Table 6.11 and Table 6.12. Compared to the results predicted for the linear type with the north-south axis, it is obvious that this type provides less comfortable conditions. The benefits and disadvantages of having an east orientated fenestration were discussed for type B; morning sun can provide a passive warm-up which can be very beneficial on chilly winter mornings. Solar control however, can be quite challenging for west-facing fenestrations especially during the summer months and can lead to excessive overheating. A west orientation means that the benefit from solar radiation during winter will be late in the afternoon hours, which doesn't include the time that the building is occupied.

		SUMMER						WINTER		
		vent 5			vent 10			vent5		
		glazing type			glazing type			glazing type		
		clear	lowe	reflective	clear	lowe	reflective	clear	lowe	reflective
pe3	f0	981.0	976.0	916.0	960.0	945.0	863.0			
	f30	961.0	956.0	879.0	937.0	916.0	820.0	96.0	94.0	98.0
	f60	951.0	934.0	846.0	917.0	886.0	785.0			
	st0	730.0	703.0	556.0	604.0	573.0	450.0			
	st30	636.0	606.0	474.0	530.0	496.0	390.0	92.0	91.0	94.0
	st60	570.0	538.0	419.0	481.0	448.0	349.0			
	v0	956.0	950.0	866.0	920.0	905.0	807.0			
	v30	932.0	918.0	823.0	892.0	870.0	760.0	95.0	95.0	96.0
	v60	910.0	892.0	786.0	865.0	838.0	725.0			
pe6	f0	911.0	883.0	751.0	855.0	817.0	682.0			
	f30	848.0	804.0	667.0	790.0	742.0	612.0	98.0	97.0	100.0
	f60	789.0	735.0	605.0	737.0	684.0	561.0			
	st0	650.0	617.0	493.0	574.0	540.0	433.0			
	st30	564.0	529.0	420.0	511.0	473.0	378.0	95.0	94.0	97.0
	st60	511.0	472.0	373.0	470.0	430.0	341.0			
	v0	872.0	848.0	706.0	815.0	781.0	642.0			
	v30	802.0	765.0	623.0	747.0	704.0	571.0	98.0	97.0	98.0
	v60	743.0	697.0	563.0	693.0	645.0	519.0			

Table 6.11: Percentage Discomfort Hours per day for atrium type E. The coloured boxes represent acceptable values of dissatisfaction scores (≤250)

PE							
glass type	**avg clear**	**avg low-e**	**avg ref**	**roof type**	**flat**	**sawtooth**	**vault**
Avg	767.1	736.6	623.7	**Avg**	830.6	509.2	787.5
diff	30.5	112.8	143.4	**diff**	321.4	-278.3	43.1
diff %	4.0	15.3	18.7	**diff %**	38.7	35.3	5.2
glazing ratio	**0%**	**30%**	**60%**	**ventilation**	**5 ac/h**	**10 ac/h**	
Avg	764.8	704.1	658.6	**Avg**	739.0	679.2	
diff	60.7	45.5	106.2	**diff**	59.8		
diff %	7.9	6.5	13.9	**diff %**	8.1		
height	**3 floor**	**6 floors%**					
Avg	770.3	647.9					
diff	122.4						
diff %	15.9						

Table 6.12: Comparative results of Percentage Discomfort Hours per day for atrium type E

Yet, the predicted results for winter show the lowest dissatisfaction scores compared to the previous types. Nevertheless, there are small differences between the predicted dissatisfaction scores.

From the results calculated for summer, the most unpleasant thermal conditions are predicted for 3-floor height with 0% glazing ratio, flat roof with clear glazing and 5ac/h (ds=981). The more acceptable thermal conditions are predicted for the 6-floor height atrium building with 60% glazing ratio, saw-tooth roof with reflective glass and 10ac/h (ds=341).

The predicted reduction in the dissatisfaction score when incorporating a saw-tooth instead of a flat roof is 38.7%, whereas the difference between the flat roof and a vault shape roof is low (5.2%). Compared to the base case for clear glazing, the reflective glass can reduce heat gains and provide 18.7% more acceptable conditions whereas the low-e glass wouldn't be so effective. When increasing the glazing ratio from 0% to 60% there is a reduction of the dissatisfaction score by 13.9%. The change in atrium height has a positive contribution to occupants' comfort of 15.9%. Ventilation, as in the previous type, can be more effective in the linear atrium. The increase of ventilation rate from 5ac/h to 10ac/h can reduce the dissatisfaction score by 8.1%.

6.5 Conclusions

In this chapter, comfort and thermal conditions for an atrium building in a Mediterranean climate were predicted from a selection of glazing types, shading, fenestration orientation and geometry, and overall atrium size and shape. A parametric study was carried out and a large number of simulations were performed for the 22nd of December for winter and 22nd of June for the summer. The weather file used was that for Athens. The results of each design alternative were analysed, and tabulated summaries of the results for each atrium type were presented and discussed. It could be argued that the month and date selected for the iterations correspond to higher for winter and lower for summer ambient temperatures than expected. However, the purpose of the parametric study and indeed of the tabulated results was not to evaluate the actual values but to assess the general trends i.e. the measure of effect of each parameter to occupants' comfort/discomfort.

The results showed that daily external temperature fluctuations clearly have an influence on the predicted results; the atrium temperature follows the pattern of the ambient temperature, which is anticipated by a naturally ventilated building.

For winter, the results indicate that all of the atrium types have the potential of raising the atrium temperature close to comfort level. Atria with east orientation provide a much more acceptable environment in the morning hours but prove to be more challenging in terms of shading. The parametric analysis showed that there is none of the parameters had a prominent effect in occupants' comfort, as long as the atrium air temperature was kept in reasonable acceptable levels.

In summer the main concern is to prevent overheating. Even for the enclosed type of atrium, which has the smallest temperature fluctuations, the atrium temperatures can still be very high due to the large amount of solar radiation. However, as it was predicted, it is difficult to reduce air temperatures in the atrium below ambient temperature throughout the day; a combination of shading and ventilation can keep the temperature increment to within 1^0C or 2^0C above ambient during peak hours.

In general, the results indicate that more people are going to be dissatisfied in the atrium type B (open-sided with east orientation) with flat roof, low-e glass, 5 ac/h and with no glazing in the adjacent building overlooking the atrium space. This is due to the combination of east orientation, which builds up heat from the early morning hours, the flat roof that receives intense solar radiation and the low ventilation rate.

After the first stage analyses, it becomes clear that there are elements of the atrium design connected with local discomfort; 2D and 3D visual representations show variation in comfort in various spots and heights within an atrium. As the programme predicts there are issues of local discomfort; where there is direct solar direction this is expressed by the highest PPD even if the average air temperature inside the atrium does not vary significantly between different models.

The roof shape that proved to be more suitable for the atrium in a Mediterranean climate is the saw-tooth roof; it admitted useful solar radiation during winter and provided adequate shading during summer. Vault and flat roof could be used but with but have an increased amount of shading requirements

Acceptable thermal conditions were achieved during summer with the use of reflective glass; the results also indicated that there is no significant increase in comfort when replacing a clear double-glazing system with a low-e type of glazing. Additionally, what seemed to have a most noticeable impact on comfort is shading. In fact, as some of the results indicated, a flat roof with appropriate shading results in more acceptable conditions than the same type of atrium with a saw-tooth roof. Therefore, it has to be considered whether it is worth investing in an expensive shaped glazing system as well as in a shading device system? Or whether comfort can be achieved with a normal double-glazed clear glass and shading devices in order to avoid local discomfort and at the same time have adequate solar gains in winter?

The tabulated results show that the 5ac/h of ventilation is not adequate to remove warm air and reduce discomfort and, in some cases, the increase of ventilation from 5ac/h to 10ac/h can have a positive impact on comfort. There was also evidence of thermal stratification; the graphical representation of the results indicated acceptable conditions at occupant levels, but a lot higher temperature distribution at the upper levels of the atrium space.

Variations in the proportion of the glazing shared by the atrium and the adjacent building also have an influence in the heat transfer between them and the range of temperature fluctuations in the atrium space.

In general, the enclosed and the linear type of atria seem to be the most appropriate in the specific climatic context. This supports the notion that covered courtyard buildings and glazed streets and walkways are most effective climate modifiers.

Some irregularities of the temperature in the early morning hours attributed to the weather file used were detected but they don't affect the main results.

In the current study some critical questions regarding the atrium thermal comfort conditions in respect to geometry, ventilation, roof glazing material and ambient climate were answered. It was also established which strategies result in best comfort if no auxiliary heating and cooling is used. Additionally, in this chapter the concept of discomfort hours was used as a benchmark of acceptable indoor conditions. The research produced a table of optimum design-options in terms of comfort for atrium buildings in a Mediterranean climatic context. The acceptable design options are highlighted and are those that result in equal or less than 250 of discomfort hours.

A summary of the findings of the research and recommendations for the design of atrium buildings in Mediterranean climate are presented in the final chapter.

CHAPTER 7

RECOMMENDATIONS AND CONCLUSIONS

7.1 Research Summary

In principle, buildings are designed to optimise the thermal environment and achieve acceptable indoor thermal conditions. The current research focused on the atrium building type. Some of the reasons were the fact that they create an aesthetically interesting environment and they fill social and economic needs. Furthermore, the multiple functions of atria increase their appeal to building owners but make the design analysis more complex.

Atria were originally defined as open courtyards of buildings in the Mediterranean region. In their covered/glazed form they have only evolved since the last century and have generally been developed for temperate or cool climates where they attempt to create the environment to be found outside in typically warmer climates, i.e. the Mediterranean. Thus when such glazed spaces are used in warmer climates, potential for overheating occurs. Research and literature refers to atrium buildings' attributes and the potential energy contribution to their parent buildings, and covers a wide range of atrium design. Extensive research also exists on thermal comfort and occupants requirements for dwellings and offices. Some also cover aspects of thermal comfort in transient conditions, [Hensen, 1990], [Jitkhajornwanich, 2002] and [Nakano, 2002].

The current research is an attempt to cover the gap of knowledge regarding atrium building design, climate and occupant comfort. This has been done in an effort to optimise both the comfort and the thermal performance of the whole building, particularly when set in a warm climate.

Consequently it was considered important to investigate both the main features of the local climate as well as the occupants' thermal expectations. The main research methods used have been physical measurements of a case study building in a Mediterranean climate along with an occupant thermal comfort survey and, a parametric study, with the use of a dynamic thermal simulation programme. This enabled the investigation of the thermal conditions of various selected atrium types in relation to occupant comfort. The selected alternatives were building type, building proportion and orientation, glazing type, glazing ratio overlooking the wall separating the atrium from the parent building, shape of the roof, ventilation rate and the use of shading. Some of these parameters are determined early in the design stage, which means that proper analysis of the above will have a decisive impact on the atrium thermal conditions.

7.2 Main Findings

7.2.2 Findings from background research

From the analysis of the Mediterranean climate it was concluded that buildings in that region generally need heat in winter and cooling in summer. The use of the Bioclimatic Chart indicated a number of possible strategies in order to improve thermal conditions with passive means. Many researchers claim that an atrium can contribute to passive heating, can be useful in overall ventilation and cooling strategy, and always makes daylight more available to the spaces surrounding it. The atrium buildings visited in Greece are thermally heavy and were considered as a "climate modifier", shielding the indoor environment from the external climate. Most of them were used during the hottest part of the day, making cooling a very important concern.

7.2.3 Findings from the field studies

The results from the field study showed that the atrium space, even without any mechanical heating or cooling, had an overall good performance in relation to the ambient climate for both seasons. The mean interior temperature in the cool season (12 ^{0}C) fell short of the comfort temperature (14.96^{0}C) but the result was quite satisfactory compared to the mean outside temperature (6 ^{0}C). For the warm season, the mean interior temperature was 25 ^{0}C, very close to the comfort temperature (24.22 ^{0}C), whereas the mean outside temperature was 24.25 ^{0}C. During the warm season, the diurnal external temperature fluctuation was a lot higher than that inside the atrium and that even during the time of peak summer temperature, less than 20% of the occupants were dissatisfied. The measured data was also compared to the results predicted by the thermal and comfort analysis simulation programme. The predicted results showed very good agreement with those measured, providing a good validation method for the thermal simulation programme.

The thermal comfort survey established the neutral temperatures for winter and summer, as well as the comfort limits for 90% and 75% of thermal acceptance. These temperature limits were well below (for winter) and higher (for summer) than it would have been for a normal space (dwelling, office). Generally, the occupants of the atrium are likely to accept temperature fluctuations in the atrium building. There is evidence of adaptation of occupants to the conditions resulting inside the atrium. The results of the comfort survey also indicated that the subjective judgments were always affected by the preceding environmental conditions or reference level which seemed to be a very important and decisive factor in the subject's questionnaire. Additionally, it was concluded that expectation also plays a key role on how people experience comfort. In some cases, an expectation for lack of comfort leaded to a greater tolerance for temperature variation. Although little work has been done on thermal comfort in such environments, it was concluded that people expect environments differing from indoors, and the thermal comfort conditions may differ from that of indoor steady state. From the current study it can be reckoned that glazed spaces with no environmental control can be found acceptable but the expectations of the thermal environments to be found by building users introduces an additional complexity for the designer. The use of controls was also observed and recorded by the researcher.

The above are confirmed by other researchers in thermal adaptation in the built environment such as that of Baker [1996]: *"The different questioning of thermal comfort has challenged the notion of neutrality being optimal and the idea that adaptive exercise is a fundamental human need has been put forward"*, and Brager and de Dear [1998]: *"In naturally ventilated buildings, indoor temperatures more closely match the diurnal and seasonal variations in outdoor temperatures. People recognize this, relax their expectations or individual "comfort criteria" and not only become more tolerant of the more varied, dynamic and non-uniform conditions, but often prefer having a closer connection with weather and seasonal changes"*.

The overall conclusion is that less stringent thermal comfort requirements for atrium spaces should be considered. Especially during summer, where the ambient temperatures are very high and can create highly uncomfortable conditions, the atrium temperatures were within or very close to the comfort limits established from the comfort survey. It was therefore evident that there are weather conditions when the atrium's interior air temperature will be comfortable without the need for heating or cooling.

7.2.4 Findings from the parametric study

The parametric study yielded two main outcomes that formed the incentive for design recommendations, applicable by designers in future projects and also in the case of refurbished buildings.

Firstly, it established the significance of the effect of various factors in the thermal conditions and thermal comfort in the atrium space. The effect of parameters such as the geometry of the building, type of glazing, orientation, ventilation and sunshades affect thermal comfort in the atrium space, varies for different types of atria.

Secondly, the predictions show that with the selection of appropriate design parameters, acceptable comfort limits can be achieved in an atrium space situated in a warm climate, for both seasons. The simulated virtual atrium models showed that the internal air temperatures had the ability to rise within comfort limits in winter. It was also demonstrated that the temperatures during summer were slightly above comfort limits. That was anticipated for a naturally ventilated building with no additional cooling or heating. But at the same time this may have an effect to the overall building energy requirements by avoiding succeeding uncomfortable spaces.

The findings of the parametric study regarding each of the selected parameters and the conditions in the atrium during the occupancy hours are summarised in the following paragraphs.

7.2.4.1 Building type, proportion and orientation

The atrium type is determined often by its use. Therefore, it is concluded that what is of most importance is for the atrium solar heat gains to match the building's heat requirements and the occupancy usage patterns. The types of buildings simulated were all acting as buffers between the adjacent buildings and the ambient climate and they were, to a certain extent, successive climatic modifiers by achieving acceptable thermal conditions.

In general, the study shows that southern exposure of the fenestration system was beneficial from the daylighting point of view but increased heat gain. The atrium types with east orientation were found to have lower dissatisfaction scores during winter, especially during the early morning hours. They were more challenging however, in protection from extensive solar gains and heat build up in summer. In general, the enclosed and the linear type of atria seem to be the most appropriate in the specific climatic context.

The change of height and proportion was also predicted to have an effect in the internal conditions of each atrium type, mainly in summer. An air temperature drop of up to 4 ^{0}C occurs with the change of height in the open-sided atria for both the south and east orientations and the enclosed atria. For the linear types of atria the average drop of temperature is 2.8 ^{0}C due to the self-shading effect of the taller building.

7.2.4.2 Roof shape

The roof shape proved to be an important feature of the atrium design; that was evident in the variations of the dissatisfaction scores between the three different shapes of roof, particularly in the summer months.

The saw-tooth shaped roof proved to be more suitable for an atrium in a Mediterranean climate; it admitted useful solar radiation during winter and provided adequate shading during summer. Vault and flat roof could be used but receive intense solar radiation, especially during summer months and should have an increased amount of shading.

7.2.4.3 Glazing ratio facing the atrium space

Variations in the proportion of the glazing shared by the atrium and the adjacent building also have an influence in the heat transfer between them and the range of temperature fluctuations in the atrium space. It was predicted that during winter, these variations are very small and resulted in the atrium air temperatures increasing slightly. During summer, and by increasing the glazing ratio, the air temperatures in the atrium decrease slightly due to the heat transfer from the warmer atrium to the cooler adjacent spaces. This was also predicted to result in slightly smaller temperature fluctuations in the atrium.

The above results were more applicable to the courtyard type that shared the highest amount of surfaces with the adjacent buildings. From the analyses, it is difficult to determine an optimum glazing ratio considering that this is most of the times determined by other important factors such as lighting requirements.

7.2.4.4 Glazing Type

The predicted results indicate that the type of glazing influence the comfort conditions in the atrium space, particularly in summer. Three types of glazing were used in the simulation, clear double-glass, low-e and reflective. The general trend was that the results for the clear and low-e were quite similar and more acceptable conditions were obtained with reflective glass.

The open-side type has larger surfaces exposed to solar radiation; therefore even the use of a high performance glass (low-e and reflective) was offset by the large amount of solar gains. In this case, the combination of various types of glasses in the external atrium surfaces could result in more comfortable and acceptable conditions.

The results for atrium buildings with shading combined with low-e and reflective glass showed that the difference in internal conditions was low. The question therefore raised is whether it is cost effective to invest in an expensive glazing system as well as a shading device system? Or if comfort can be achieved with a normal double-glazed clear glass and a movable shading system, which will contribute, in less local discomfort and at the same time admit adequate solar gains in winter.

The results suggest that the use of low-e glazing, will not significantly improve (compared to the clear glazing) the internal conditions of atrium buildings with extensive glazing surfaces in a climate like the Mediterranean with large amounts of solar radiation.

7.2.4.5 Ventilation

The change of the selected ventilation rates from 5ac/h and 10ac/h do not have a major impact on comfort. Perhaps, higher ventilation rates will have a different result. Conventional wisdom suggests that the effect of cross ventilation during summer nights is an appropriate strategy of keeping the building unventilated during the hot daytime hours and cooling the high mass structure at night for lowering indoor air temperature. This is most effective in a climate like the Mediterranean that has large diurnal temperature variations. If ventilation is achieved through the atrium roof openings then, due to the high solar gains, results in high air temperatures. The above suggests careful placement of the openings: airflow must be induced from a lower opening to a higher one so that warm air can be removed.

Cross ventilation would be more effective if the incoming air was from the lower vents of the vertical south facing fenestration is pre-cooled. That could be achieved by placing external shading in the atrium south or east facade or even by evaporative cooling from water-features outside the building.

7.2.4.6 Shading

It was concluded that it is not easy to obtain a high degree of thermal comfort inside the atrium space merely by reducing the air temperature to 20 ^{0}C on a warm summer day. Solar radiation has a strong influence on the way the thermal environment will be perceived.

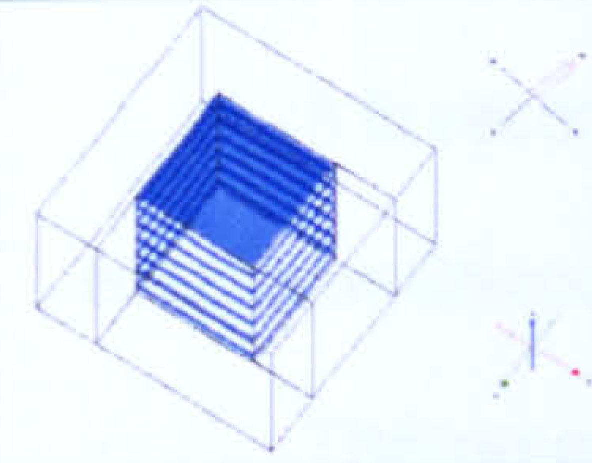
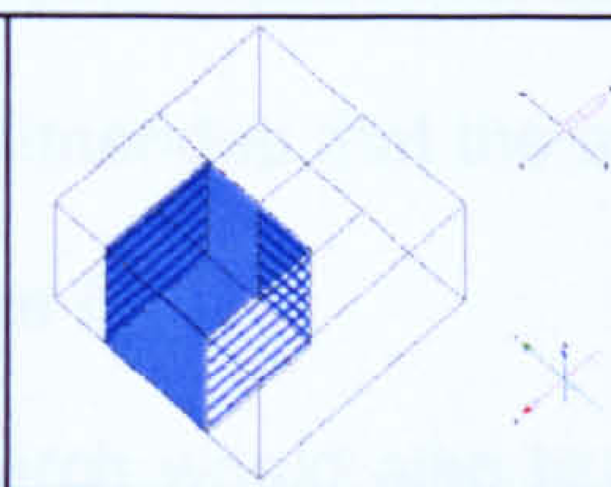
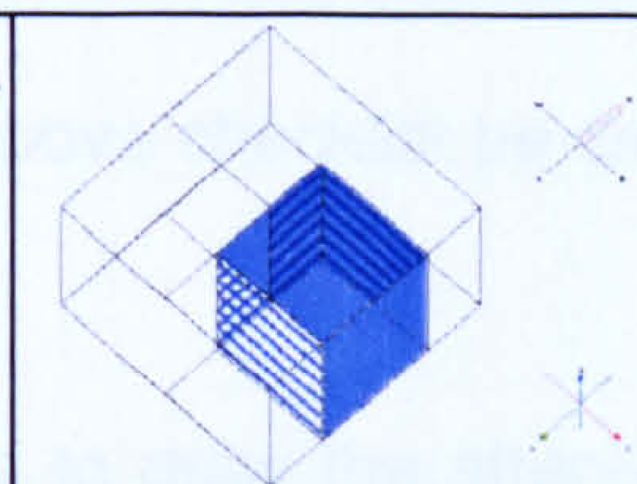
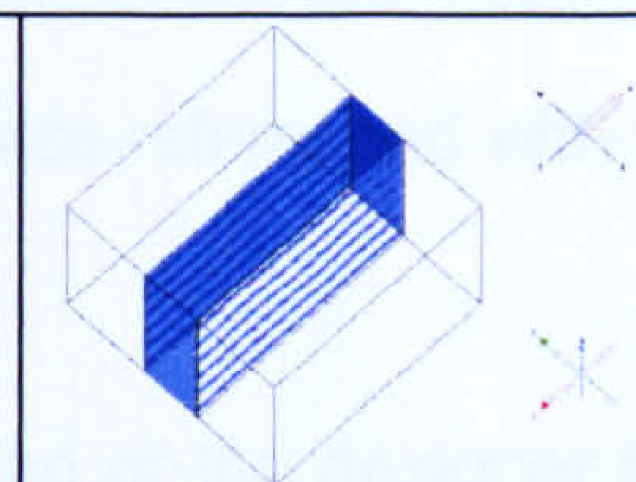
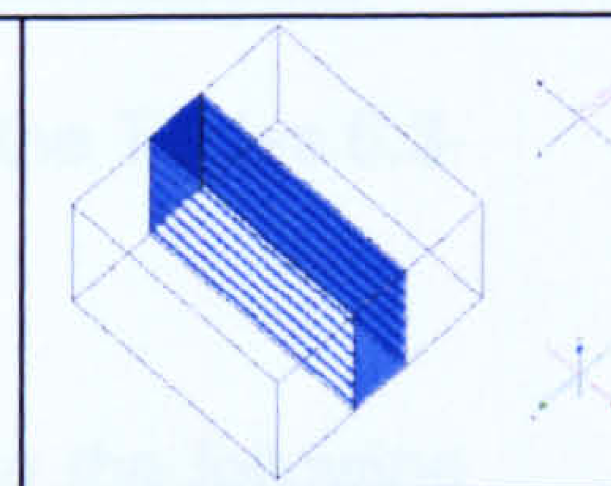
As the simulation programme predicted that there are issues of local discomfort; the spots in the atrium floor receiving direct solar direction corresponded to higher PPD even if the temperature inside the atrium is represented as unified. What has a noticeable impact on comfort is the shading. An example of an atrium with a flat roof with appropriate shading predicted to have more acceptable internal conditions than the one with a saw tooth roof. Therefore, shading is an effective way of reducing local discomfort. Appropriate shading devices that admit useful daylighting and protect from unwanted solar gains can have a noticeable impact on thermal conditions.

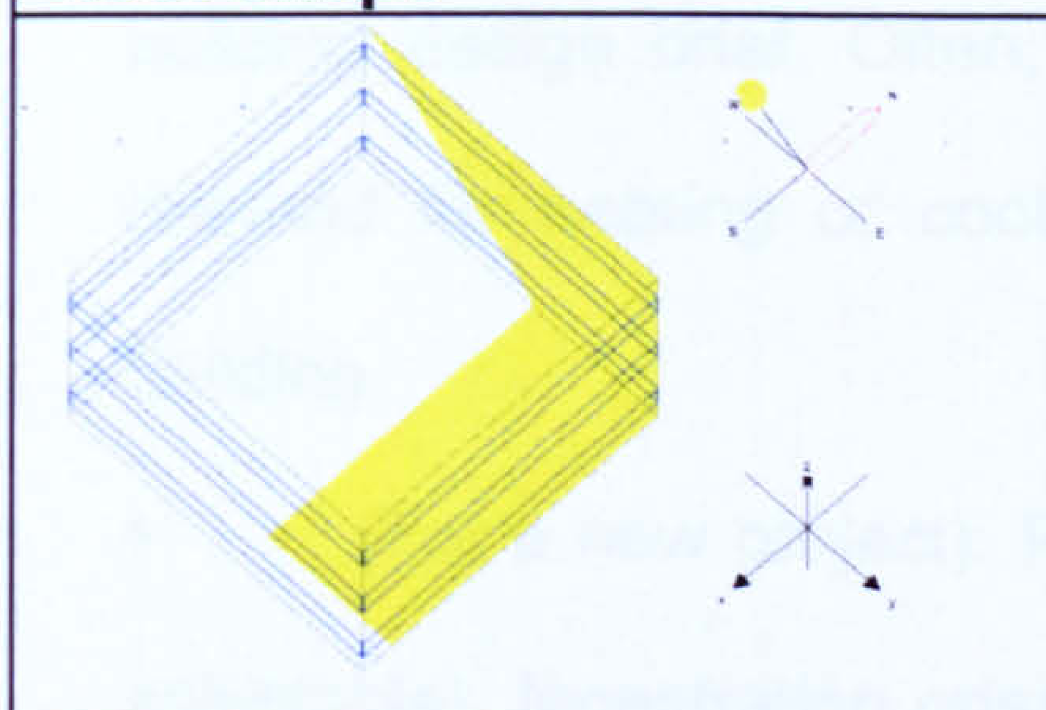
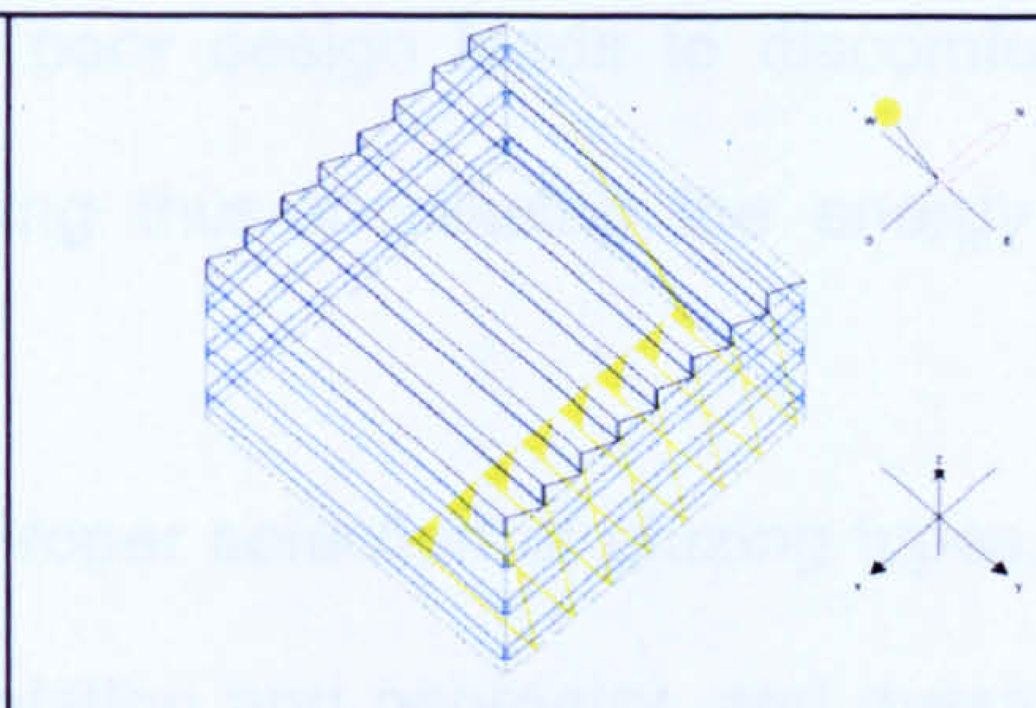
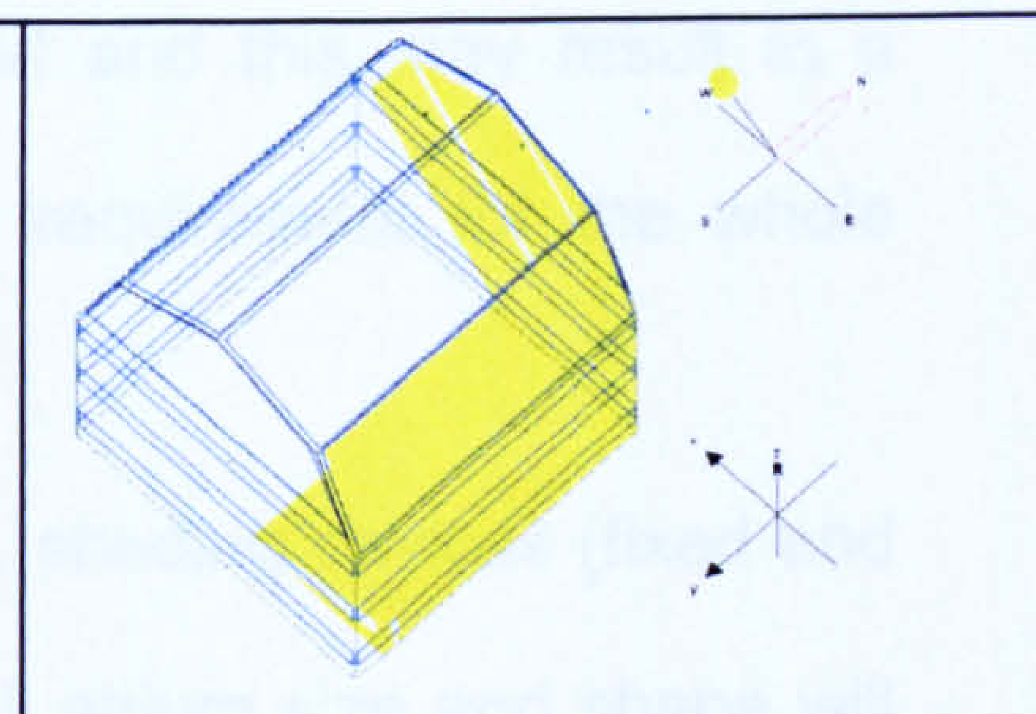
Moreover, if a roof with a clear glass that incorporates a shading system is satisfactory in terms of comfort and efficient in terms of thermal conditions, then the design should be considered successful. This will also have an effect on temperature stratification and reduce discomfort conditions in higher levels.

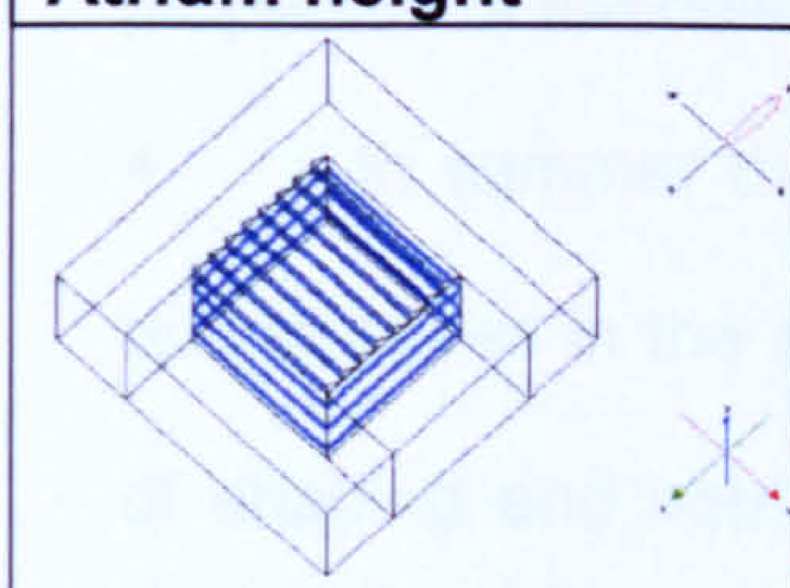
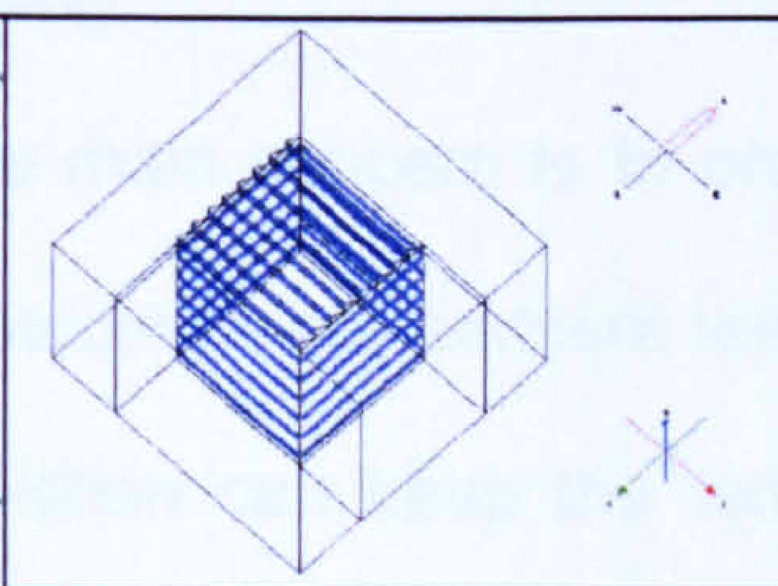
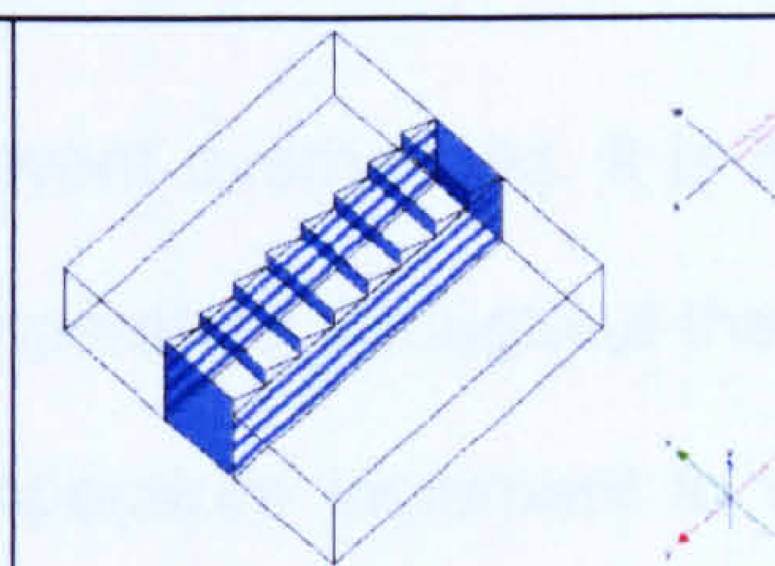
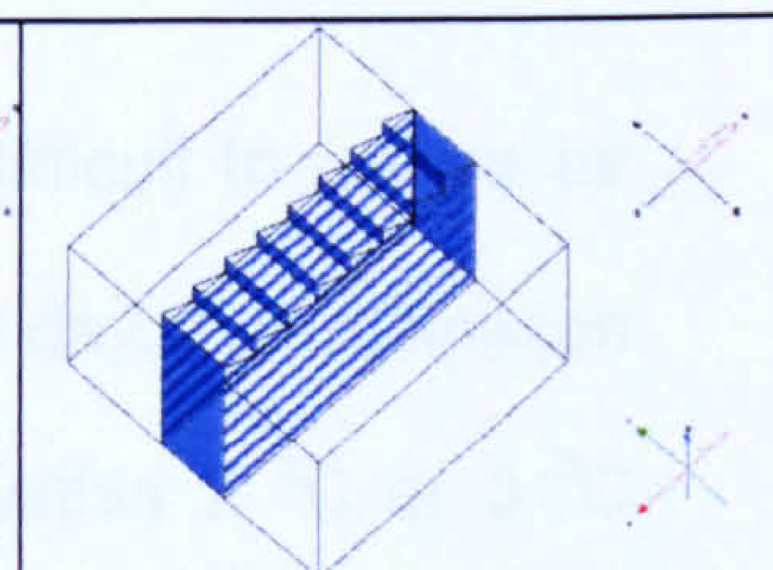
7.3 Atrium design recommendations

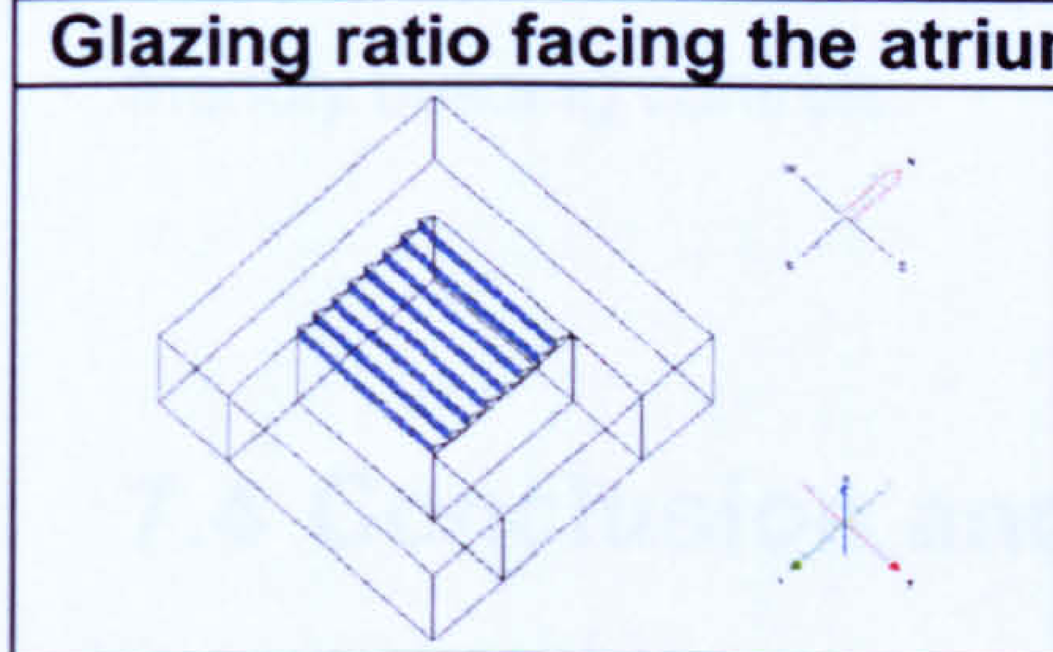
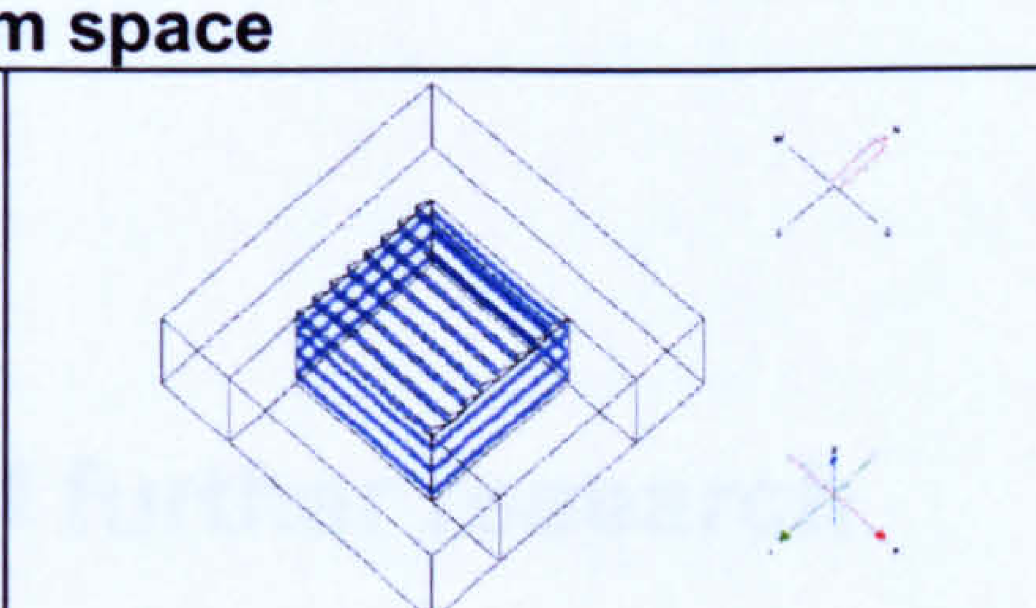
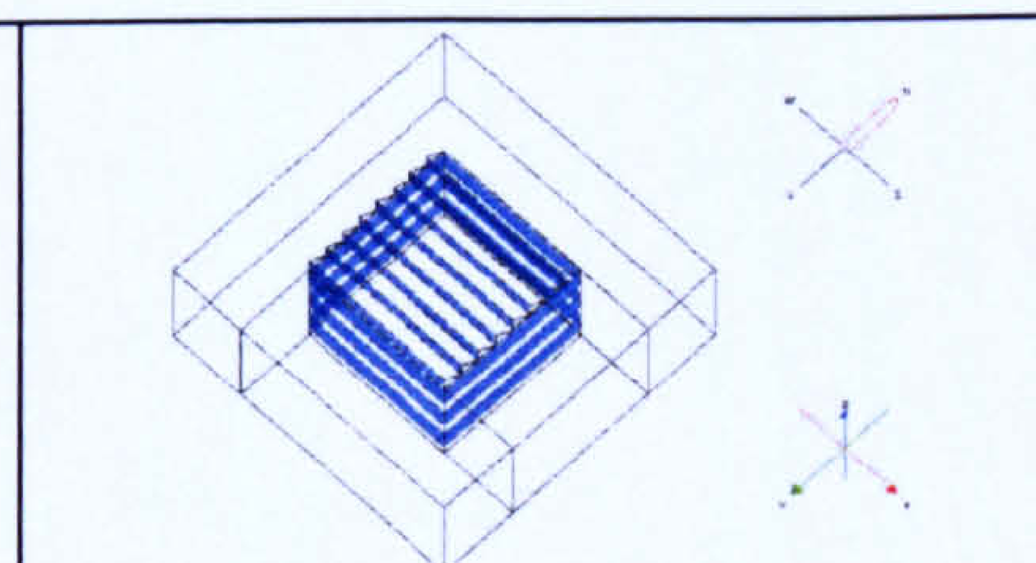
A number of observations from the results, outlines the complexity of the atrium internal environment and the implications in predicting thermal comfort. The following recommendations in Table 8.1 will concentrate on selected parameters and the practical ways of improving the design, applicable to naturally ventilated atrium buildings in a warm climate.

Atrium Design Checklist in a Mediterranean Climate

Atrium type and orientation				
				
√√√	√√	√	√√√	√
Select optimum type and orientation by matching solar heat gains with building's heat requirements. Enclosed (courtyard type) and linear (long-axis north/south) are recommended				

Roof shape		
		
X unless shaded	√√√	**X** unless shaded
Saw-tooth shape roof is recommended as it reduces the penetration of direct solar radiation Flat and vault roof should be avoided unless there is adequate shading		

Atrium height			
			
√√	√√√	√√	√√√
Taller atrium is preferred as it will be shaded by the adjacent building			

Glazing ratio facing the atrium space		
		
0%	30%	60%
Up to 60%. High thermal mass for the adjacent building surfaces is recommended		

Glazing type	Combination of Clear and Reflective Glass. Low-e should be considered
Ventilation	**Winter**: up to 5ac/h, **Summer**: from 10 ac/h up to acceptable limits Locate vents and openable windows to enhance cross-ventilation
Shading	External/internal shading devices on flat and vault roof, as well as on vertical atrium surfaces to avoid direct solar radiation falling onto the occupants

√= acceptable, √√= preferable, √√√= the optimum choice

It is recommended that the above checklist be cross-referenced with the Tables 6.3-6.12 from Chapter 6.

The research would also like to draw the attention of the designer to the following suggestions:

- The internal design condition of an atrium space is an essential component of any building design brief. Often, poor design leads to discomfort and this may result in a demand for heating or cooling thus increasing the energy requirement for the whole building.
- (For a new project): Proper selection of glazing types, shading devices (fixed and adjustable), fenestration orientation and geometry, and overall atrium size and shape will determine the energy costs and benefits for a specific building in a given climate zone.
- (For an existing project): Limit the extremes of thermal conditions by the inherited properties of the building
- In summer the main concern is to prevent overheating. It is difficult to reduce air temperatures in the atrium below ambient temperature throughout the day; a combination of shading and ventilation can keep the temperature increment to within 2 ^{0}C or 3 ^{0}C above ambient.
- Provide (where possible) adaptive opportunity by environmental variety and user-friendly building controls.

7.4 Conclusion and further research

7.4.5 Research contribution

Although in certain parts limited in scope, the research intended to contribute to the following:

- Successful integration of building design strategies, in relation to thermal comfort and climate.
- Extended the current knowledge on atrium performance in a warm hot climate and most importantly linked the case of the atrium thermal conditions with the actual preferences of the users.
- Produced a table of "dissatisfaction scores" to which designers can refer to as a checklist of the thermal conditions resulting due to the selection of certain parameters.

7.4.6 Limitations

The study is restricted in scope to the following:

- There was only one building selected for the field studies. As it was discussed in the relevant chapter, the case study chosen represents one of the generic types of atrium buildings.
- In the thermal comfort study only measurements of air temperature and relative humidity were taken due to restrictions of available equipment.
- The study is concentrated in Greece but the results can be generalised and applied for case studies in a similar climate.
- There is an obvious link between daylighting and atrium buildings; however, in the current study is not the prominent topic of discussion as it focuses on the thermal environment of the atrium building and the occupants' comfort. Atrium buildings and daylighting issues have been discussed and covered in detail in other researches.
- The results of the study apply only to natural ventilated buildings with no heating, cooling or air conditioning.

7.4.7 Directions for further research

The future research subsection is included so that researchers picking up this work in future have the benefit of the ideas that have been generated from this project. Some suggestions include the following:

- The further investigation of the thermal mass effect. The study indicated that the heat exchange between the atrium space and the parent building could influence the comfort levels of the occupants.
- The investigation of comfort in relation to ventilation strategies. Higher ventilation rates and variations in positions of openings may have different impact on comfort in different levels of the atrium space.
- Thermal comfort in the atrium in relation to clothing, and activity (metabolic rate). Because of its use, people may feel more relaxed in their activities and the choice or alterations in their clothing.
- Shading devices in relation to daylighting factor and visual comfort. The choice of shading is invariable and the indication of its link with local discomfort in the atrium suggests that it should be investigated further.
- Variety of glazing types for the atrium fenestration should be investigated. Most of the research carried out for atrium buildings are restricted in variations of a clear glass (single, double or triple clear glazing). The current research experimented with three different types of glass with different thermal characteristics. Further research in relation to new, high performance glazing for the atrium fenestration and even with synthetic and plastic products is encouraged.
- The majority of simulation tools available still predict discomfort indexes according to the ISO standards which refer to environmentally controlled spaces where most of the time the user is restricted in its clothing as well as the interfering with its environment. It is

suggested that further information should be incorporated in the available simulation tools in the form of "enclosed, environmentally-controlled space", "semi-open", "transient".

- An investigation into the application of the guidelines formed in atrium buildings incorporated in large urban blocks and the potential for passive solar retrofitting.

Finally, it is proposed that studies and research related to atria in the same climatic zone should be combined, with the aim of providing information that can be used by designers in both future projects and in cases of retrofitting buildings. This way, new design techniques can be adopted and used when considering atria schemes in order to optimise the energy efficiency of the whole building.

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APPENDIX A
Description of measurement equipment

HOBO RH Temp onset computer corporation

Temperature + RH Data logger

HOBO H8 SERIES

2 CHANNELS: TEMPERATURE + RH

Technical Characteristics	
Size	68 x 48 x 19mm
Weight	1oz (29 grms)
Temperature range	Internal Sensor -20°C to +70°C
Temperature range with sensor extended outside case	40°C to +120°C
Accuracy	± 0.7°C
Relative Humidity	25% to 95%
Accuracy	±3%
Capacity	7,943 measurements

APPENDIX B
Thermal Comfort Survey Questionnaire

The following Questionnaire is part of a research undertaken for the Degree of Doctor of Philosophy at the School of Architecture at the University of Sheffield, UK. Research Student: Elena D. Douvlou

Interview No: Date: Time:

1. Personal details

1.1 Age:

1.2 Gender ☐ Male ☐ Female

1.3 Weight: (Kgr) **Height:** (m)

1.4 Occupation

☐ Student ☐ Visitor

☐ Teaching Staff ☐ Other

1.5 Clothing at the time of interview

☐ Trousers ☐ Long sleeve shirt ☐ T-Shirt

☐ Dress ☐ Short sleeve shirt ☐ Vest

☐ Long Skirt ☐ Sweater ☐ Other accessories (please specify)

☐ Short Skirt ☐ Jacket

2. The Atrium Environment – Activities - Comfort

2.1 What kind of activity do you usually do in this part of the building?

☐ Sitting ☐ Passing by ☐ Other (please specify)

2.2 How long have you been here today?

☐ Less than 10min ☐ More than 20min

☐ Less than 20min ☐ More than an hour

2.3 How often do you come here?

☐ Once a day ☐ Once a week

☐ Few times a day ☐ Few times a week

2.4 What time do you usually come here?

08	09	10	11	12	13	14	15	16	17	18	19	20
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

2.5 Where were you immediately before coming here?

....

2.6 How did you expect to fell before coming into the atrium space?

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

2.7 How do you feel now?

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

2.8 how would you like to feel?

Cooler	No change	Warmer

2.9 What would you do to fell more comfortable?

☐ Remove clothes ☐ Change activity (if so, how)

☐ Wear on clothes ☐ Anything else

2.10 Does the sensation you fell now change in different parts of the atrium?

☐ No ☐ Yes (if so, which parts)

2.11 Do you feel there is a gradual or sudden change in environmental conditions between the surrounding buildings and the atrium?

Sudden	Gradual	Little/No change

2.12 Do you feel there is adequate light in the atrium space?

Too dark	OK	Too light

2.13 Do you experience difficulties with glare?

....

2.14 How do you feel in terms of humidity?

Dry	Just right	Humid

2.15 how do you feel in terms of airflow?

Still	Just right	Breezy

APPENDIX C
Thermal Comfort Survey Results

Thermal Comfort Survey Results- Winter

Dare	Time	Qcode	Weight	Height	BodyShape	Gender	Occupation	Ta (^{0}C)	RH(%)	VP (mb)	ev	sv	pv	rhv
12/22/99	21:35	77	78	185	2	M	Student	10.8	70	896.5	0	-1	1	1
12/23/99	21:30	100	56	165	1.6	F	Student	11	72	948.3	0	-1	1	1
12/21/99	21:25	53	68	157	1.6	F	Cleaner	13.8	70	1099	0	-1	0	1
12/23/99	21:05	99	52	162	1.5	F	Student	11	72	940.5	0	-1	1	1
12/22/99	21:00	76	73	171	1.8	M	Student	10.8	68	879.1	-1	-2	1	1
12/21/99	20:45	52	86	185	2	M	Student	14	69	1095	-2	-1	0	1
12/23/99	20:30	98	80	172	1.9	M	Porter	11.1	72	943.4	1	-1	1	1
12/22/99	20:25	75	69	170	1.7	M	Student	10.8	67	870.9	-1	-1	1	1
12/22/99	20:10	74	76	167	1.8	M	Teaching	10.9	68	881.7	0	-1	1	1
12/21/99	20:05	51	54	155	1.5	F	Student	14.1	70	1125	-1	0	0	1
12/23/99	20:00	97	71	160	1.7	F	Cleaner	11.4	72	969.2	0	-2	1	1
12/20/99	19:40	31	54	160	1.5	F	Teaching	12.7	68	1004	0	-1	1	1
12/23/99	19:40	96	75	162	1.7	F	Cleaner	11.4	72	970	-1	-1	1	1
12/21/99	19:35	50	76	169	1.8	M	Student	14	70	1119	-1	-2	1	1
12/22/99	19:30	73	61	165	1.6	F	Teaching	11	38	497.1	0	-1	1	0
12/20/99	19:10	30	76	160	1.7	M	Student	12.5	68	987.2	-1	-2	1	1
12/23/99	19:10	95	53	161	1.5	F	Student	11.2	73	972.3	0	-1	1	1
12/21/99	19:08	49	73	172	1.8	M	Cantine	13.9	71	1134	0	-1	1	0
12/22/99	19:00	72	55	160	1.5	F	Student	11.9	43	593.1	0	-1	1	0
12/21/99	18:50	48	69	168	1.7	F	Visitor	13.8	70	1107	-1	-1	0	1
12/23/99	18:45	94	82	177	1.9	M	Staff(me	11.2	73	973.6	-1	-1	1	1
12/20/99	18:40	29	72	164	1.7	F	Student	12.3	67	948.3	-1	-2	0	1
12/21/99	18:15	47	68	156	1.6	F	Cleaner	13.8	71	1127	-1	-1	0	1
12/20/99	18:10	28	70	178	1.8	M	Student	12.7	67	979.5	-3	-1	1	0
12/22/99	18:10	71	56	174	1.6	F	Student	11.9	42	587.4	0	-1	1	0
12/23/99	18:10	93	79	170	1.9	M	Staff(me	11	74	966.7	1	-2	1	1
12/23/99	17:55	92	54	160	1.5	F	Student	11	74	966.7	-1	-2	0	1
12/20/99	17:35	27	69	163	1.7	F	Part Tim	13.3	70	1063	-1	-1	0	1
12/22/99	17:25	70	79	170	1.9	M	Visitor	12	43	593.3	0	-1	1	0
12/23/99	17:25	91	53	158	1.5	F	Student	11	74	971.9	0	-1	1	1
12/20/99	17:15	26	57	168	1.6	F	Student	13.7	70	1100	-2	-1	1	1
12/20/99	17:05	25	69	171	1.8	M	Student	13.9	72	1132	-2	-1	0	1
12/21/99	17:00	46	54	167	1.5	F	Student	13.6	70	1090	1	1	-1	0
12/22/99	16:55	69	59	163	1.6	F	Visitor	12	41	570.8	0	-1	1	1
12/23/99	16:50	90	76	167	1.8	M	Student	11	74	971.9	-1	-1	0	1
12/20/99	16:20	24	70	163	1.7	F	Visitor	14.6	74	1220	-1	0	1	1
12/21/99	16:15	45	83	183	2	M	Teaching	13.8	73	1142	0	0	1	1
12/22/99	16:10	68	79	177	1.9	M	Student	12.8	42	613.6	0	-1	1	0
12/23/99	16:05	89	81	186	2	M	Student	11.2	74	979	0	-1	1	1
12/22/99	16:00	67	82	182	2	M	Student	12.9	43	638.4	0	0	0	0
12/20/99	16:00	23	71	162	1.7	F	Visitor	14.6	73	1214	-2	0	1	1
12/21/99	16:00	44	70	170	1.8	M	Student	13.8	72	1139	1	-1	1	1
12/23/99	15:20	88	56	159	1.5	F	Visitor	11.2	73	972.3	1	-1	0	1
12/20/99	15:10	22	85	185	2	M	Student	14.7	73	1212	-1	-1	0	1
12/21/99	15:10	43	84	174	1.9	M	Libraria	14.1	72	1161	-1	-1	1	1
12/22/99	15:00	66	64	165	1.7	F	Student	14.2	41	657.1	0	0	0	0
12/22/99	14:45	65	59	167	1.6	F	Visitor	14.7	41	686.4	1	0	0	1
12/23/99	14:45	87	80	173	1.9	M	Visitor	11.3	72	965.4	-1	-1	0	1
12/20/99	14:30	21	86	184	2	M	Visitor	14.8	72	1206	0	0	0	1

12/21/99	14:25	42	78	167	1.8	F	Secretar	14.3	70	1141	-2	-1	1	1
12/20/99	14:00	20	76	178	1.9	M	Student	14.7	70	1166	1	-1	1	1
12/22/99	14:00	64	58	166	1.6	F	Student	14.9	44	742.8	-1	-1	0	1
12/23/99	14:00	86	79	185	2	M	Gardener	11.4	72	966.5	0	-1	1	1
12/21/99	13:50	41	72	174	1.8	M	Cantine	14.4	70	1145	-2	0	0	0
12/20/99	13:40	19	60	165	1.6	F	Visitor	14.8	68	1146	1	0	1	1
12/22/99	13:40	63	78	181	1.9	M	Student	14.6	41	686.4	0	1	0	0
12/20/99	13:30	18	65	163	1.6	F	Student	14.9	67	1144	-1	1	1	1
12/20/99	13:15	17	70	163	1.7	F	Visitor	15.3	66	1140	0	-1	1	1
12/23/99	13:15	85	75	160	1.7	F	Cleaner	11.3	71	942.7	-1	-1	0	1
12/20/99	13:10	16	73	183	1.9	M	Student	15.3	66	1140	0	1	1	1
12/20/99	13:05	15	95	185	2.1	M	Visitor	15.5	64	1134	-1	1	0	0
12/20/99	13:00	13	70	178	1.8	M	Student	15.5	64	1134	1	1	1	0
12/20/99	13:00	14	49	165	1.5	F	Student	15.5	64	1134	-1	1	1	1
12/21/99	13:00	40	79	181	1.9	M	Teaching	14.4	71	1165	-1	0	1	1
12/22/99	13:00	62	60	160	1.6	F	Student	14.5	41	675.4	-1	-1	-1	0
12/23/99	13:00	84	68	176	1.8	M	Student	11.4	68	912.7	0	-1	0	1
12/21/99	12:50	39	70	163	1.7	F	Visitor	14.2	72	1171	-2	-1	1	1
12/22/99	12:30	61	45	157	1.4	F	PostGrad	14.2	38	614.7	0	0	0	0
12/23/99	12:30	83	70	164	1.7	F	Student	11.2	69	913.9	0	-1	1	0
12/20/99	12:20	12	89	176	2	M	Student	16.3	59	1092	-2	1	1	1
12/20/99	12:10	11	53	162	1.5	F	Student	16.5	59	1101	-2	1	1	1
12/22/99	12:05	60	68	160	1.7	F	Part Tim	13.1	50	755.8	-1	0	0	1
12/23/99	12:05	82	71	171	1.8	M	Student	11	70	916.9	1	-2	0	1
12/20/99	12:00	10	52	160	1.5	F	PostGrad	16.6	58	1100	1	1	1	0
12/20/99	11:50	9	72	178	1.8	M	PostGrad	16.2	58	1073	1	-1	1	1
12/21/99	11:45	38	67	171	1.7	F	Student	14.2	73	1177	1	0	0	0
12/21/99	11:40	37	70	166	1.7	F	Teaching	14.2	73	1177	-1	-1	1	1
12/20/99	11:30	7	89	181	2	M	Student	15.8	58	1037	-1	0	0	1
12/20/99	11:30	8	59	162	1.6	F	Teaching	15.8	58	1038	-2	1	1	1
12/21/99	11:30	36	65	165	1.7	F	Student	14.2	73	1179	0	0	0	0
12/22/99	11:30	59	56	165	1.6	F	Teaching	12.7	51	751.9	0	-1	1	1
12/21/99	11:25	35	74	158	1.7	F	Secretar	14.1	73	1174	-2	0	1	1
12/23/99	11:25	81	76	164	1.8	M	Visitor	10.7	68	876.2	0	-1	0	1
12/20/99	11:00	6	82	170	1.9	M	Teaching	15.5	58	1015	-1	-1	0	1
12/22/99	11:00	58	72	161	1.7	F	Secretar	12.7	55	802.4	-1	-1	1	1
12/23/99	11:00	80	65	163	1.6	F	Teaching	10.6	69	875.5	1	-1	1	1
12/20/99	10:55	5	64	163	1.6	F	Teaching	15.2	57	990.5	-2	1	1	1
12/21/99	10:50	34	70	163	1.7	F	Visitor	13.7	75	1165	0	0	0	1
12/20/99	10:40	4	52	161	1.5	F	Teaching	15.1	57	980.7	-3	1	1	1
12/20/99	10:30	2	55	157	1.5	F	Student	15	57	962.5	0	-1	1	1
12/20/99	10:30	3	76	160	1.7	F	Secretar	15	57	969.3	-2	1	0	1
12/20/99	10:20	1	59	165	1.6	F	Student	14.8	57	953.5	-1	0	0	1
12/22/99	10:20	57	74	179	1.9	M	Student	12.6	59	854.5	-1	-1	1	1
12/23/99	10:20	79	78	166	1.8	M	Teaching	10.5	67	851.9	-1	-1	1	1
12/21/99	10:20	33	80	158	1.8	M	Gardener	13.4	73	1122	1	0	0	1
12/21/99	10:00	54	54	161	1.5	F	Student	13.7	69	1080	-2	-1	1	1
12/22/99	10:00	56	52	169	1.5	F	Student	12	61	853.3	0	-1	1	1
12/23/99	10:00	78	69	160	1.7	F	Secretar	10.2	67	838	0	-1	1	1
12/21/99	9:40	32	75	170	1.8	M	Student	13	74	1100	0	0	0	-1
12/22/99	9:30	55	75	158	1.7	F	Cleaner	11.2	62	820	0	0	1	1

Thermal Comfort Survey Results- Summer

Date	Time	Qcode	Weight	Height	BodyShape	Gender	Occupation	Ta (^{0}C)	RH(%)	VP (mb)	ev	sv	pv	rhv
23.06.2000	17:00	90	54	1.64	0.0559	F	Student	27.91	38	1429	-1	2	-1	0
27.06.2000	17:00	189	61	1.72	0.06094	M	Student	22.09	36.2	961.9	0	0	0	-1
21.06.2000	17:00	39	75	1.85	0.07014	M	PhD Candidate	26.34	41.3	1416	3	3	-1	0
26.06.2000	17:05	162	71	1.76	0.06609	M	Student	27.91	41.3	1553	-1	1	-1	0
20.06.2000	17:10	10	79	1.73	0.0683	M	Technician	25.95	35.5	1189	-2	1	0	0
26.06.2000	17:15	163	75	1.85	0.07014	M	Secretary	27.91	39.6	1489	3	3	-1	0
27.06.2000	17:20	190	55	1.56	0.05433	F	Secretary	22.09	36.4	967.2	0	2	-1	0
25.06.2000	17:25	137	61	1.72	0.06094	F	Teaching Staff	28.7	31.5	1240	-2	0	-1	1
24.06.2000	17:25	119	84	1.8	0.07215	M	Visitor	28.7	32.3	1271	-2	1	-1	0
22.06.2000	17:25	65	75	1.8	0.06876	M	Technician	27.52	33.6	1235	1	0	0	0
21.06.2000	17:30	40	80	1.82	0.07124	M	Visitor	26.34	40.7	1396	-2	0	-1	1
20.06.2000	17:30	11	68	1.79	0.06569	M	Technician	25.56	36.3	1188	-1	0	-1	0
26.06.2000	17:35	164	68	1.55	0.05918	F	Teaching Staff	27.91	38.5	1447	3	3	0	0
23.06.2000	17:55	91	68	1.63	0.06138	F	Teaching Staff	28.31	38.4	1478	-1	1	-1	0
25.06.2000	17:55	138	82	1.74	0.06968	M	Visitor	28.7	31.3	1232	1	2	-1	-1
20.06.2000	18:00	12	70	1.6	0.06131	F	Cleaner	25.56	38.1	1247	0	0	0	0
22.06.2000	18:10	66	55	1.64	0.05633	F	Visitor	27.52	38	1396	-1	0	-1	1
25.06.2000	18:10	139	67	0.6	0.02955	F	Cleaner	28.31	29.7	1143	0	1	-1	0
26.06.2000	18:10	165	78	1.76	0.06878	M	Student	27.52	39	1433	-1	2	-1	1
24.06.2000	18:10	120	74	1.78	0.06782	M	Student	28.7	32.9	1295	0	0	0	1
23.06.2000	18:10	92	81	1.76	0.0699	M	Student	28.31	38.2	1470	2	2	-1	1
27.06.2000	18:15	191	64	1.64	0.06008	F	Secretary	25.95	39	1307	-1	2	-1	1
20.06.2000	18:25	13	51	1.6	0.05359	F	Cleaner	25.56	38	1244	0	0	0	0
26.06.2000	18:30	166	52	1.6	0.05403	F	Student	27.52	36	1323	-2	1	-1	-1
21.06.2000	18:40	41	57	1.63	0.05694	F	Student	25.95	41.6	1394	0	1	-1	0
25.06.2000	18:45	140	60	1.7	0.06	F	Student	28.31	28.7	1104	-2	0	0	0
20.06.2000	18:45	14	65	1.7	0.06207	F	PhD Candidate	25.17	39.2	1254	-1	0	-1	0
23.06.2000	18:45	93	85	1.92	0.07599	M	Student	27.91	38.6	1451	-1	0	-1	1
26.06.2000	18:45	167	80	1.88	0.07293	M	Student	27.52	37.2	1367	1	2	-1	1
27.06.2000	18:50	192	82	1.81	0.0717	M	Student	24.01	36.4	1086	-1	0	-1	1
24.06.2000	19:00	121	68	1.77	0.06516	F	Student	28.31	32	1231	-1	1	-1	1
22.06.2000	19:00	67	51	1.72	0.05624	F	Visitor	27.12	37.6	1350	3	0	1	1
26.06.2000	19:05	168	62	1.67	0.06006	M	Student	27.12	38.8	1393	-1	1	-1	-1
23.06.2000	19:10	94	62	1.69	0.06058	F	Student	27.52	39.4	1448	-2	1	0	0
25.06.2000	19:10	141	65	1.7	0.06207	F	Student	27.91	29.3	1102	-1	0	0	0
21.06.2000	19:10	42	55	1.6	0.05533	F	Student	25.56	41.4	1355	0	0	0	0
20.06.2000	19:10	15	71	1.68	0.0639	M	Teaching Staff	24.79	41	1282	-1	1	-1	0
26.06.2000	19:15	169	49	1.64	0.05363	F	Student	27.12	40.2	1443	0	1	-1	0
27.06.2000	19:15	193	50	1.73	0.05623	F	Visitor	22.86	35.6	991.3	3	0	1	1
24.06.2000	19:30	122	59	1.75	0.06084	F	PostGraduate	27.91	33.9	1274	0	1	-1	1
22.06.2000	19:30	68	65	1.83	0.06548	M	PhD Candidate	26.73	38	1333	-2	1	-1	0
26.06.2000	19:30	170	70	1.76	0.06569	M	Student	26.73	40.6	1424	1	0	0	0
20.06.2000	19:35	16	60	1.62	0.05794	F	Teaching Staff	24.79	41.4	1295	-1	1	-1	0
21.06.2000	19:35	43	55	1.65	0.05658	F	Student	25.56	42.8	1401	0	0	0	0
27.06.2000	19:35	194	70	1.77	0.06596	M	Student	21.33	35.2	892.9	-1	-1	-1	0
25.06.2000	19:40	142	55	1.68	0.05733	F	Student	27.91	31.3	1177	-2	0	-1	0
23.06.2000	19:40	95	56	1.68	0.05777	F	Student	27.52	40.7	1496	-1	0	-1	0
25.06.2000	20:00	143	63	1.7	0.06126	F	Student	27.52	31.4	1154	-2	1	0	0
26.06.2000	20:00	171	61	1.6	0.05782	F	Researcher	26.34	45.6	1564	-2	1	-1	0
23.06.2000	20:00	96	55	1.64	0.05633	F	Student	27.12	40.4	1450	-1	0	-1	0
20.06.2000	20:00	17	100	1.92	0.08142	M	Student	24.4	43	1314	-1	-1	0	0

21.06.2000	20:05	44	72	1.69	0.06456	M	Student	25.17	42.1	1347	1	0	0	0
22.06.2000	20:10	69	62	1.7	0.06084	F	Student	26.34	38.1	1306	-2	0	0	0
24.06.2000	20:10	123	87	1.93	0.07703	M	PostGraduate	27.52	33.3	1224	0	0	0	1
27.06.2000	20:10	195	73	1.8	0.06797	M	Student	19.81	34.8	803.7	0	0	0	0
20.06.2000	20:20	18	56	1.63	0.05652	F	Student	24.01	44.8	1337	0	0	0	0
26.06.2000	20:20	172	57	1.63	0.05694	F	Student	25.56	48.1	1575	0	0	0	1
22.06.2000	20:25	70	89	1.79	0.07365	M	Staff	26.34	38.1	1306	-2	2	0	1
23.06.2000	20:30	97	63	1.72	0.06178	F	Student	27.12	42	1508	-1	0	0	0
25.06.2000	20:30	144	75	1.7	0.06597	M	Porter	27.12	30.3	1088	0	0	0	0
21.06.2000	20:45	45	49	1.58	0.0522	F	Student	24.79	44.5	1392	0	0	0	0
27.06.2000	20:45	196	76	1.77	0.06831	M	Student	19.04	34.8	766.1	0	0	0	0
22.06.2000	21:00	71	63	1.63	0.05942	F	Researcher	26.34	40.3	1382	-2	1	-1	0
23.06.2000	21:00	98	52	1.67	0.05573	F	PhD Candidate	26.73	43.4	1523	-2	0	-1	0
20.06.2000	21:00	19	87	1.75	0.07175	M	Visitor	23.24	48.3	1376	-2	0	-1	0
23.06.2000	21:10	99	55	1.66	0.05683	F	Student	26.73	44.4	1558	-2	0	-1	1
20.06.2000	21:15	20	76	1.76	0.06803	M	Student	23.24	48.7	1388	0	0	0	1
23.06.2000	21:25	100	58	1.64	0.05762	F	Student	26.34	43.4	1488	-1	-1	0	0
21.06.2000	21:25	46	62	1.62	0.05875	F	PostGraduate	24.4	47.5	1451	0	0	0	1
27.06.2000	21:25	197	80	1.86	0.07237	M	Student	24.4	38.3	1170	0	0	0	0
22.06.2000	21:35	72	63	1.7	0.06126	M	Student	25.95	39.5	1324	-1	1	-1	-1
20.06.2000	21:40	21	74	1.77	0.06754	F	Student	22.48	51.1	1390	-1	0	0	1
27.06.2000	22:00	198	74	1.63	0.06362	F	Researcher	26.34	37.1	1272	-1	1	-1	0
21.06.2000	22:00	47	80	1.83	0.07152	M	PostGraduate	24.01	48.5	1448	0	0	0	0
22.06.2000	22:10	73	53	1.62	0.05496	F	Student	25.17	43.2	1382	-2	1	-1	-1
23.06.2000	22:10	102	54	1.67	0.05664	F	PhD Candidate	25.95	41.7	1397	-2	1	-1	0
27.06.2000	22:10	199	53	1.68	0.05643	F	Student	26.73	37	1298	-2	-1	-1	0
20.06.2000	22:10	22	59	1.75	0.06084	F	Student	22.48	52.6	1431	0	0	0	1
22.06.2000	22:25	74	67	1.58	0.05963	F	Teaching Staff	25.17	43.7	1398	1	1	-1	0
23.06.2000	22:35	103	53	1.65	0.0557	F	Student	25.56	41.1	1346	-1	0	-1	0
20.06.2000	22:35	23	87	1.93	0.07703	M	PhD Candidate	22.48	52.7	1434	0	0	0	1
21.06.2000	22:35	48	86	1.9	0.07579	M	PostGraduate	23.63	49.9	1456	0	0	0	1
27.06.2000	22:40	200	60	1.62	0.05794	M	Student	27.12	37.1	1332	-1	2	-1	0
22.06.2000	22:45	75	58	1.61	0.05685	F	Teaching Staff	24.79	44.5	1392	-1	0	-1	0
21.06.2000	22:55	49	91	1.94	0.07881	M	PostGraduate	23.63	50.6	1476	0	0	0	1
23.06.2000	23:00	104	82	1.93	0.07512	M	Student	25.56	35.4	1159	-1	-1	-1	1
20.06.2000	23:00	24	79	1.72	0.06801	M	Porter	22.48	52.9	1439	0	0	-1	0
22.06.2000	23:10	76	91	1.81	0.07495	M	Technician	24.79	47.6	1489	2	-1	-1	0
27.06.2000	09:30	174	76	1.82	0.0697	M	Technician	26.73	45.6	1600	1	0	0	0
23.06.2000	09:40	25	67	1.65	0.06153	F	Student	24.01	52.2	1558	-2	-1	-1	0
21.06.2000	10:00	51	70	1.7	0.06406	F	Cleaner	24.79	48	1501	0	1	-1	0
27.06.2000	10:00	77	70	1.64	0.06241	F	Student	25.56	50.3	1647	0	1	0	1
20.06.2000	10:00	105	59	1.72	0.06008	F	Student	25.95	45.5	1525	1	1	-1	1
22.06.2000	10:00	124	53	1.67	0.05619	F	Student	26.34	40.7	1396	1	1	-1	-1
22.06.2000	10:20	78	63	1.71	0.06152	F	Teaching Staff	25.95	48.1	1612	-2	1	-1	1
23.06.2000	10:20	175	68	1.63	0.06138	F	Teaching Staff	25.95	49.1	1645	-2	2	-1	0
24.06.2000	10:20	125	68	1.65	0.06192	F	Student	26.34	40.9	1402	0	1	0	1
23.06.2000	10:20	145	68	1.66	0.06219	F	Student	25.95	46	1541	0	1	0	1
27.06.2000	10:20	106	83	1.8	0.07178	M	Student	26.34	43.8	1502	-1	1	-1	0
25.06.2000	10:20	26	80	1.85	0.07209	M	Student	23.63	54.6	1593	1	2	-1	1
25.06.2000	10:30	52	70	1.63	0.06214	F	Teaching Staff	24.79	48.9	1529	-2	2	-1	-1
24.06.2000	10:50	27	77	1.7	0.06671	M	Teaching Staff	24.01	52.7	1573	-1	0	0	1
21.06.2000	10:55	53	54	1.7	0.05737	F	Student	25.17	48.7	1558	-1	1	-1	0
22.06.2000	10:55	107	55	1.67	0.05708	F	Student	26.34	42.2	1447	1	1	-1	-1

21.06.2000	11:00	79	61	1.7	0.06042	F	Teaching Staff	26.34	48.3	1656	-2	1	-1	1
22.06.2000	11:00	126	60	1.65	0.05871	F	Teaching Staff	26.73	42.4	1488	-2	1	-1	0
24.06.2000	11:00	146	64	1.72	0.06167	F	Teaching Staff	26.34	47.2	1618	-2	1	-1	1
21.06.2000	09:00	173	88	1.73	0.07151	M	Staff	25.17	49.5	1584	-2	0	0	1
23.06.2000	11:10	176	45	1.62	0.05127	F	Cafetiria Staf	26.34	47.8	1639	-2	2	-1	0
25.06.2000	11:15	147	71	1.67	0.06362	F	Visitor	26.73	48.3	1695	1	1	-1	1
26.06.2000	11:25	28	60	1.63	0.0582	F	Teaching Staff	24.4	52.3	1598	-1	1	-1	1
27.06.2000	11:25	127	84	1.81	0.07244	M	Student	27.12	41.5	1490	-1	1	-1	0
26.06.2000	11:25	80	84	1.69	0.06893	M	Visitor	26.73	48.2	1691	1	2	-1	-1
21.06.2000	11:30	148	55	1.6	0.05533	F	Staff	26.73	46.8	1642	-2	3	-1	1
25.06.2000	11:30	108	87	1.77	0.07235	M	Student	27.12	42.4	1522	0	1	-1	1
23.06.2000	11:30	54	69	1.75	0.06502	M	Student	25.56	48	1572	1	0	-1	0
26.06.2000	11:30	177	74	1.68	0.06503	M	Visitor	26.34	48.9	1677	1	0	0	0
24.06.2000	11:40	149	46	1.58	0.05082	F	Student	27.12	45.2	1623	0	1	-1	1
22.06.2000	11:40	178	48	1.61	0.05246	F	Visitor	26.73	43.4	1523	0	0	0	0
27.06.2000	11:45	179	71	1.68	0.0639	M	Teaching Staff	26.73	43.4	1523	-1	1	-1	0
26.06.2000	11:50	29	65	1.7	0.06207	F	Student	25.17	47.5	1520	-1	1	-1	1
27.06.2000	12:00	55	69	1.63	0.06176	F	Visitor	25.95	48.7	1632	1	1	-1	0
27.06.2000	12:04	31	56	1.68	0.05777	F	Student	25.56	43.4	1421	1	1	-1	0
21.06.2000	12:05	109	65	1.7	0.06207	F	Secretary	27.52	41.9	1540	-2	0	-1	1
22.06.2000	12:05	128	54	1.65	0.05614	F	Visitor	27.91	36.4	1368	-1	0	-1	1
24.06.2000	12:10	81	55	1.6	0.05533	F	Staff	27.12	47	1687	-2	3	-1	1
25.06.2000	12:10	150	65	1.68	0.06154	F	Teaching Staff	27.52	45.3	1665	1	0	-1	1
23.06.2000	12:20	151	72	1.62	0.06261	F	Visitor	27.52	45.3	1665	2	2	-1	1
26.06.2000	12:20	30	70	1.75	0.06542	M	Student	25.56	46.9	1536	-1	1	-1	0
26.06.2000	12:20	180	64	1.68	0.06114	M	Student	27.52	44.1	1621	0	0	-1	1
21.06.2000	12:30	82	71	1.63	0.06251	F	Visitor	27.52	45.7	1679	1	1	-1	1
27.06.2000	12:30	110	82	1.7	0.06852	F	PostDoc	27.91	38.5	1447	3	0	-1	0
23.06.2000	12:30	56	81	1.82	0.07162	M	Student	26.34	46.1	1581	-1	0	-1	1
24.06.2000	12:30	1	87	1.76	0.07205	M	Technician	25.17	36.3	1161	0	0	0	0
22.06.2000	12:30	129	70	1.63	0.06214	M	Visitor	28.31	35.8	1378	1	1	-1	0
20.06.2000	12:40	181	48	1.6	0.05222	F	Student	28.31	42.3	1628	-2	2	-1	0
25.06.2000	12:45	152	58	1.62	0.05711	F	Student	27.91	39.6	1489	-2	0	-1	0
27.06.2000	12:50	153	62	1.73	0.06162	M	Researcher	27.91	38.6	1451	1	2	-1	1
26.06.2000	13:00	83	62	1.65	0.05954	F	Teaching Staff	27.91	44.9	1688	-2	1	-1	0
26.06.2000	13:00	130	53	1.65	0.0557	F	Student	28.31	35.9	1381	-2	0	-1	1
27.06.2000	09:05	101	72	1.71	0.06511	F	Student	26.34	41.2	1413	-2	-1	-1	0
21.06.2000	09:30	50	59	1.62	0.05753	F	Cleaner	25.17	47.2	1510	-1	0	0	1
23.06.2000	13:00	182	70	1.69	0.06379	M	Staff	28.31	42.7	1643	-1	1	0	0
25.06.2000	13:03	183	65	1.6	0.05941	F	Staff	28.31	39.8	1532	-1	1	0	1
27.06.2000	13:10	111	59	1.7	0.05957	F	PostDoc	28.31	37.1	1428	-1	2	-1	0
24.06.2000	13:10	57	62	1.71	0.0611	M	Student	26.34	46.1	1581	0	0	0	-1
22.06.2000	13:10	154	71	1.86	0.06879	M	PhD Candidate	27.91	37	1391	2	2	-1	0
26.06.2000	13:15	2	46	1.58	0.05082	F	Student	25.17	33	1056	1	0	-1	0
20.06.2000	13:15	131	67	1.63	0.06099	F	Secretary	28.31	37.4	1439	2	2	-1	1
25.06.2000	13:30	84	52	1.62	0.05452	F	Student	27.91	45.3	1703	2	0	-1	-1
23.06.2000	13:30	155	62	1.7	0.06084	M	Visitor	27.91	38.3	1440	-2	1	0	1
26.06.2000	13:30	32	86	1.9	0.07579	M	Student	25.95	42.1	1411	1	1	-1	0
21.06.2000	13:40	112	65	1.7	0.06207	F	Teaching Staff	28.31	34.2	1316	-2	0	-1	1
24.06.2000	13:45	3	86	1.86	0.07463	M	Student	25.56	31.6	1035	0	0	-1	0
20.06.2000	13:50	58	48	1.6	0.05222	F	Teaching Staff	26.73	44	1544	-2	1	-1	1
22.06.2000	13:50	156	68	1.61	0.06083	F	Secretary	27.91	38.8	1459	-1	1	-1	0
26.06.2000	13:50	33	80	1.81	0.07095	M	Student	25.95	36.9	1236	1	1	-1	0

21.06.2000	14:00	132	67	1.65	0.06153	F	Secretary	28.31	33.8	1301	-2	-1	-1	0
25.06.2000	14:00	184	57	1.68	0.0582	F	PostGraduate	29.1	40.4	1627	-1	-1	0	0
27.06.2000	14:00	85	65	1.68	0.06154	F	Teaching Staff	27.52	43.9	1613	1	0	-1	1
23.06.2000	14:00	113	85	1.8	0.07251	M	Student	28.31	32.2	1239	0	1	-1	1
24.06.2000	14:00	59	80	1.84	0.07181	M	Student	27.12	43.3	1554	2	1	-1	0
22.06.2000	14:01	34	78	1.82	0.07048	M	Student	25.95	37.4	1253	1	1	0	0
26.06.2000	14:05	157	82	1.77	0.07055	M	Student	27.91	39.6	1489	3	3	-1	1
21.06.2000	14:30	35	45	1.6	0.05081	F	PhD Candidate	26.34	41.5	1423	-2	1	-1	0
26.06.2000	14:30	158	49	1.6	0.05268	F	Teaching Staff	27.91	41.3	1553	-2	1	-1	1
20.06.2000	14:30	4	72	1.63	0.06289	F	Visitor	25.56	32.7	1071	1	0	0	0
23.06.2000	14:30	86	73	1.61	0.06269	F	PhD Candidate	27.52	39.2	1441	1	2	-1	1
24.06.2000	14:45	114	73	1.7	0.06521	F	Student	28.31	33.6	1293	-2	2	-1	0
22.06.2000	14:45	60	55	1.65	0.05658	F	PostGraduate	27.12	41.4	1486	-1	1	0	0
25.06.2000	14:45	133	86	1.74	0.07111	M	Technician	28.7	31.1	1224	0	0	0	0
20.06.2000	15:00	5	60	1.67	0.05923	F	Student	25.95	32	1072	-2	2	-1	0
22.06.2000	15:00	61	73	1.61	0.06269	F	Teaching Staff	27.52	39.2	1441	1	2	-1	1
24.06.2000	15:00	115	58	1.7	0.05914	F	Student	28.7	32.9	1295	1	1	-1	0
27.06.2000	15:10	185	67	1.68	0.06234	M	Cafetiria Staf	24.79	36	1126	0	0	0	0
26.06.2000	15:10	159	90	1.8	0.0743	M	Technician	27.91	46.4	1744	2	2	-1	0
23.06.2000	15:20	87	57	1.62	0.05669	F	Student	27.91	39.9	1500	-2	0	-1	0
25.06.2000	15:20	134	79	1.81	0.07058	M	Technician	28.7	30.6	1204	-2	2	-1	0
21.06.2000	15:30	36	80	1.75	0.06924	M	Student	25.95	39.3	1317	-1	2	-1	1
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26.06.2000	16:20	161	57	1.62	0.05669	F	Teaching Staff	27.91	42.2	1587	-1	0	-1	0
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25.06.2000	16:50	136	54	1.6	0.0549	F	Student	28.7	31.5	1240	-1	1	-1	0
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22.06.2000	16:55	64	69	1.59	0.06066	F	Secretary	27.52	33.1	1216	2	2	-1	1

APPENDIX D

Software Description

General Description

ROOM is a single cell dynamic thermal model based on an explicit finite difference formulation for unsteady heat flows within the building fabric. Internal radiation exchange between surfaces is carried out using a radiosity method, the long-wave radiant heat flows (those due to surface temperature differences) being handled separately from short-wave radiation (due to the sun and lights). It is assumed that all reflections are non-specular. The short-wave radiant gain to the space is therefore the sum of the direct radiation on that surface plus that reflected (from an infinite number of reflections) from all other surfaces. Solar gains are calculated using standard optical theory and distributed over the room surfaces according to the relative positions of sun, surface and windows. Natural ventilation due to stack effect and wind is calculated within the programme from open areas at high and low level and the vertical separation between them. Dry bulb temperatures can be calculated for either a two-zone stratified model or a uniform, mixed flow model.

ROOM is particularly suitable for determining the environmental conditions in spaces with a low level of servicing, such as atria, naturally ventilated buildings and shopping malls. It is also intended to provide space heating and cooling loads.

Modes of Operation

There are five main stages in ROOM:

1. Data input through EDETA
2. THERMAL analysis of the space
3. COMFORT analysis
4. Visualization of SUN patches
5. Process results

The main THERMAL results are hourly values of:

1. Air dry bulb temperature
2. Dry resultant temperature
3. Plant loads

4. The ventilation rate
5. Solar radiation transmitted through translucent elements
6. Surface temperatures

The COMFORT analysis can be run following a THERMAL analysis has been completed. This analysis is based on Fanger's theory referred to the previous chapter and predicts the comfort parameters

- Percentage of People Dissatisfied (PPD)
- Predicted Mean Vote (PMV)
- Dry Bulb Temperature (^{0}C)

The above variables can be given for a number of different positions across the room. The dry resultant temperature, used by CIBSE as an indicator of comfort, is also calculated (CIBSE 1986). Sun path visualization is used to depict solar where solar radiation falls within the space.

Limitations

The following limitations apply:

1. There may be up to 10 windows in any one surface. There must be a minimum of 0.1m of the parent wall around the edge of the window. A window must not be placed on a glazed surface
2. All included angles on any surface must be less than 1800. This means that the floor of an L-shaped room must be made up from two surfaces.
3. The space must be a complete enclosure, i.e. there must be no surface missing
4. Each surface may not have more than 6 vertices
5. A maximum of five glazing elements can be used
6. One blind is allowed for each window
7. A maximum of 20 shades is allowed
8. Maximum number of general shade point is 16
9. Shading is only calculated in relation to its parent window and not surrounding walls and windows
10. All Fabric elements are assumed to be opaque to short-wave radiation
11. Vapour barriers are ignored by ROOM
12. Only 10 internal and 10 external obstructions are allowed
13. No more than 4 vertices can be defined for each obstruction

ROOM Output

ROOM output consists of both the on-screen graphics produced by the Sun path and comfort plots as well as writing the results to spreadsheet.

The format chosen for the current research is the csv – Microsoft Excel compatible, and it gives written information on the following:

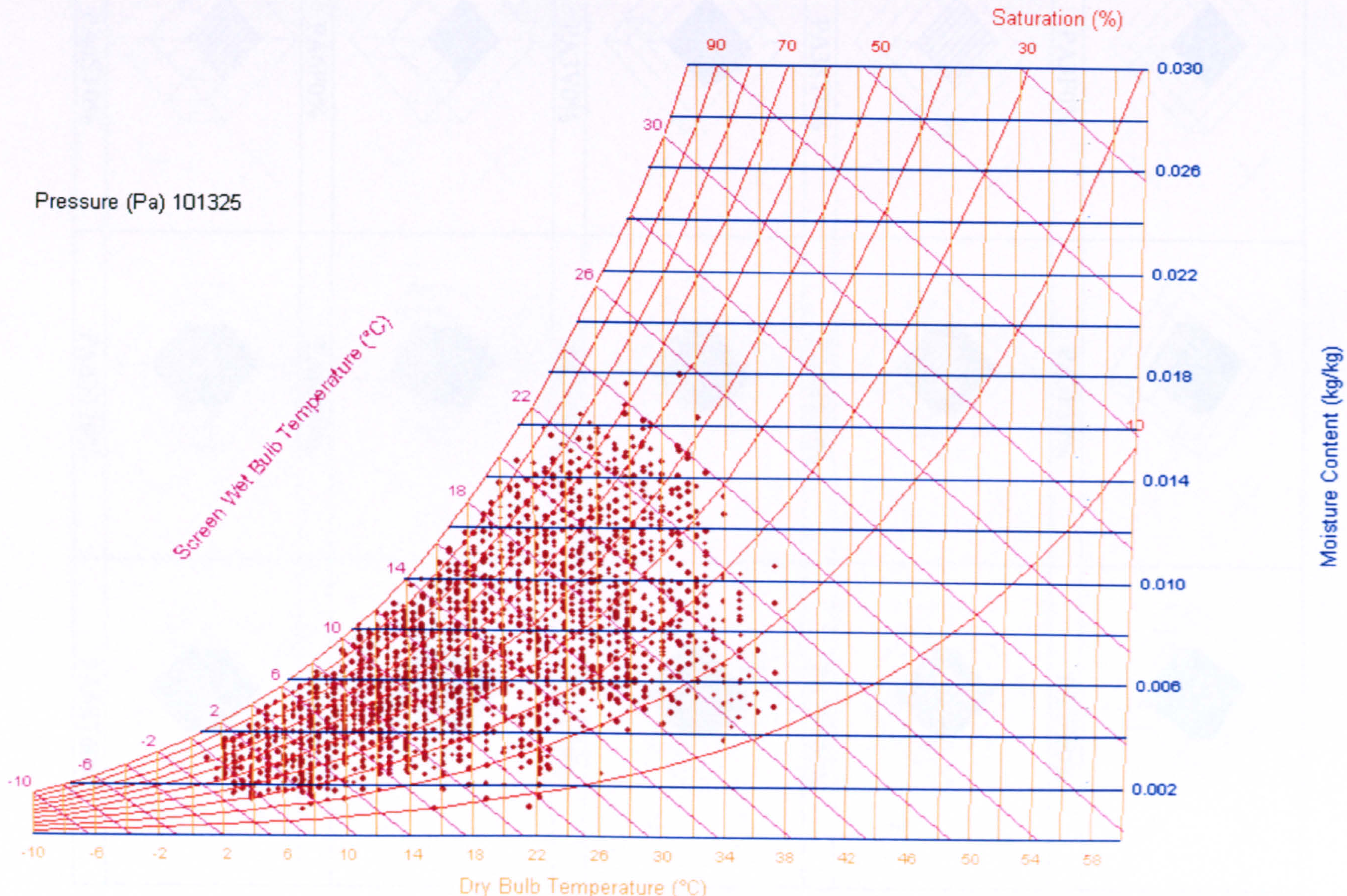
- Runtime input data
- Cyclic/ main day results
- Comfort results
- Load and ventilation results
- Surface temperature results
- Heat transfer temperature results
- Transmitted solar radiation results
- Re-transmitted solar radiation results
- Sequential weather results

ROOM advantages

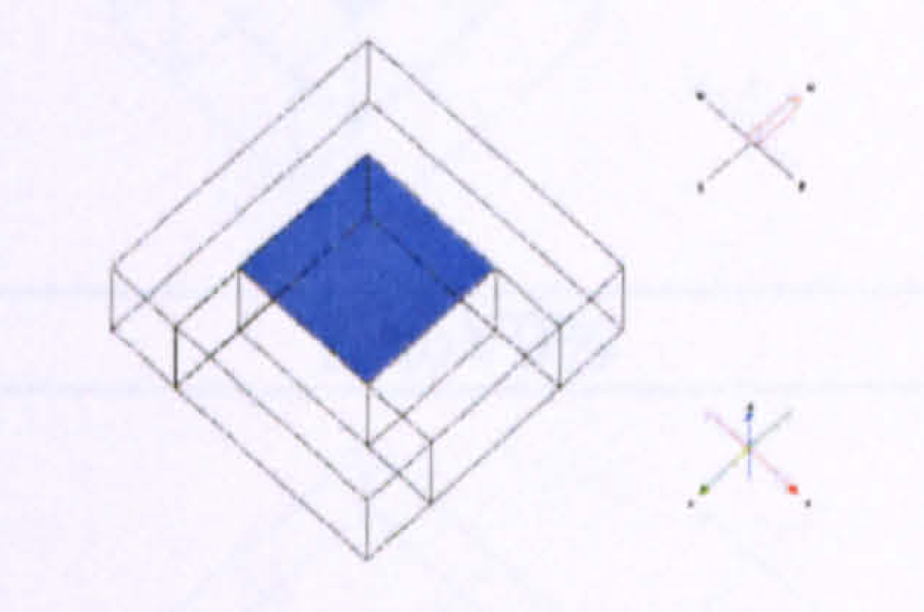
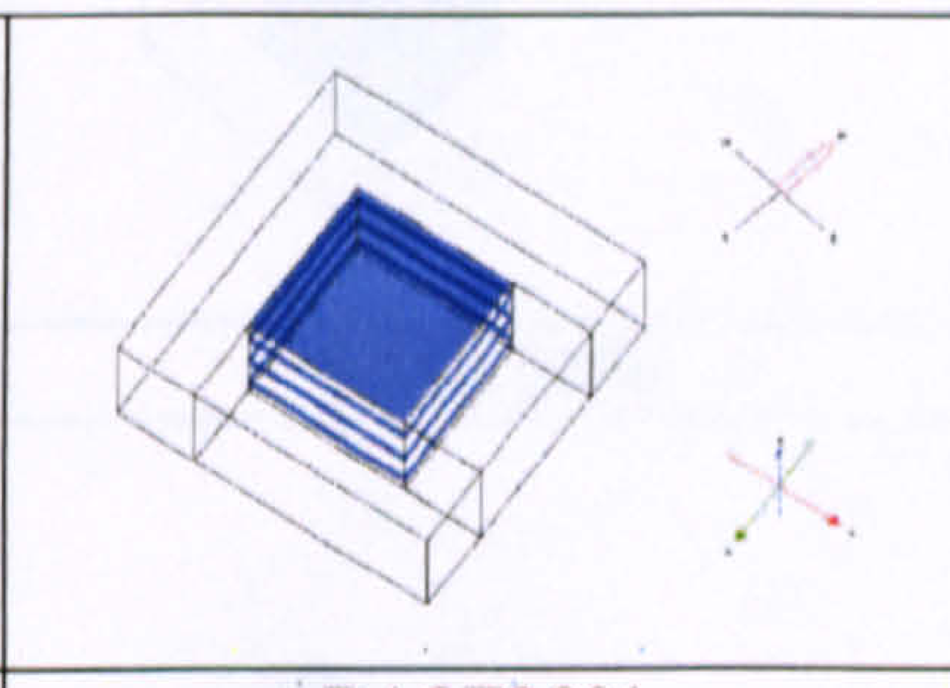
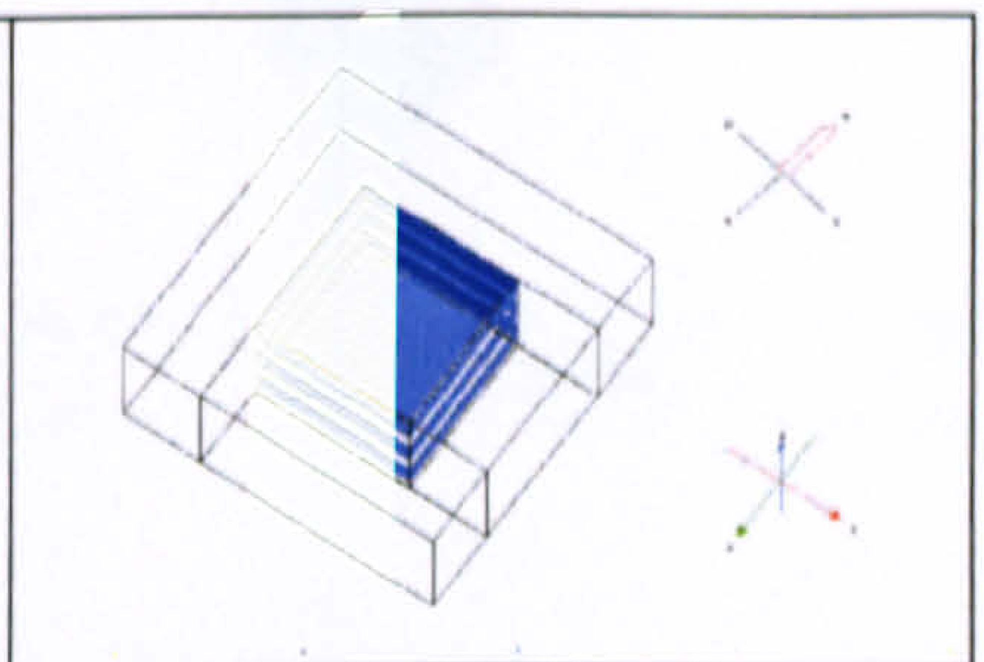
Analysis of the thermal environment requires a complete solution to the equations representing air movement and thermal response of the building fabric under dynamic conditions. According to Simmonds [1994], conventional thermal analysis methods, such as the environmental temperature and admittance methods used in other programmes, make simplified assumptions about heat transfer. Usually these assumptions are about the uniformity, homogeneity, and direction of heat flow and temperature gradients. As spaces get larger, the validity of these assumptions decreases and more rigorous calculation methods are appropriate. This is not always true and ROOM calculates the dry resultant temperature and the dry-bulb temperature in the occupied zone. Heat is transferred by conduction, convection and radiation, each of which must be considered separately. The calculation of radiation form factors is essential to the assessment of radiant heat flow: these are calculated for the space. Conduction through the enclosure surfaces is calculated dynamically, with time steps adjusted by the programme. ROOM takes account of the spatial arrangement of the surface and the way in which each surface affects the others. This makes it possible for the sunlight falling on each surface to be treated separately. ROOM also takes into account the effects of humidity and room temperature on the heat given off by occupants, as well as the level of activity

APPENDIX E
Psychrometric Chart for Athens

Psychrometric Chart for Athens



APPENDIX F List of simulated atrium models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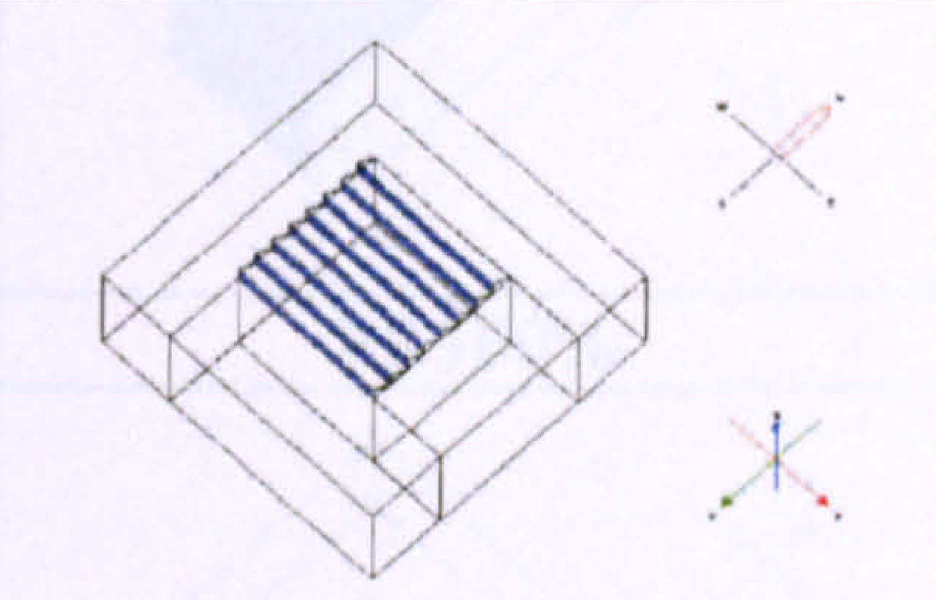	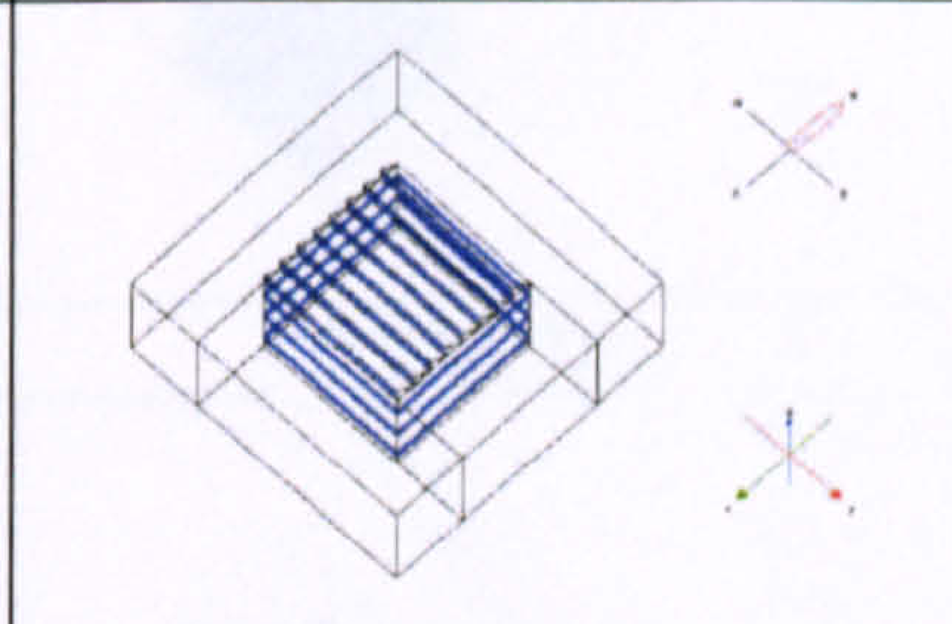	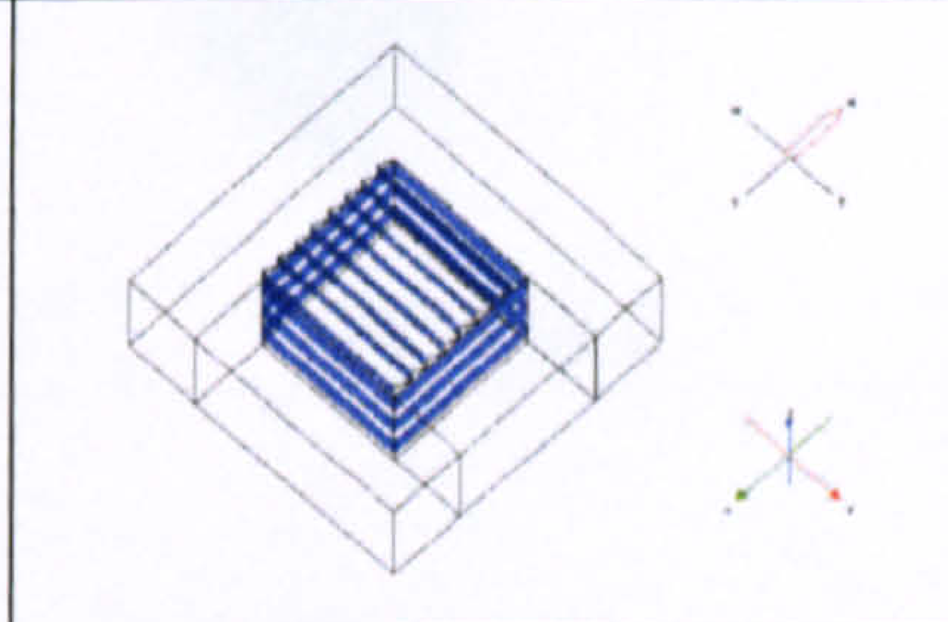
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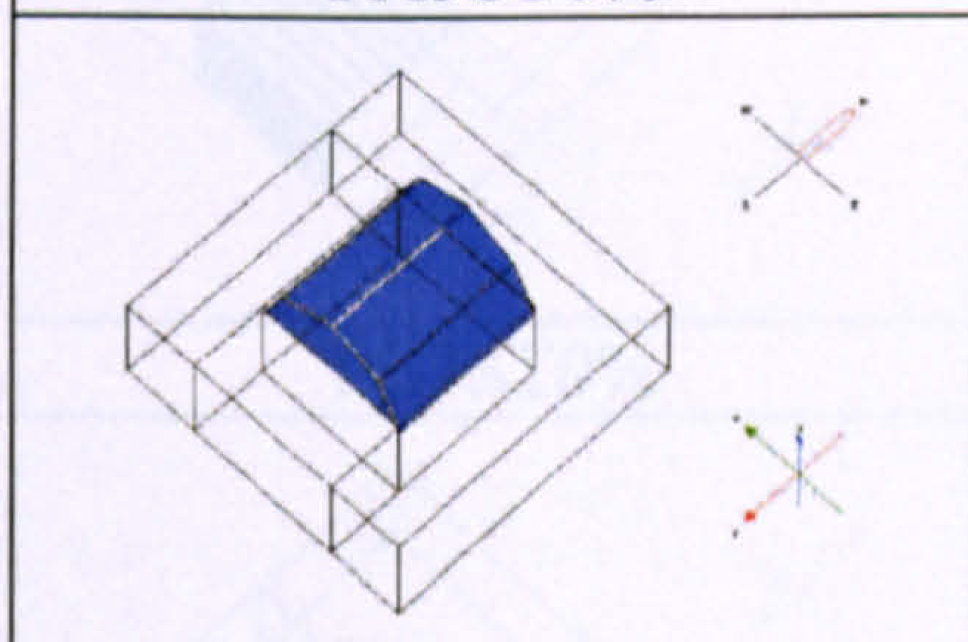	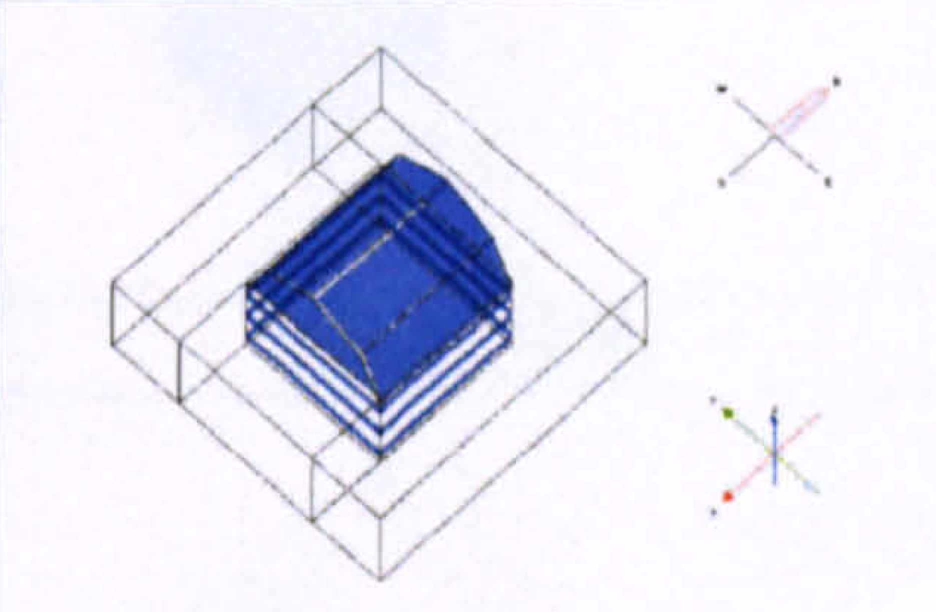	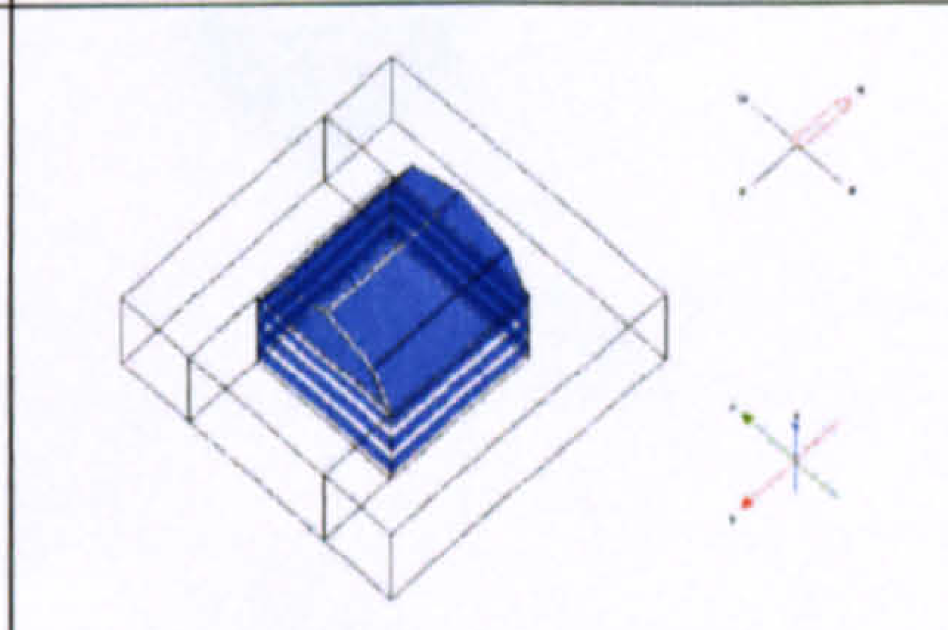
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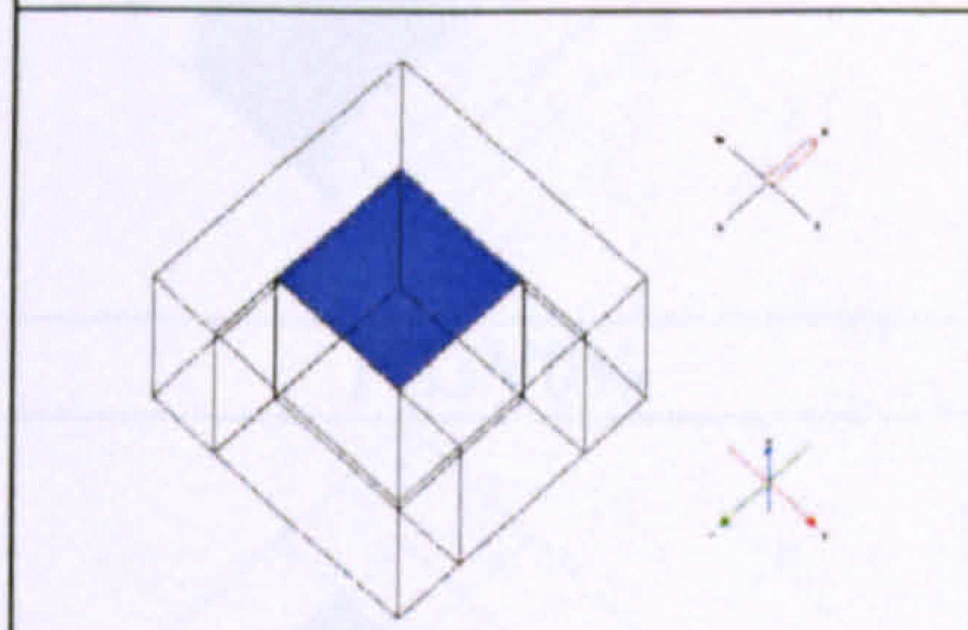	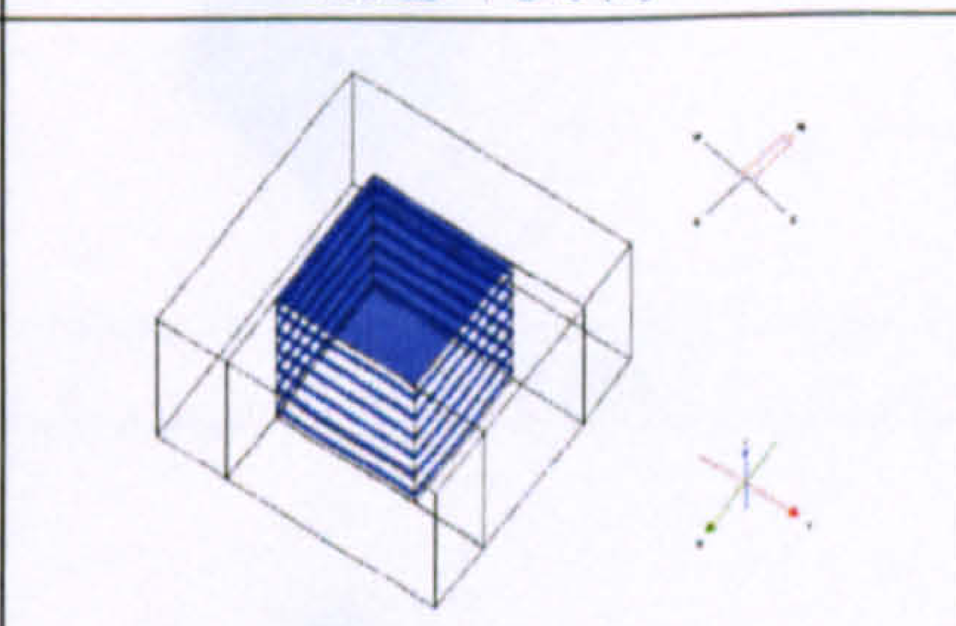	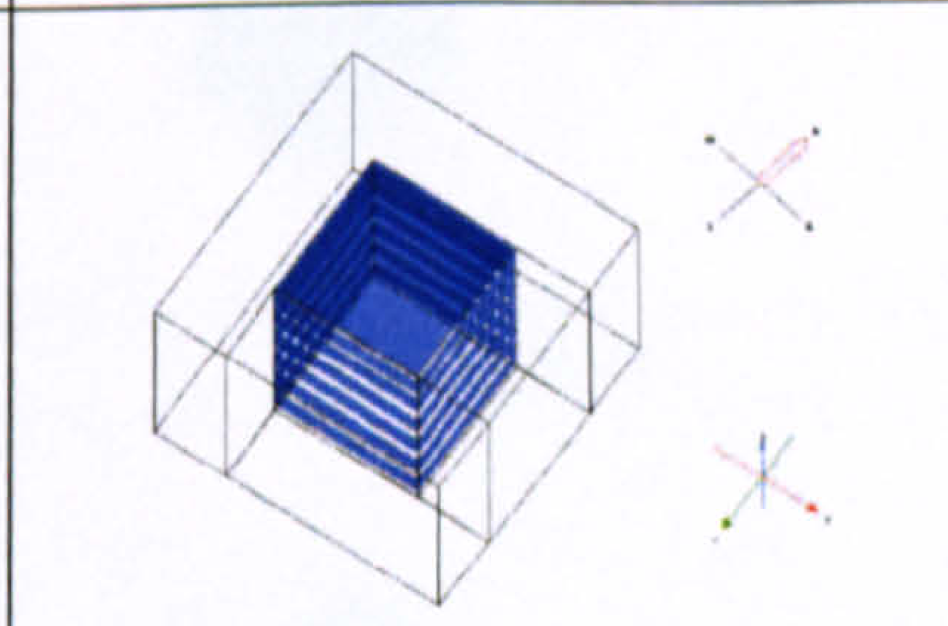
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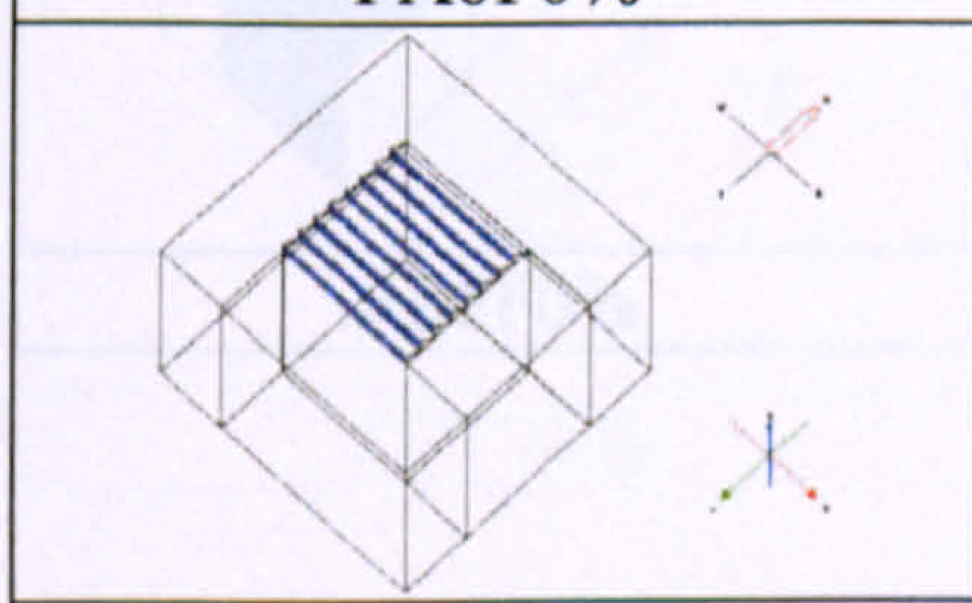	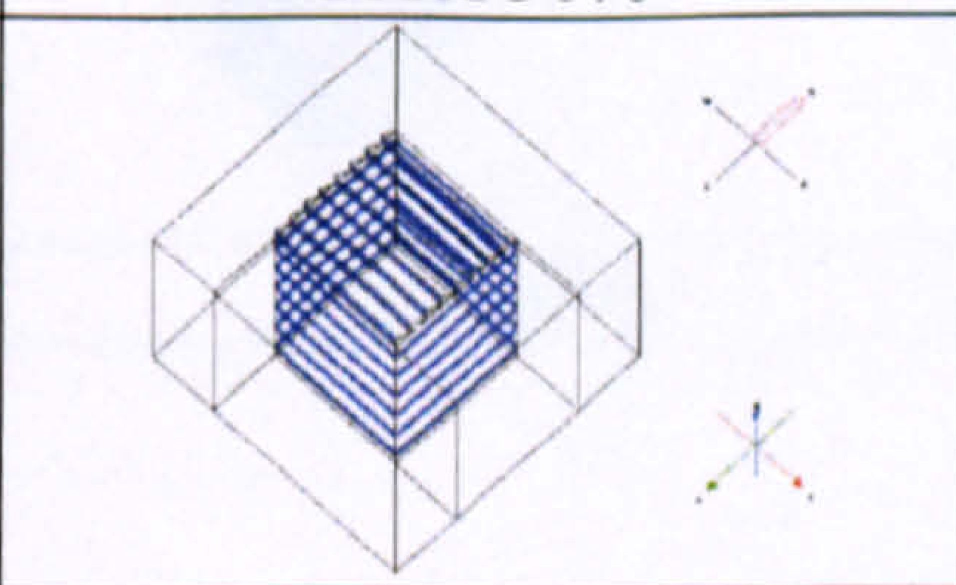	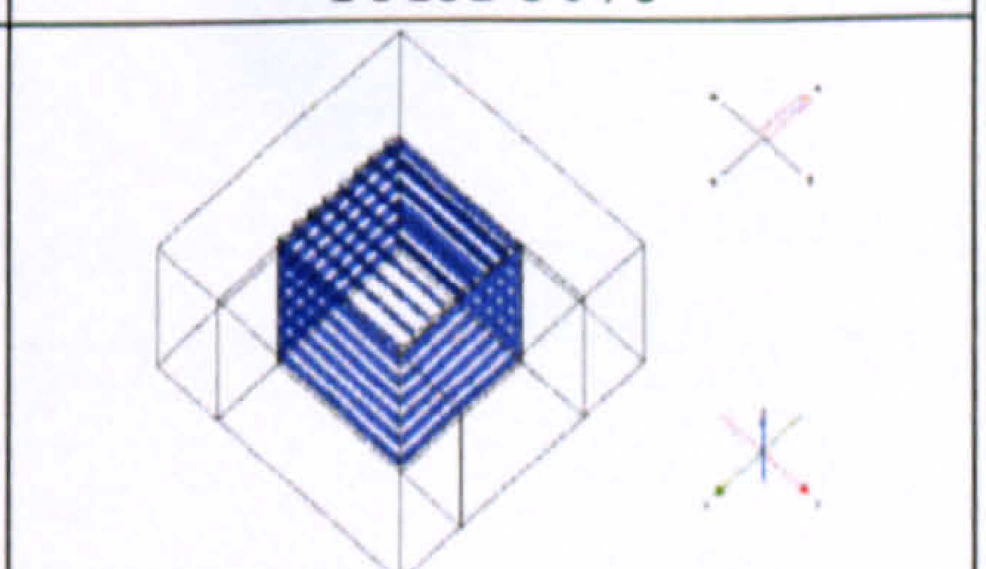
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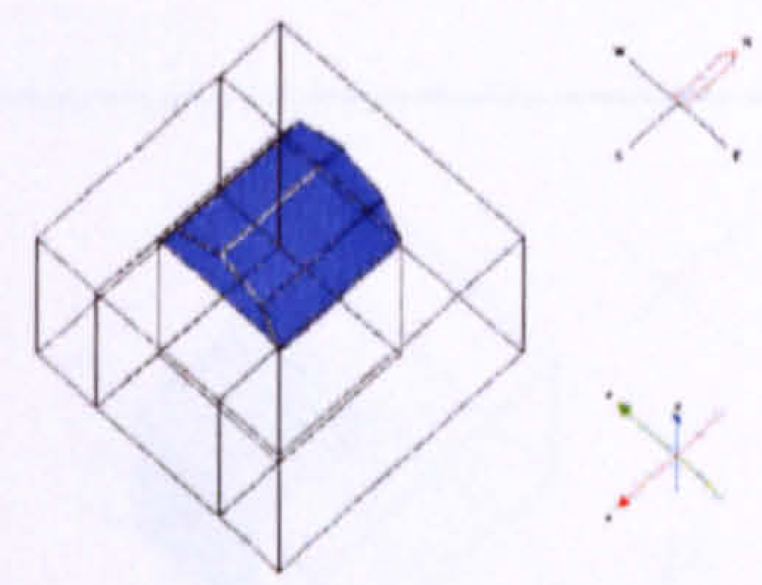	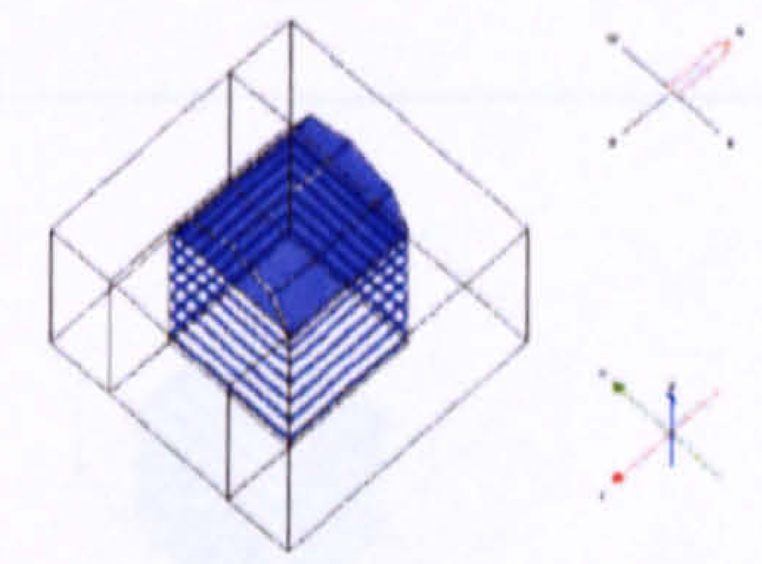	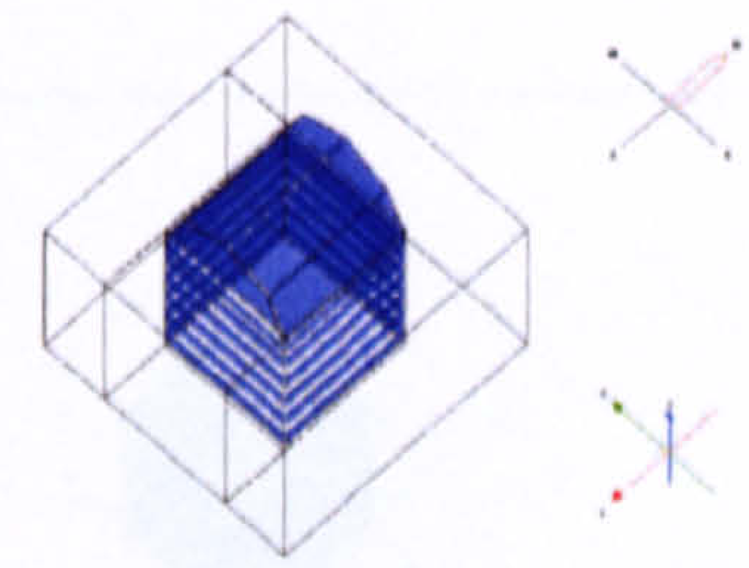
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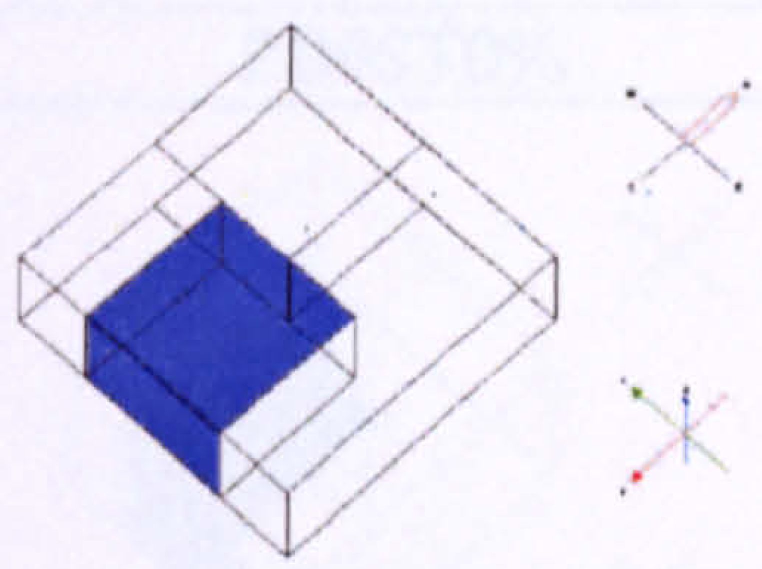	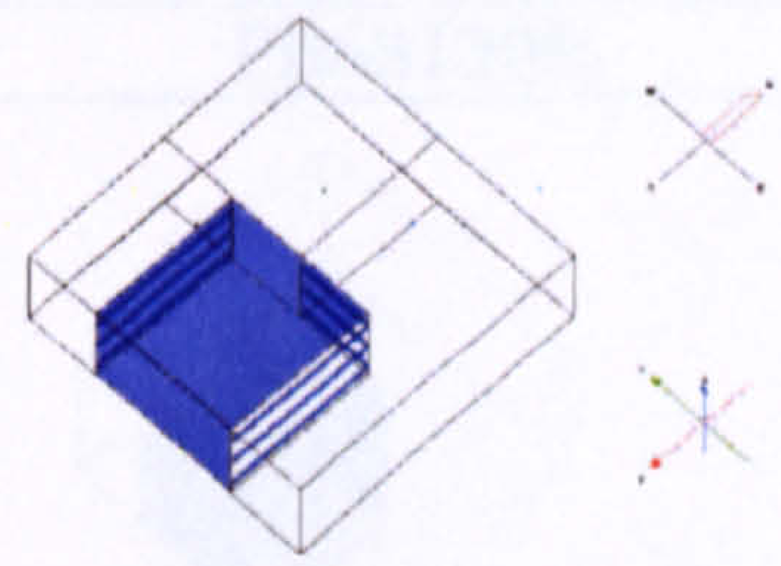	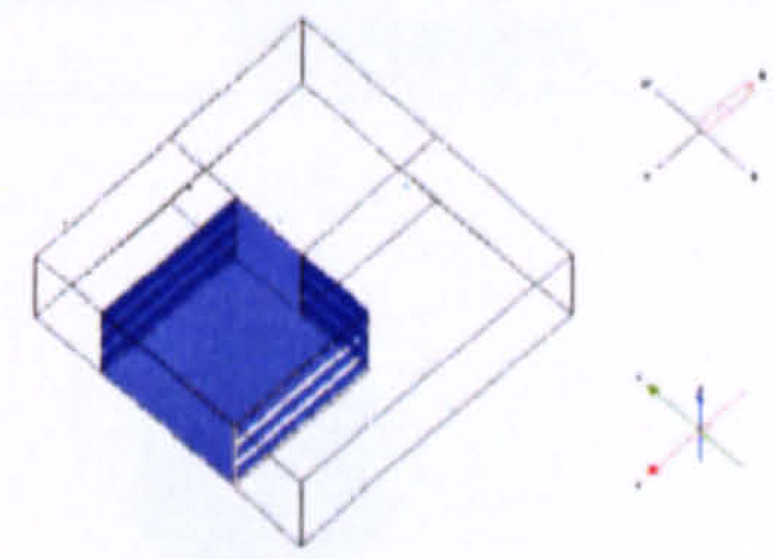
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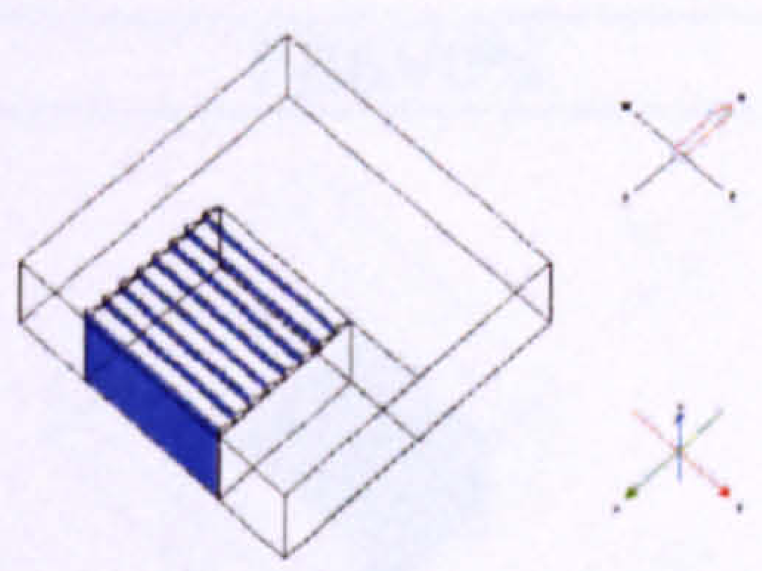	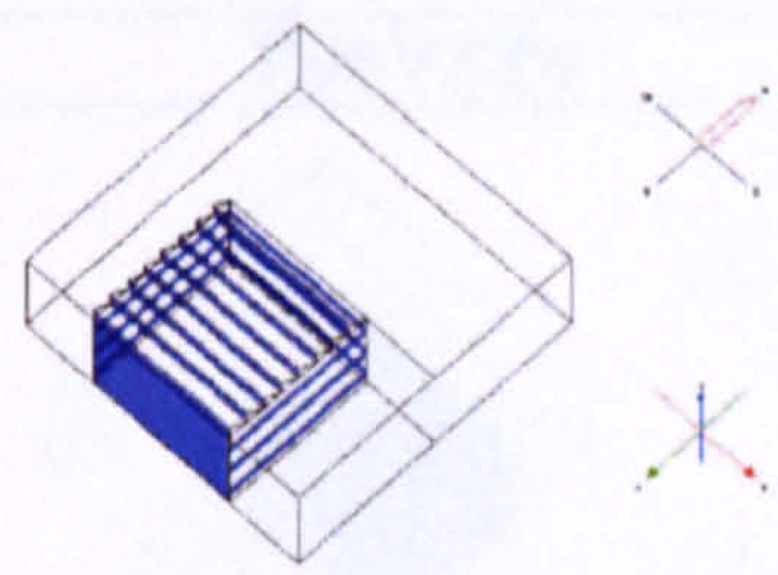	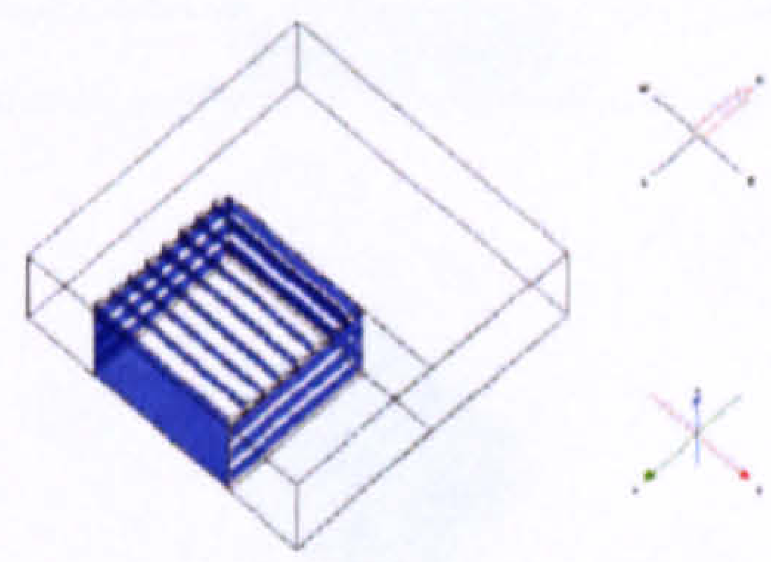
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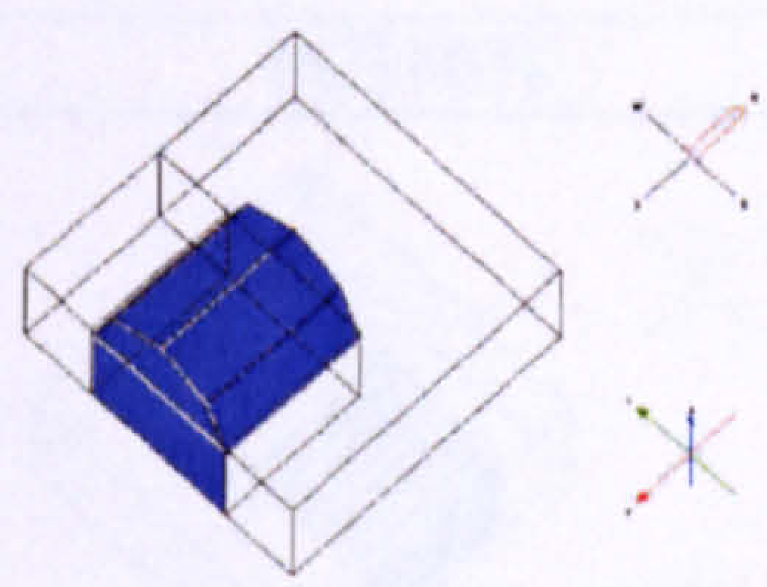	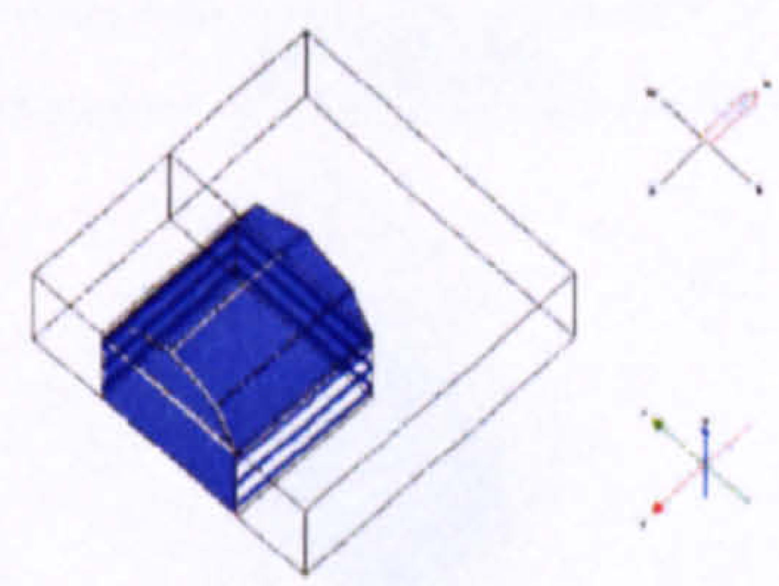	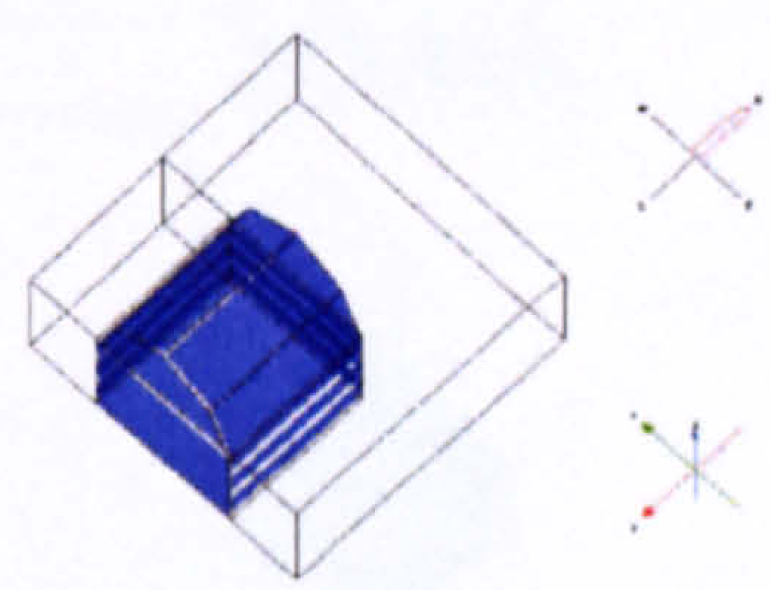
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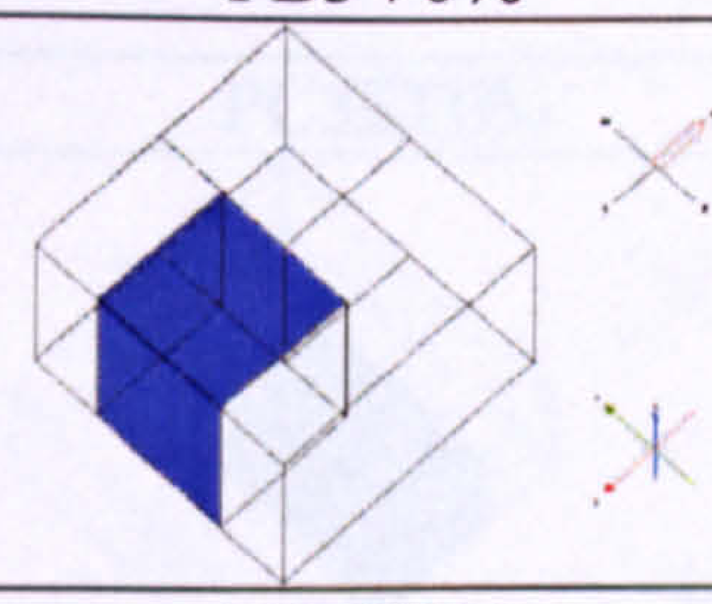	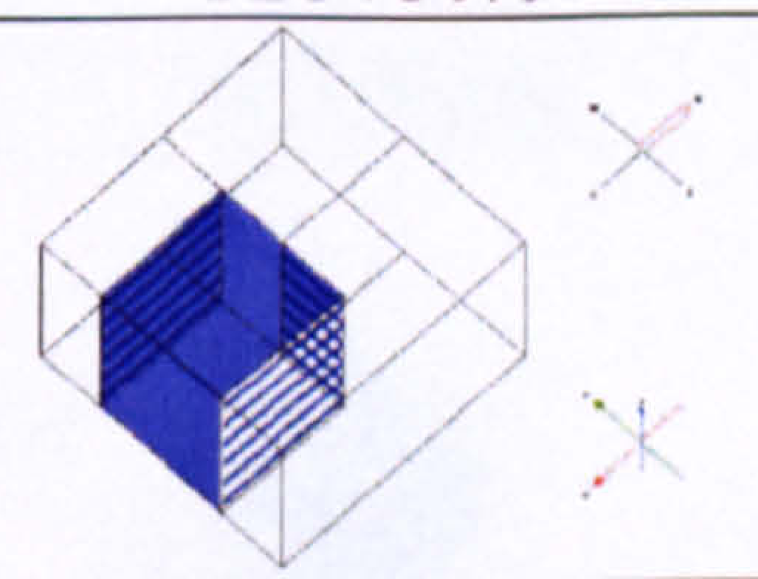	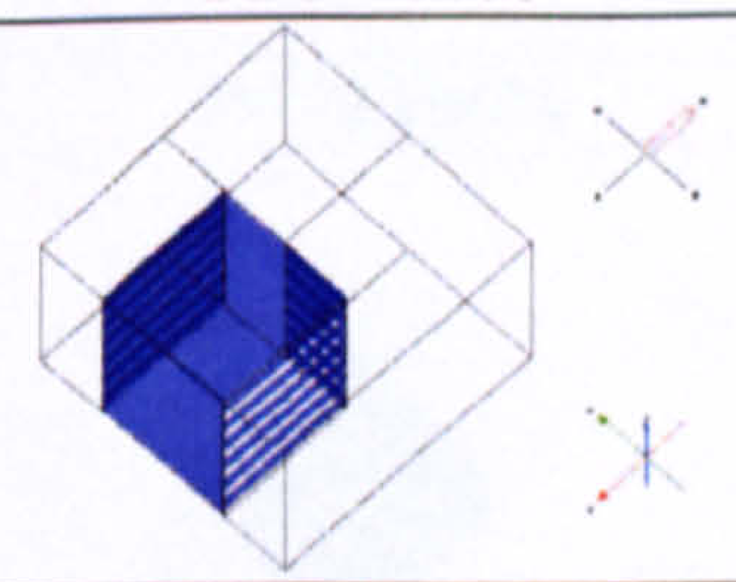
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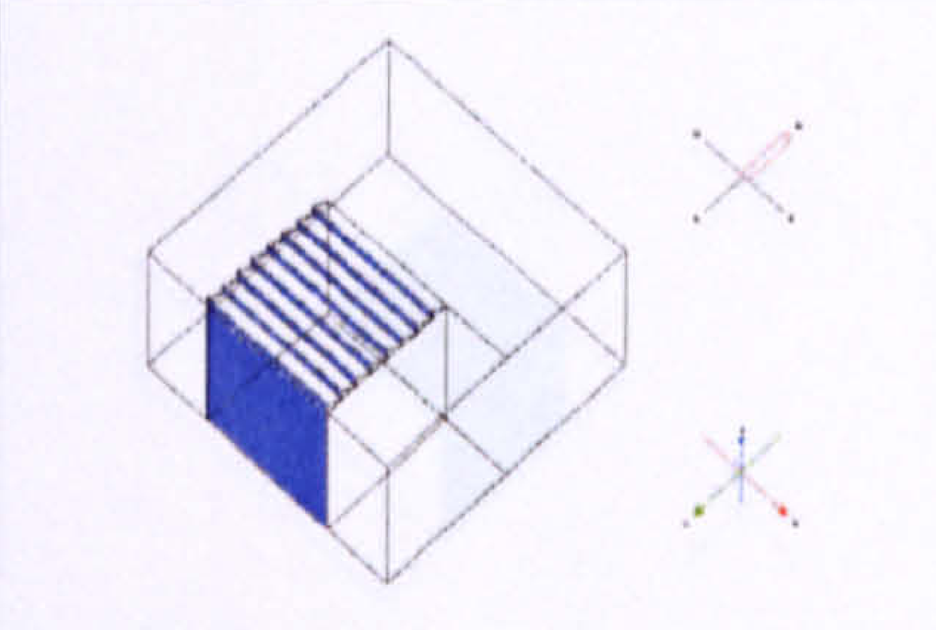	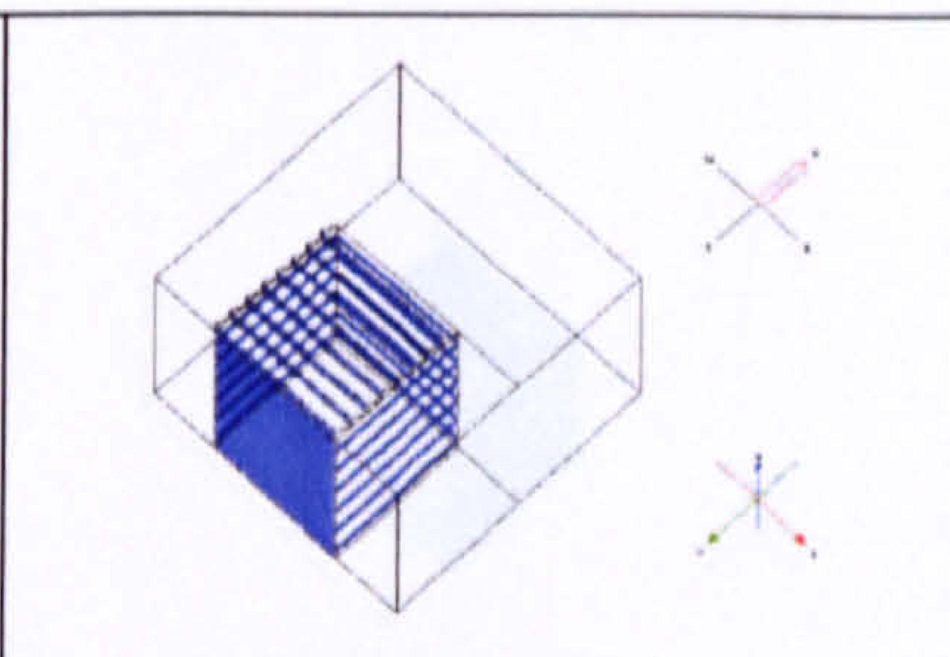	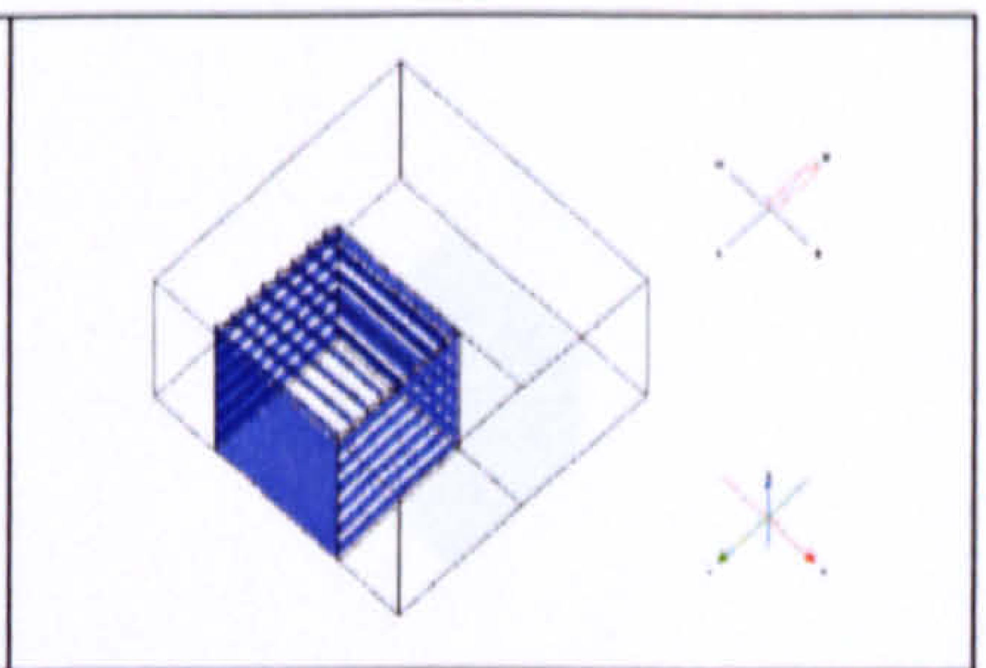
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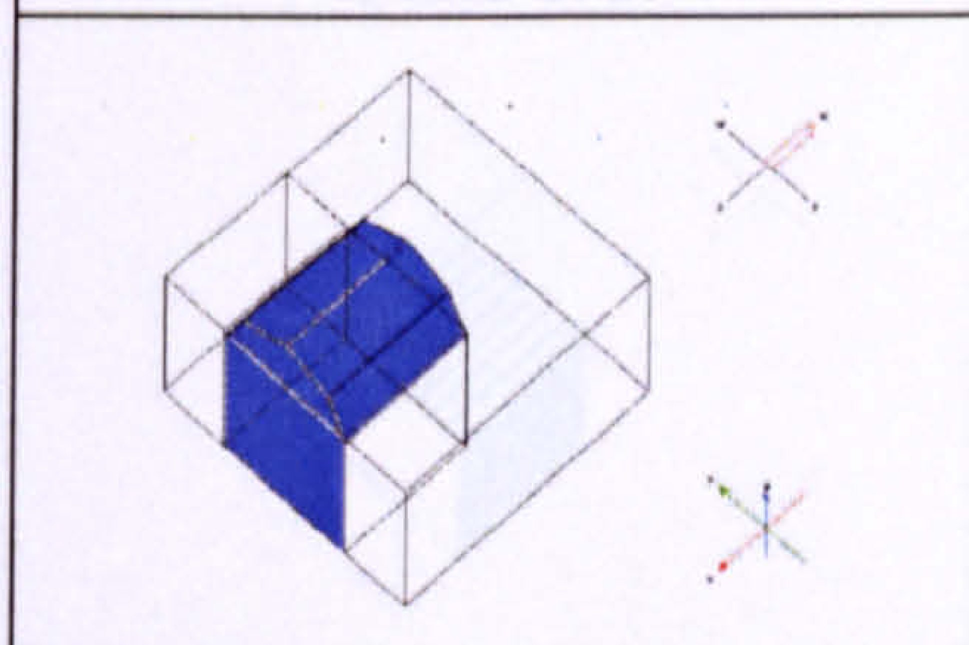	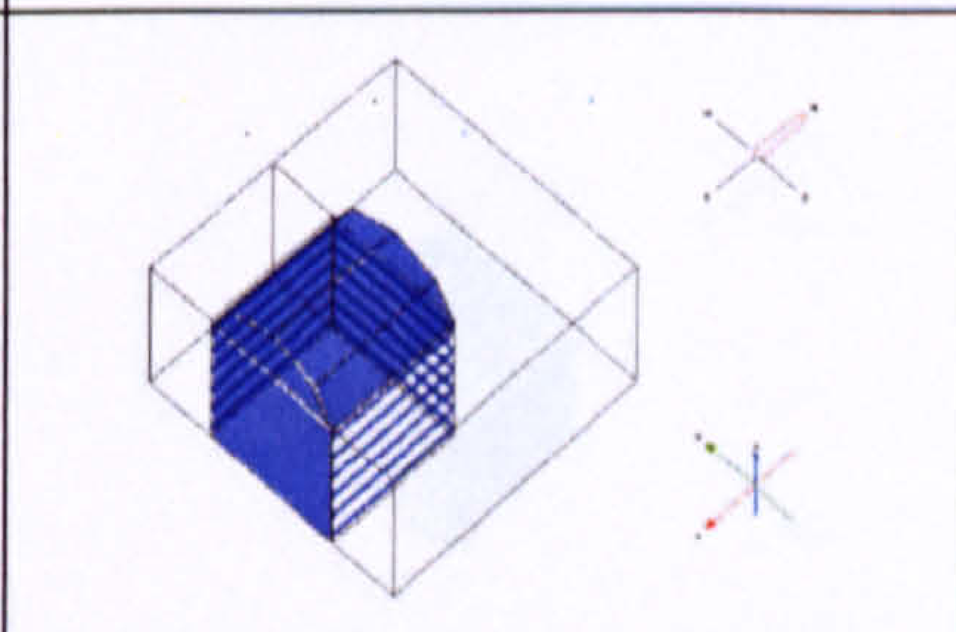	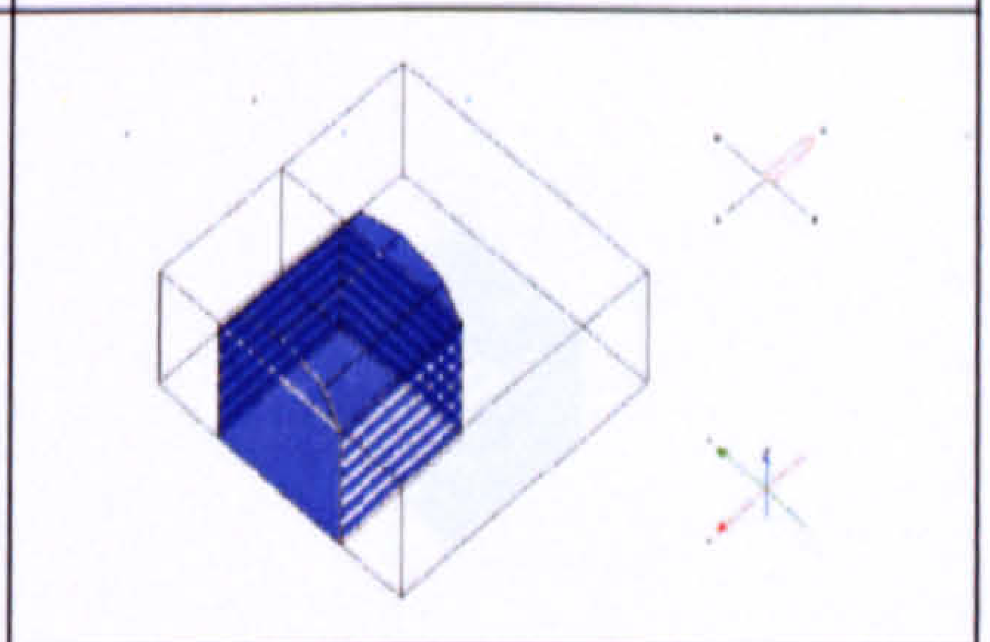
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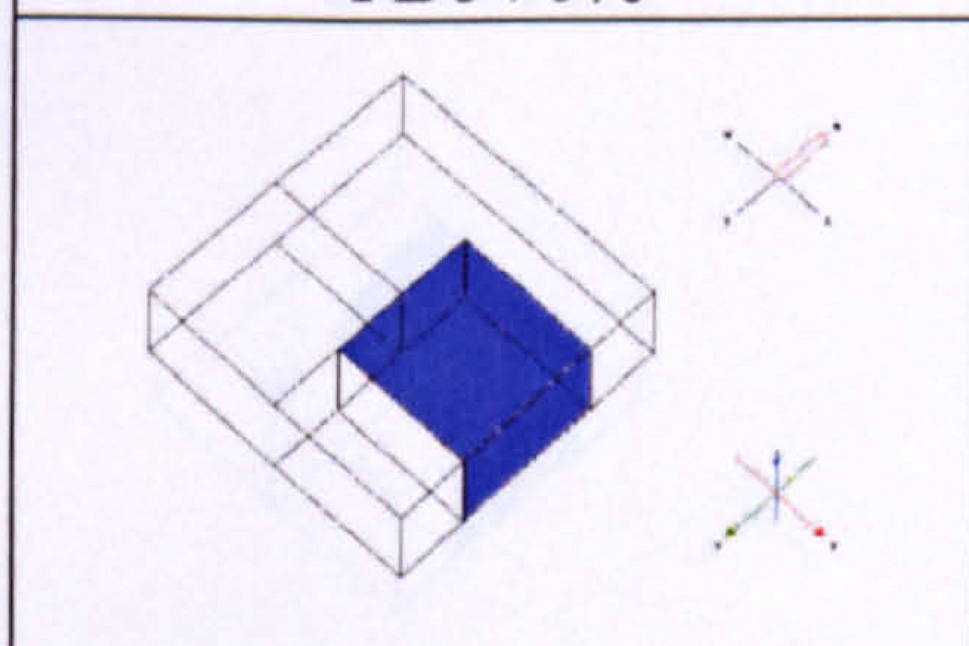	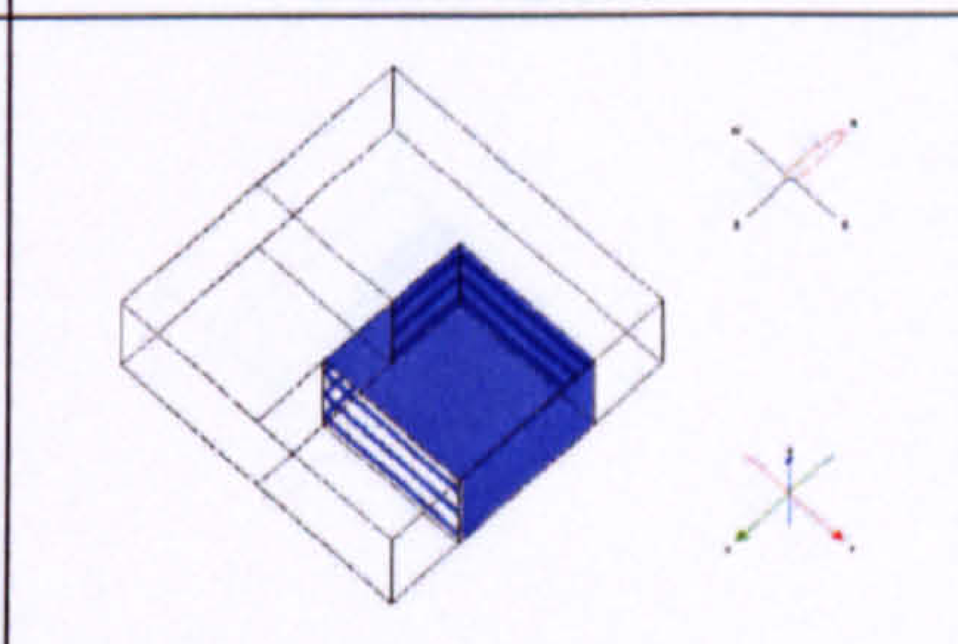	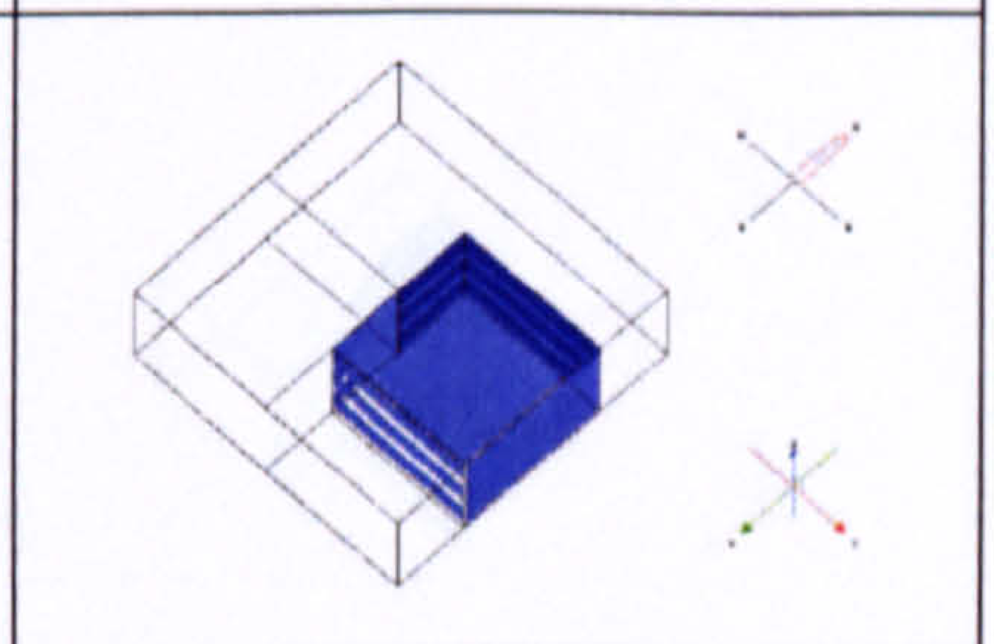
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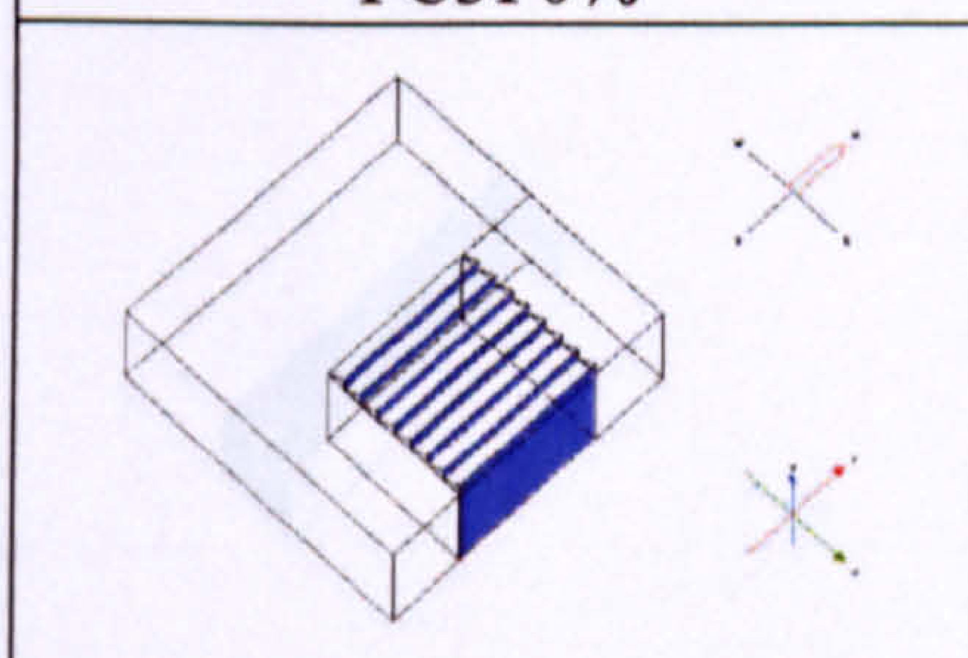	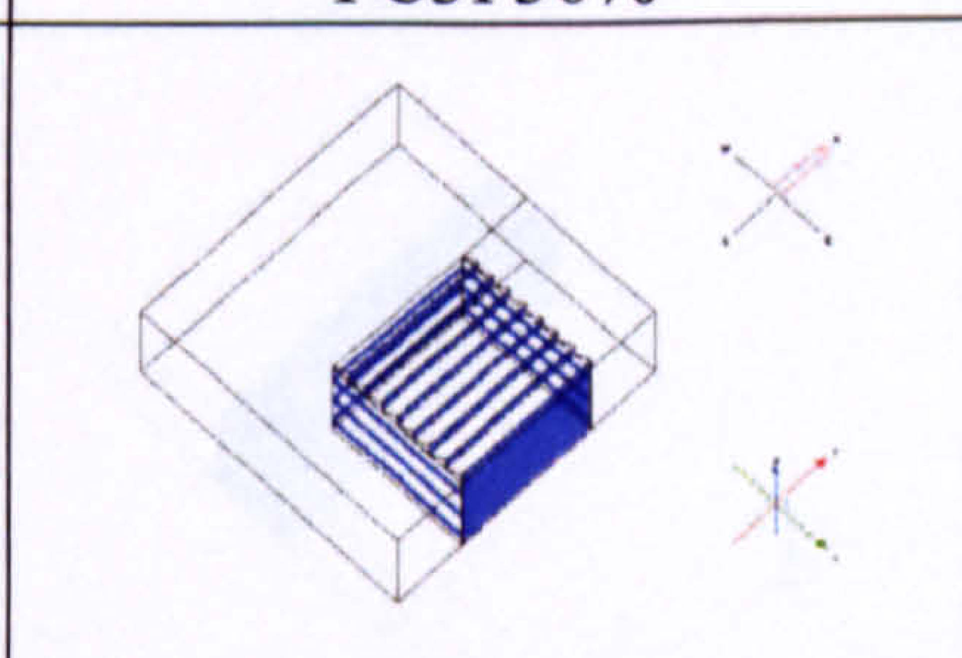	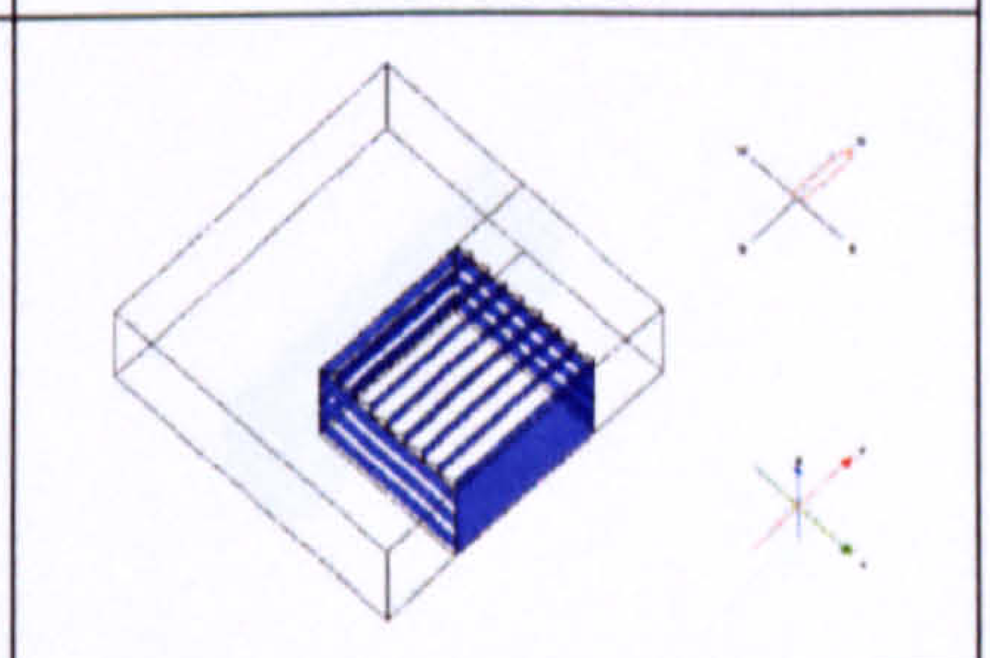
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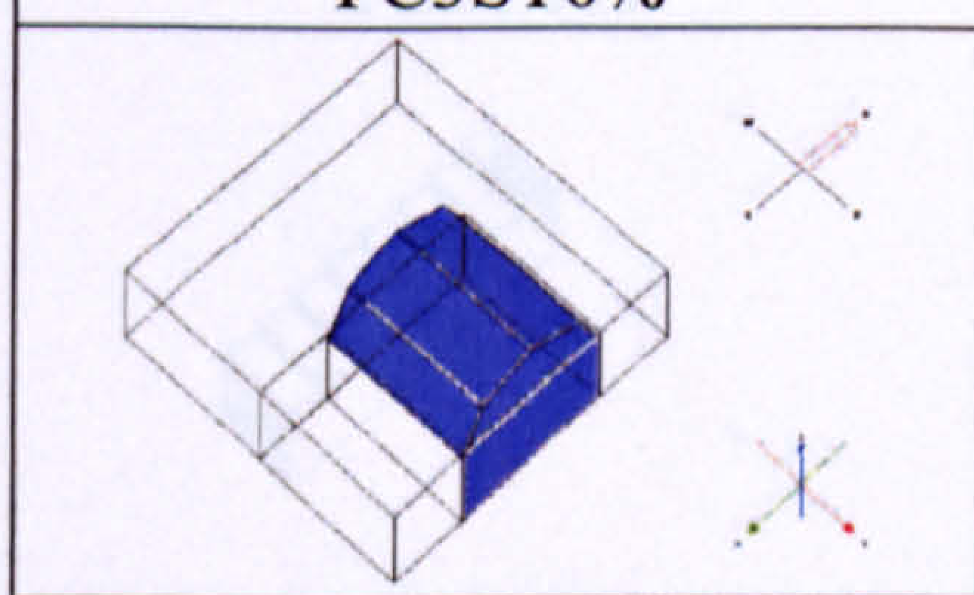	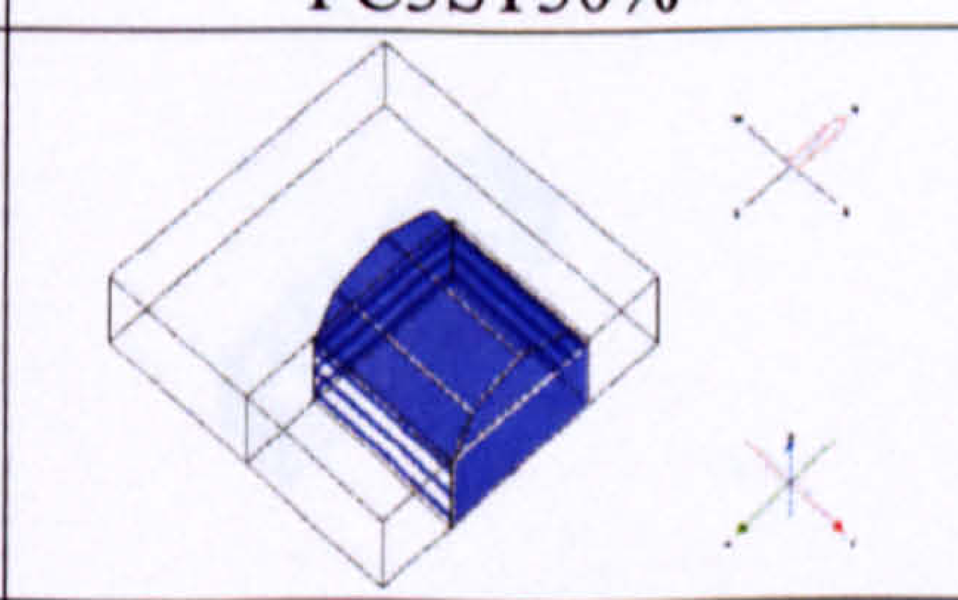	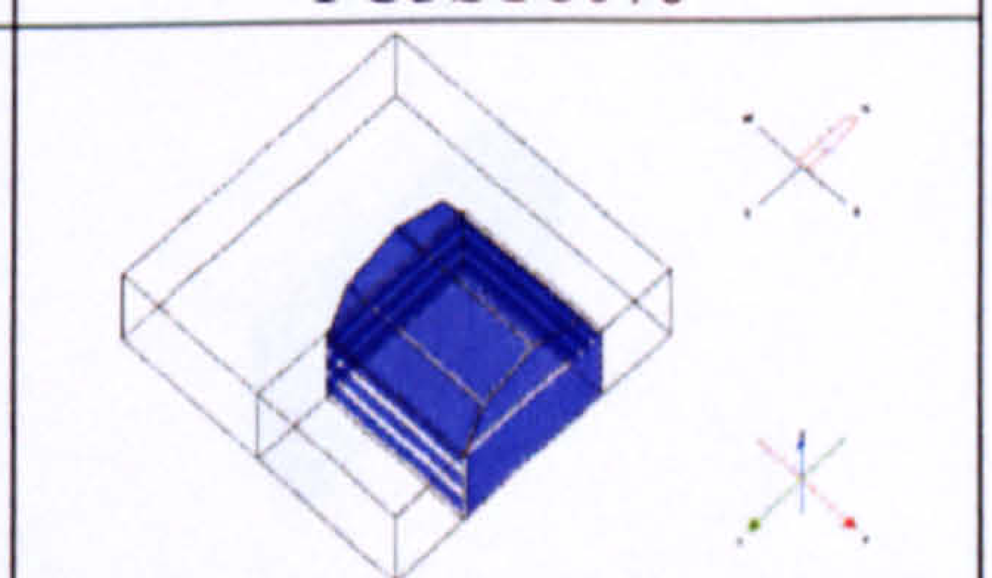
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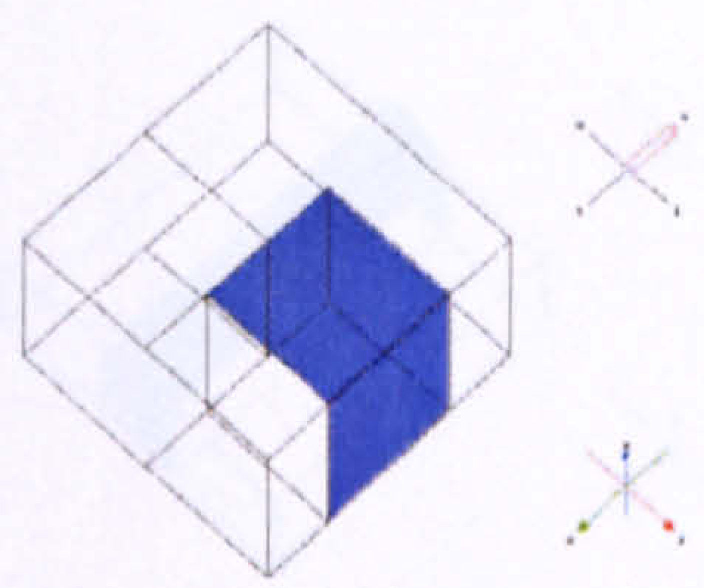	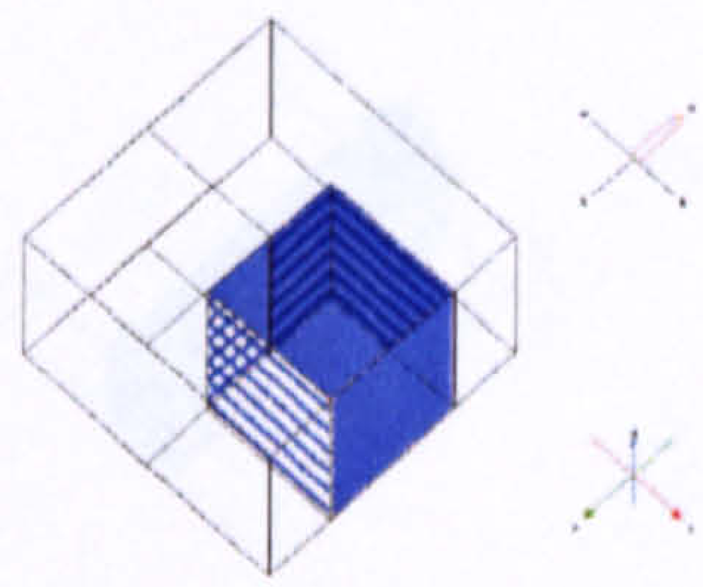	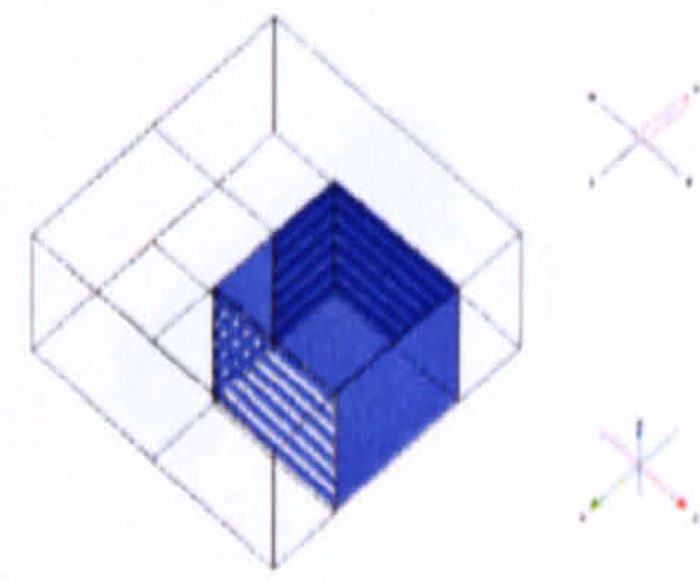
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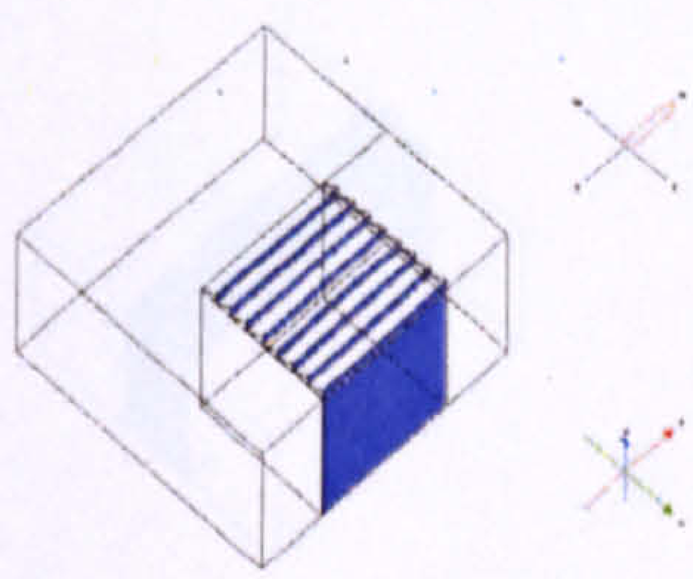	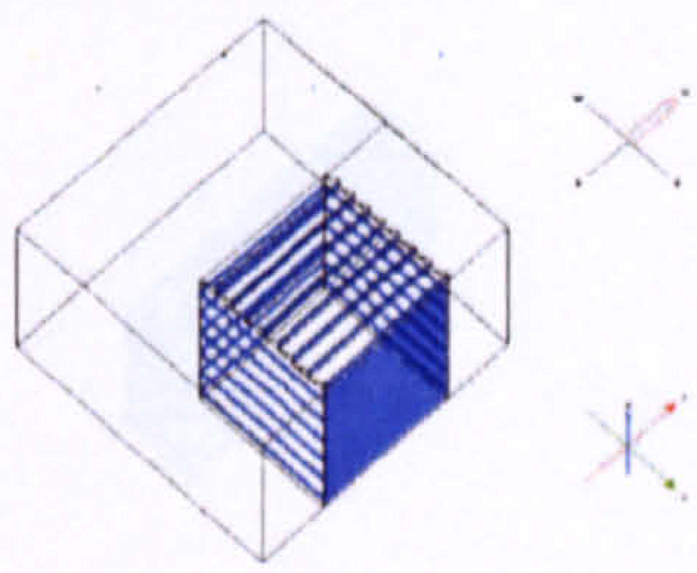	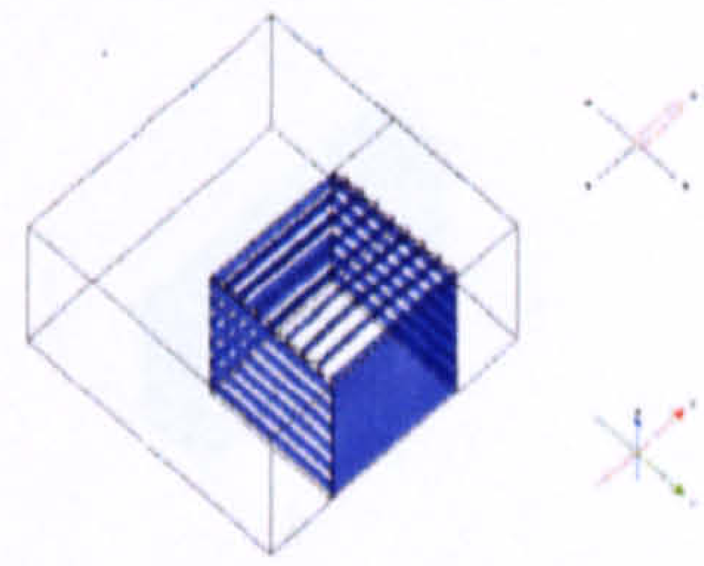
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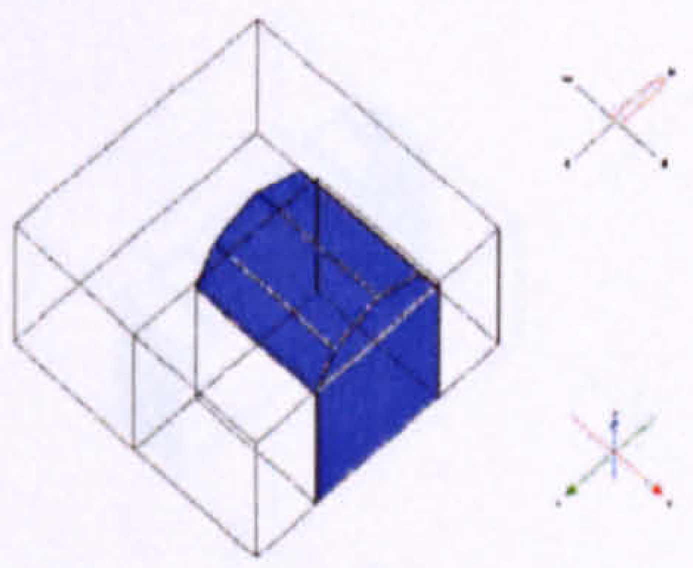	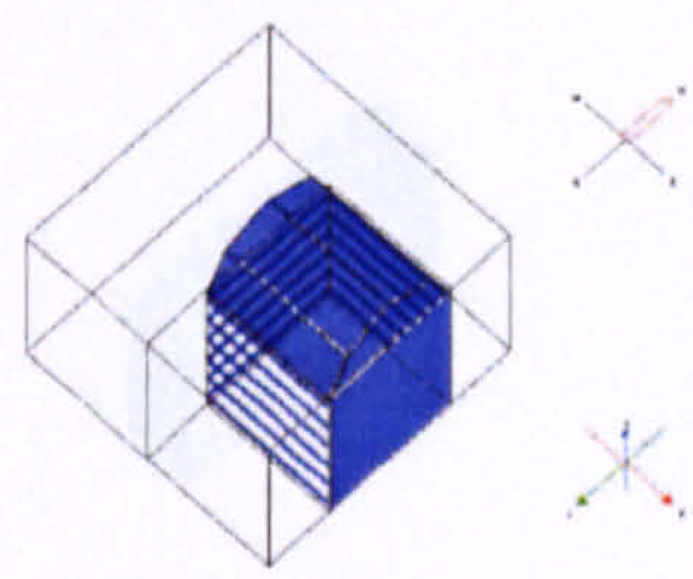	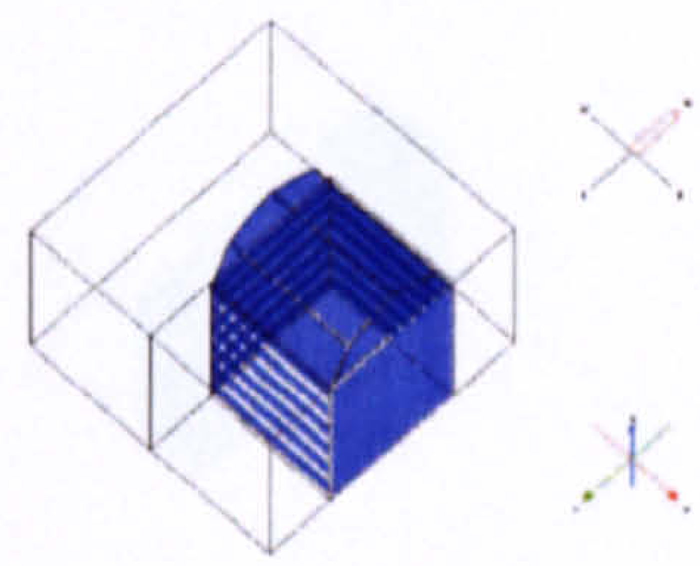
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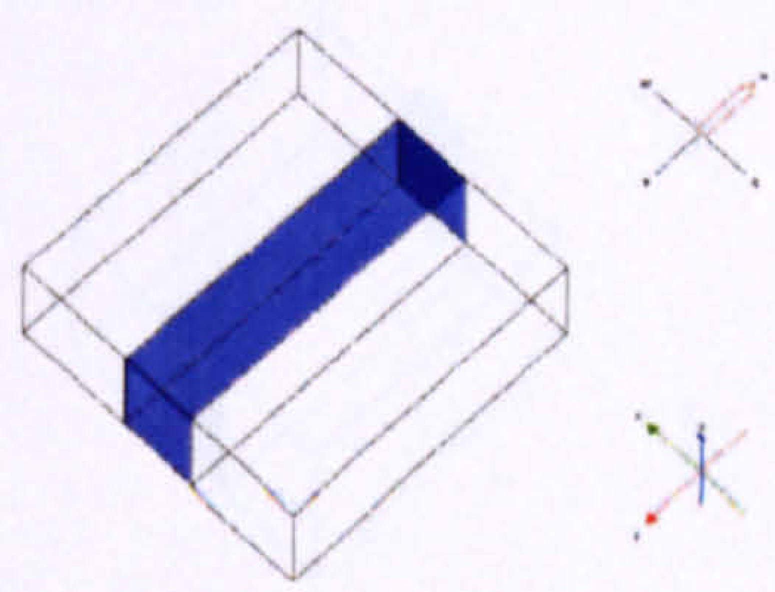	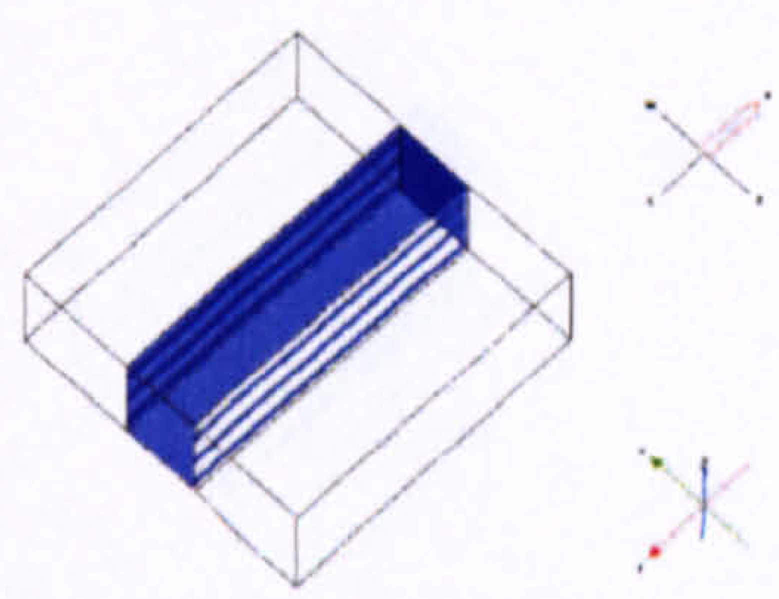	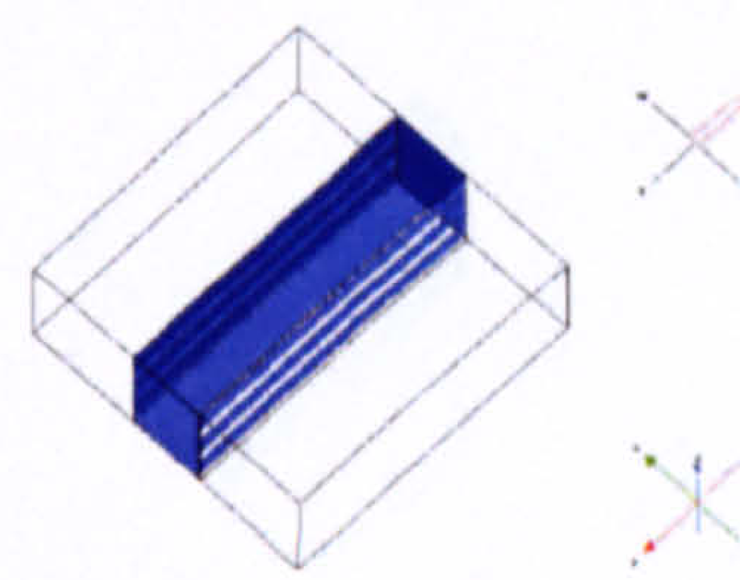
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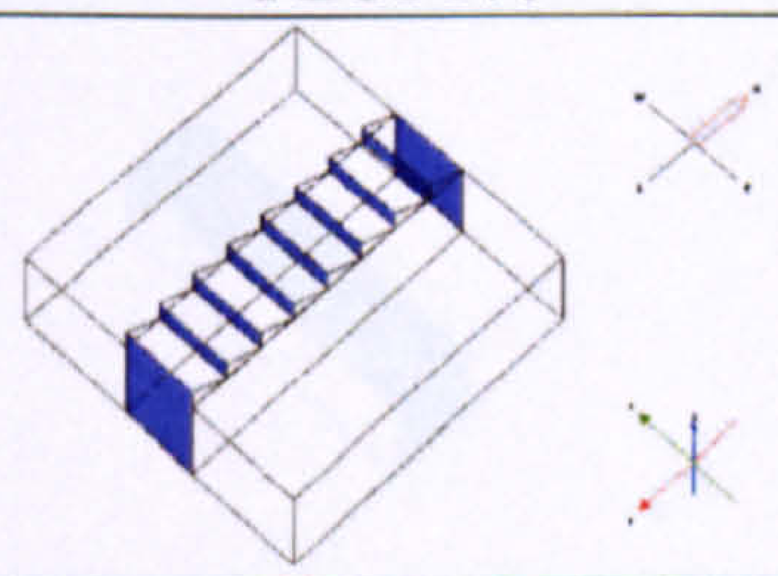	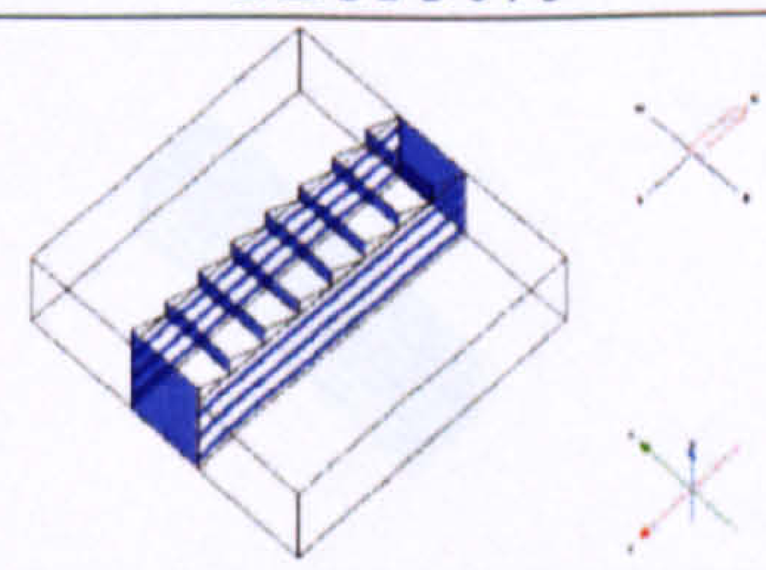	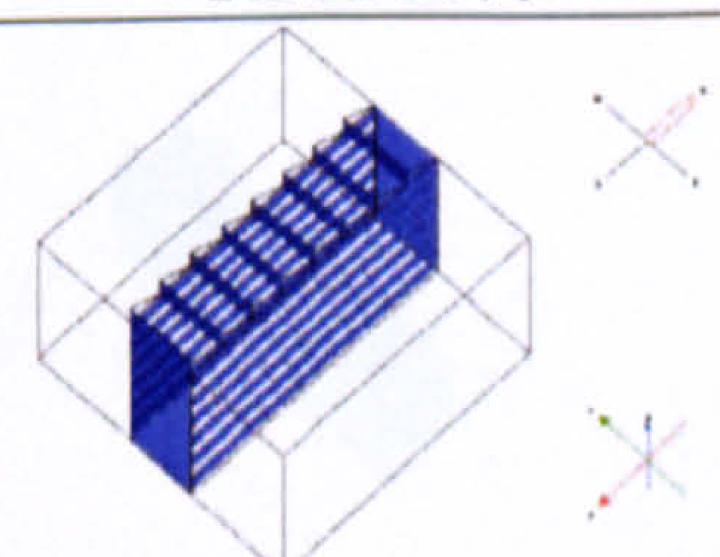
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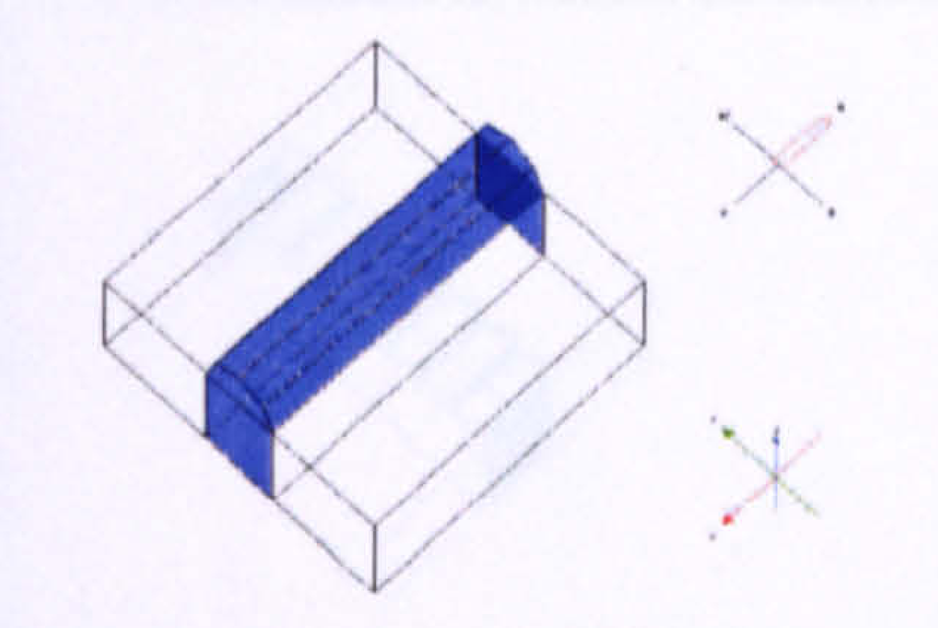

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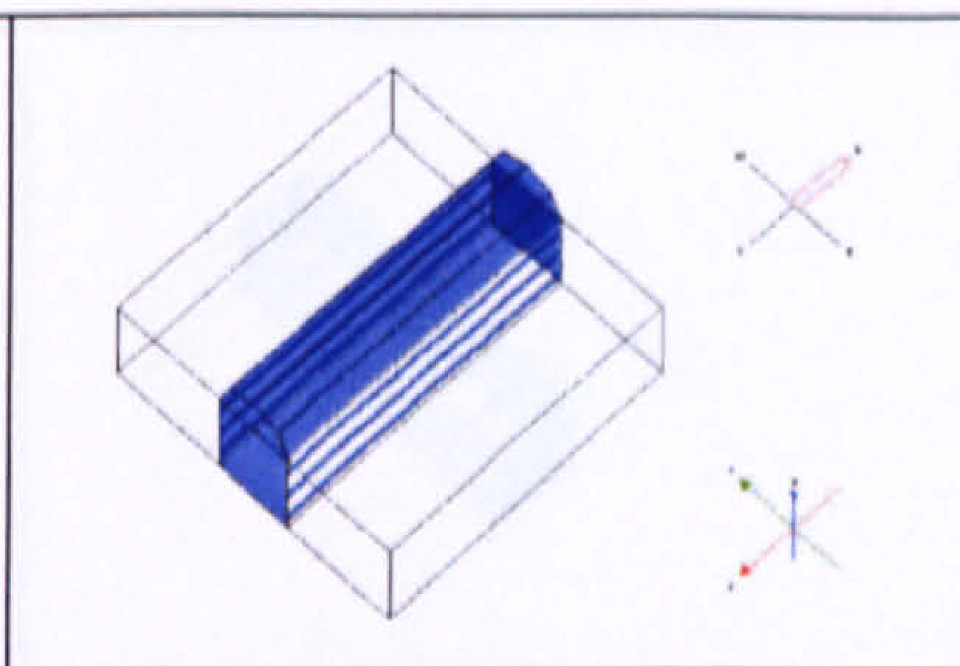

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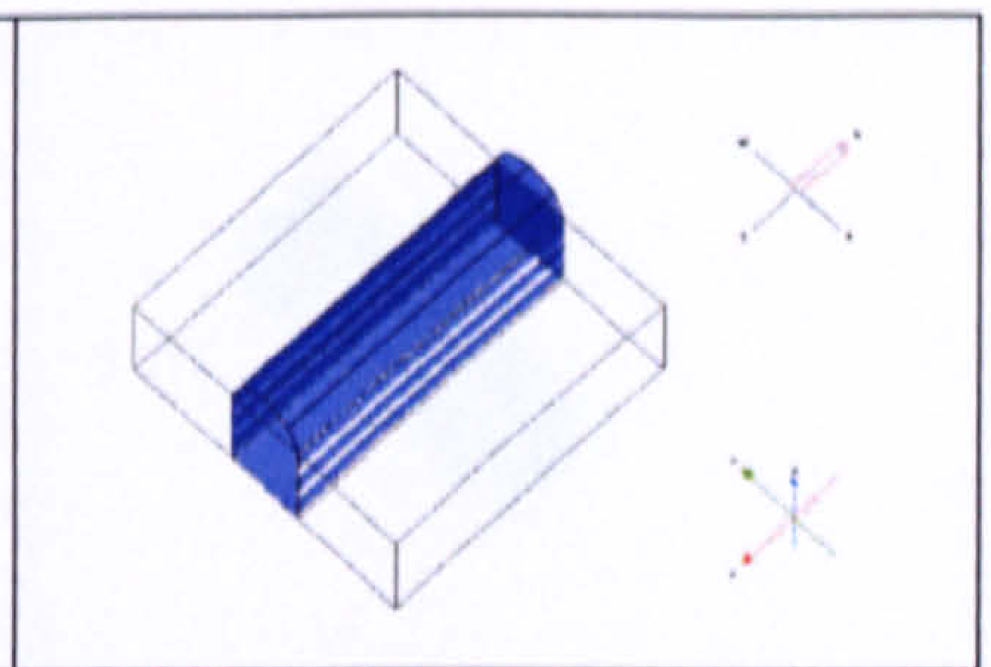

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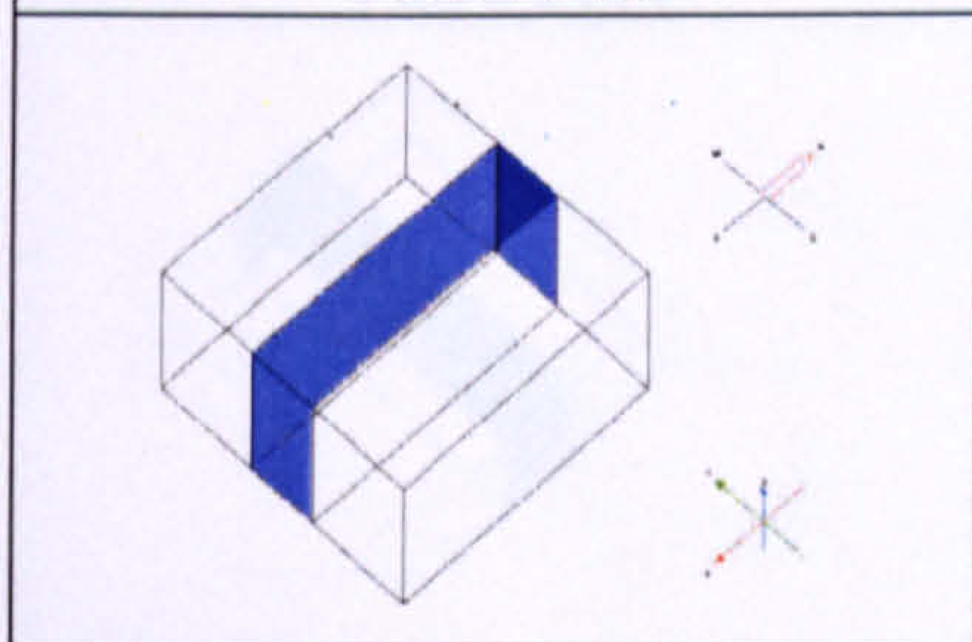

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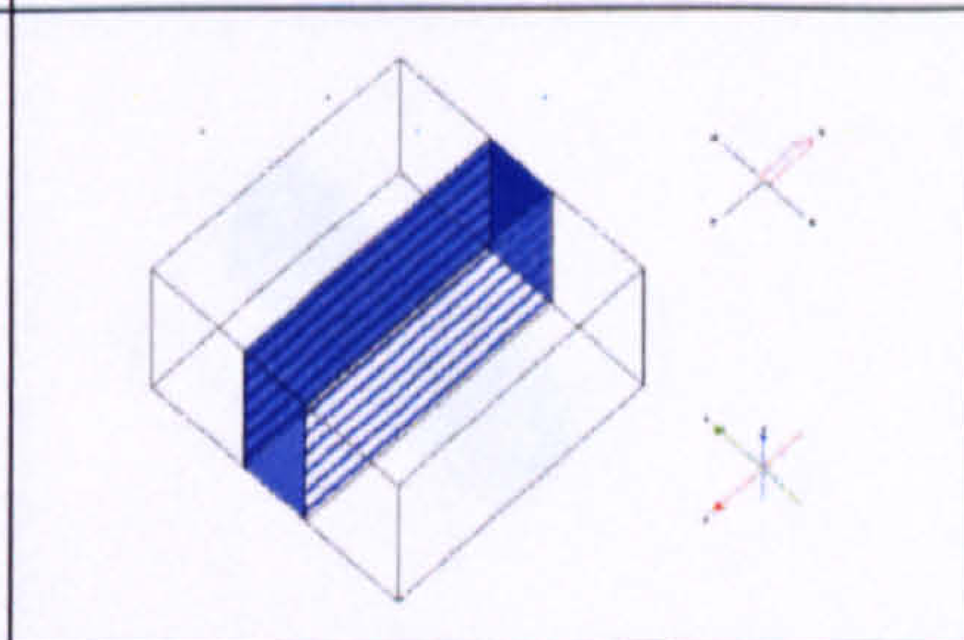

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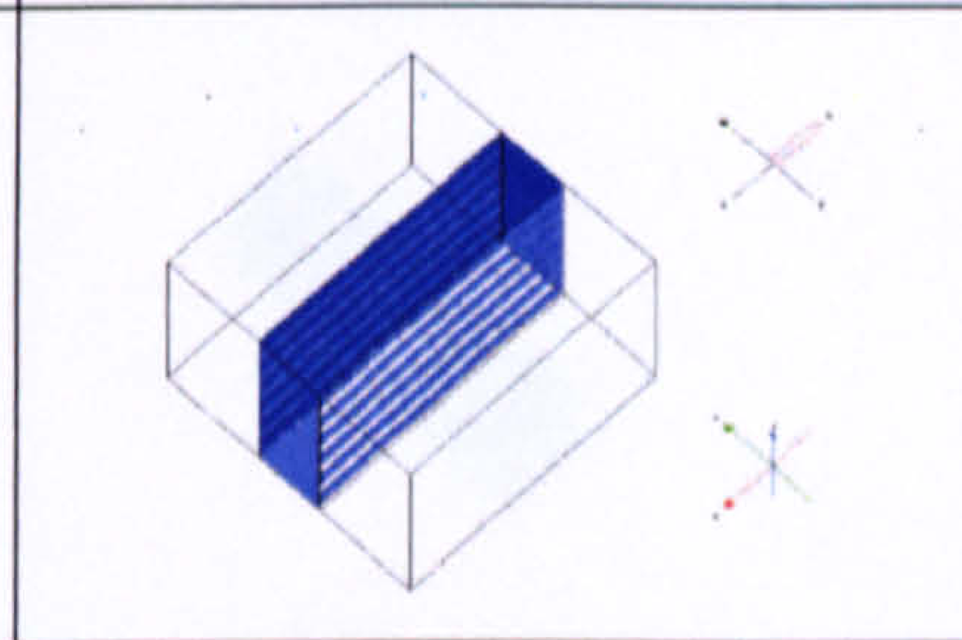

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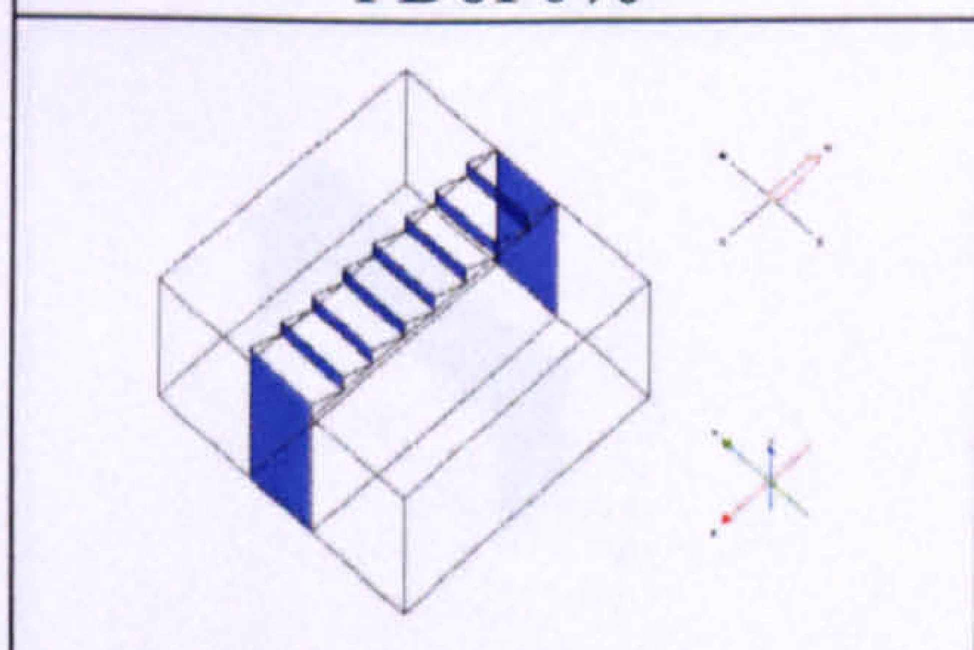

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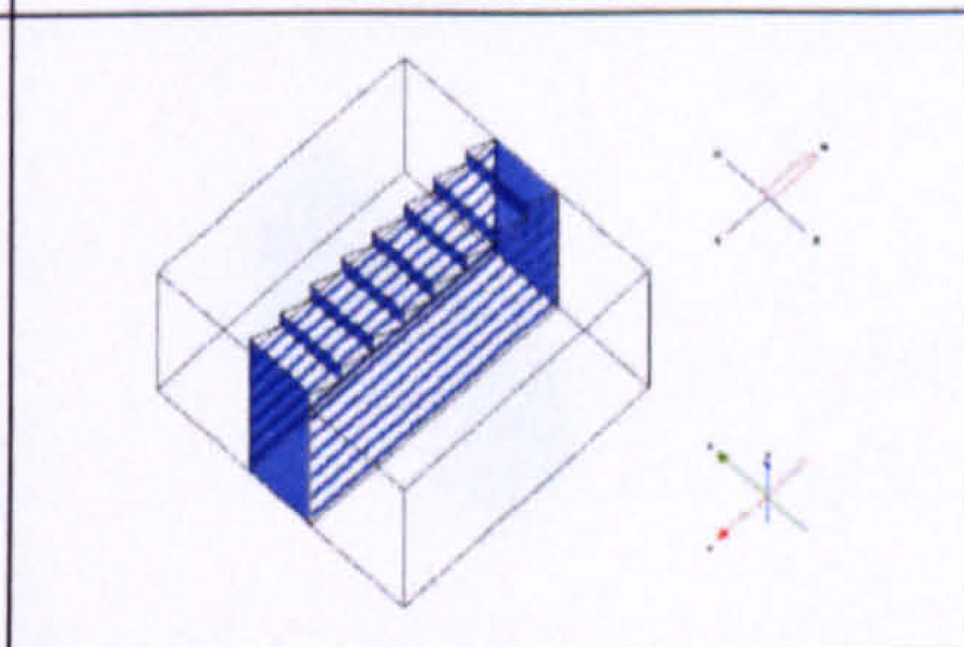

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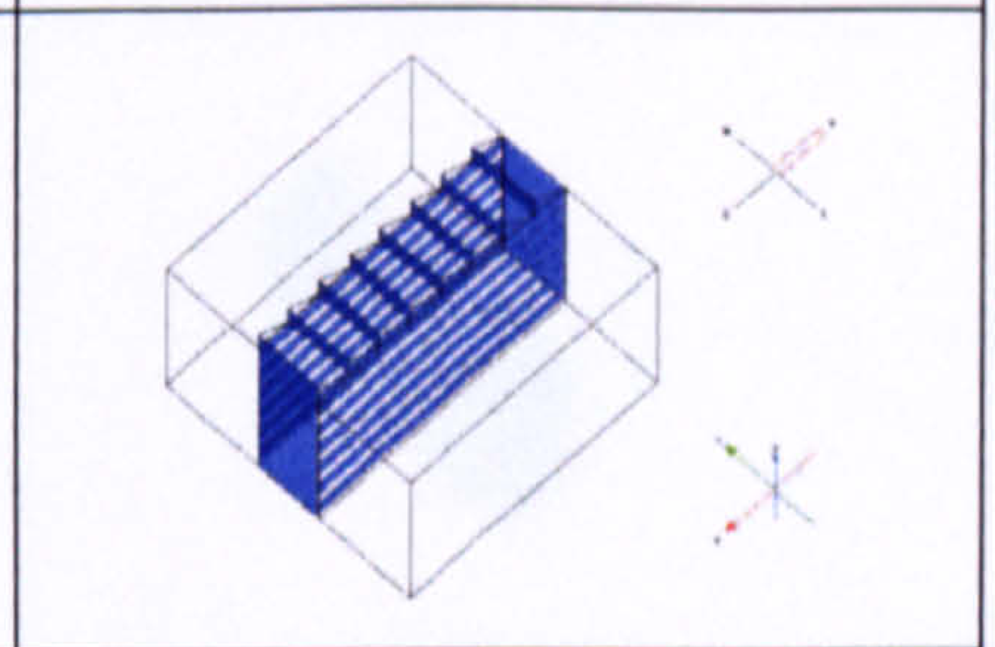

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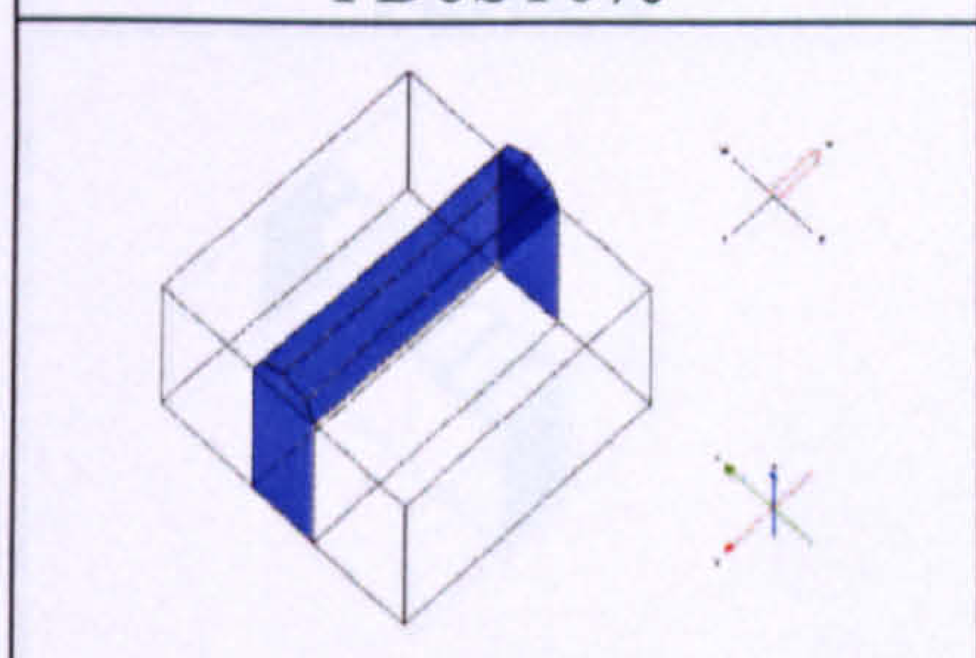

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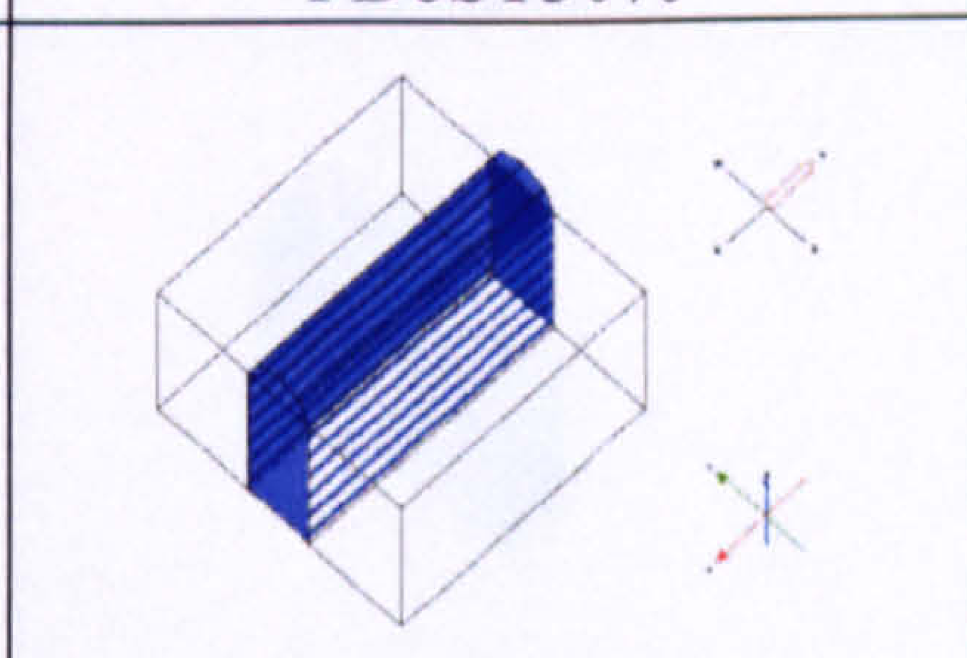

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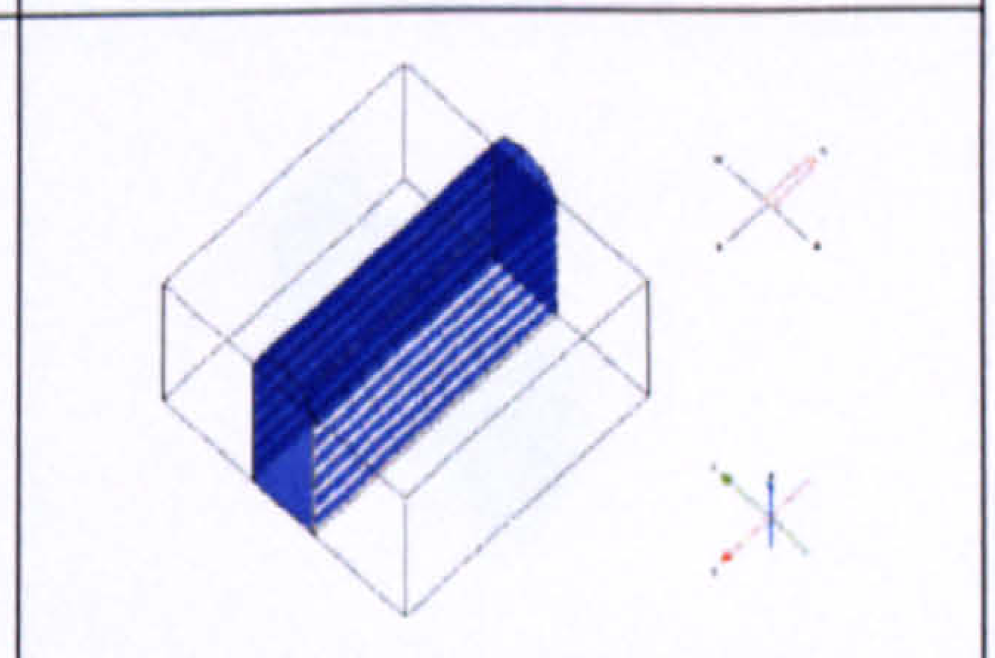

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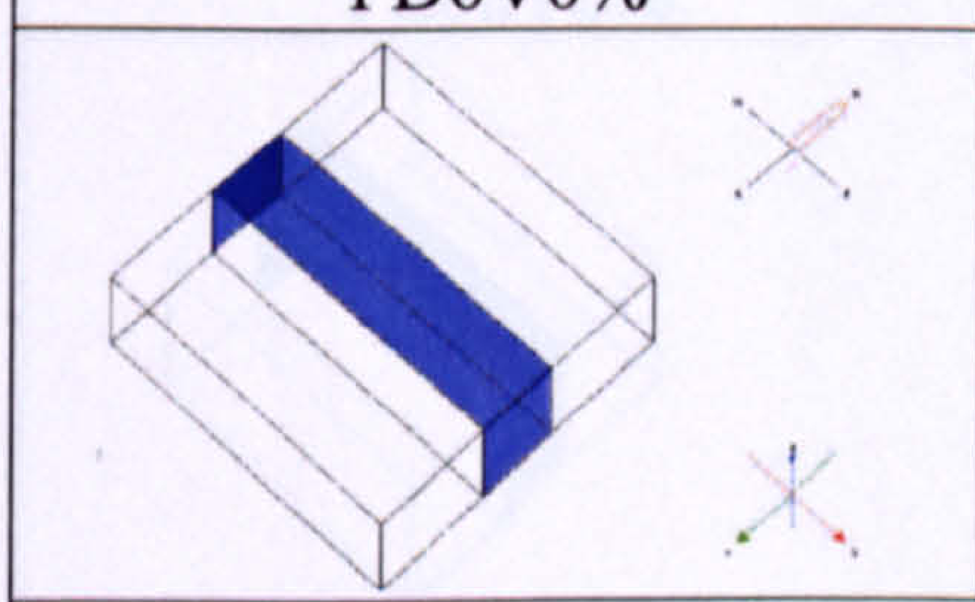

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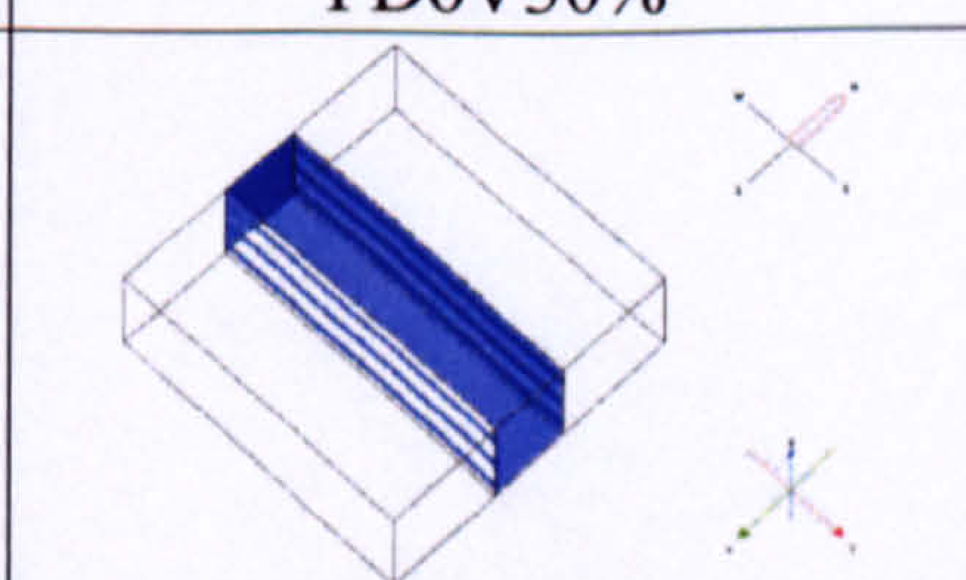

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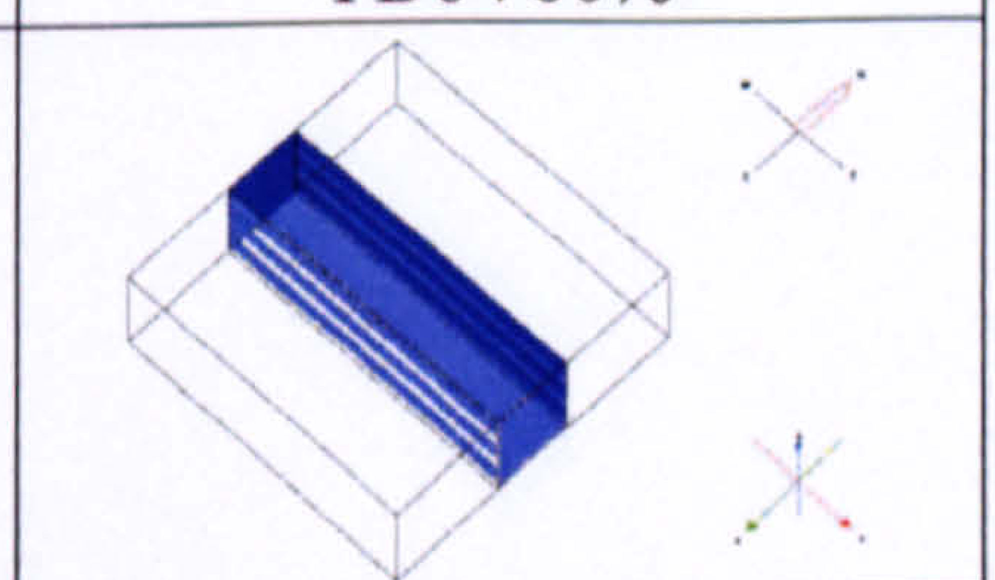

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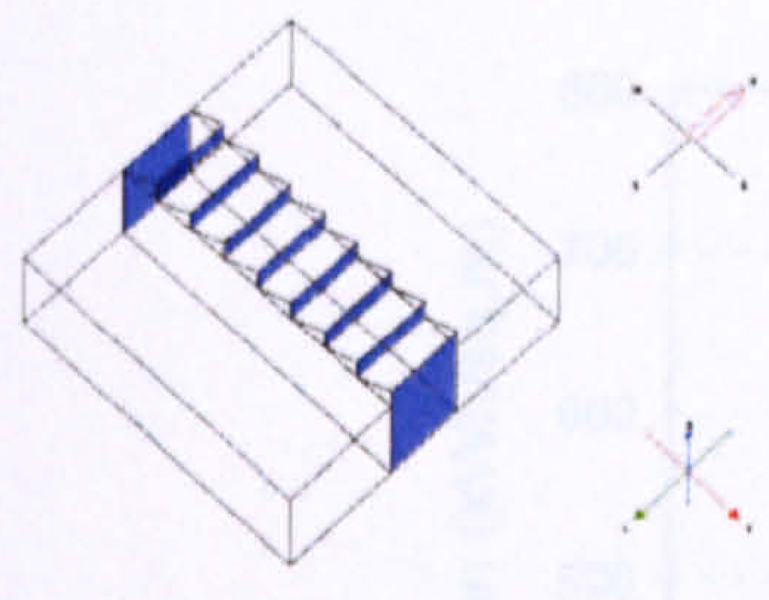	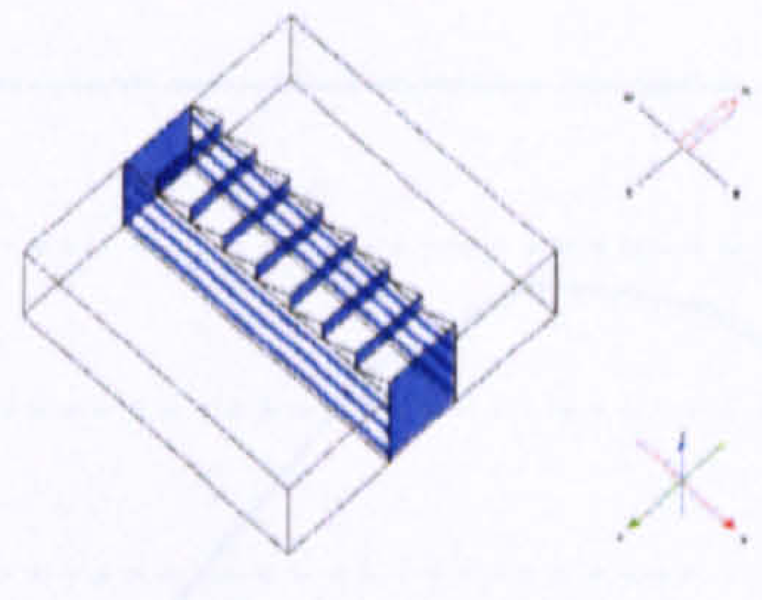	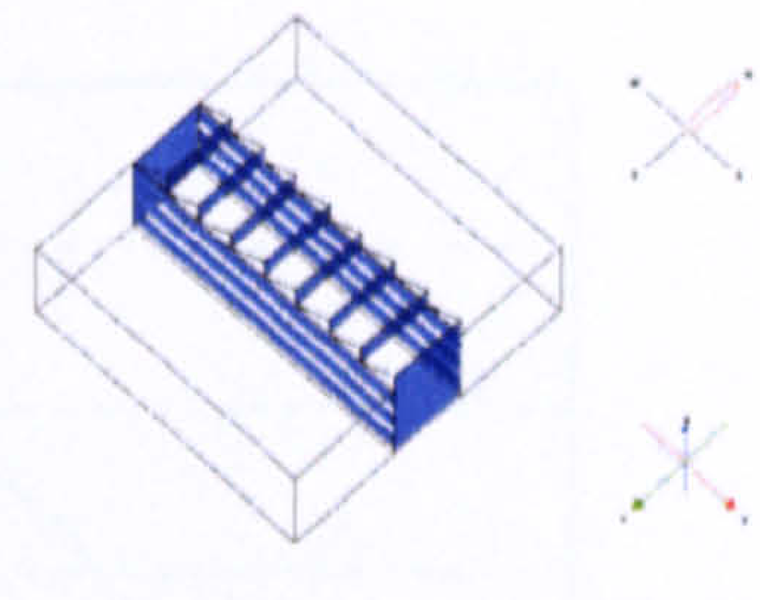
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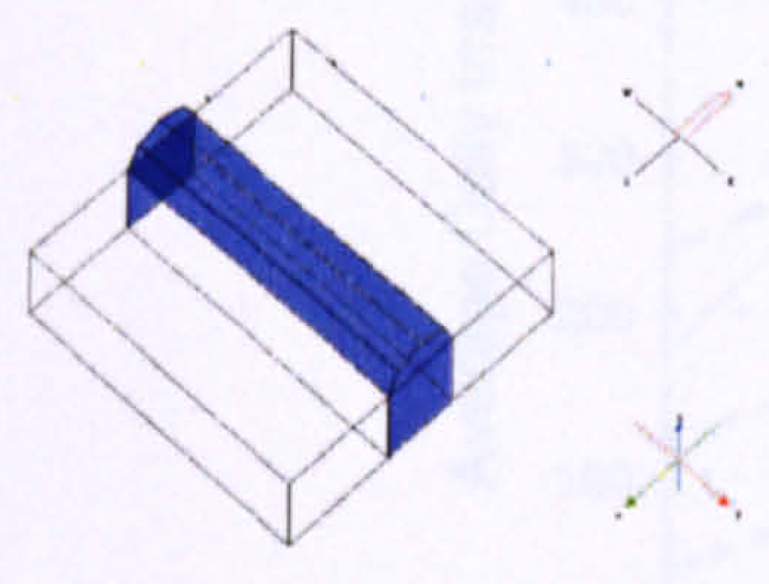	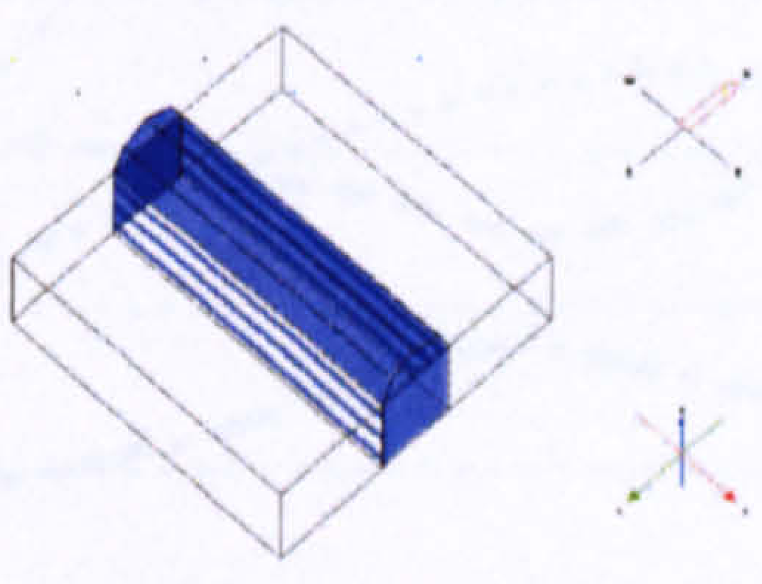	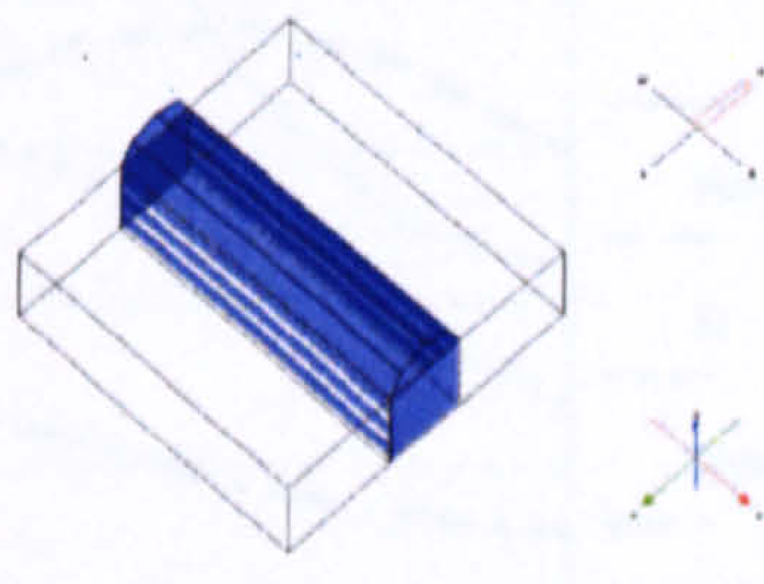
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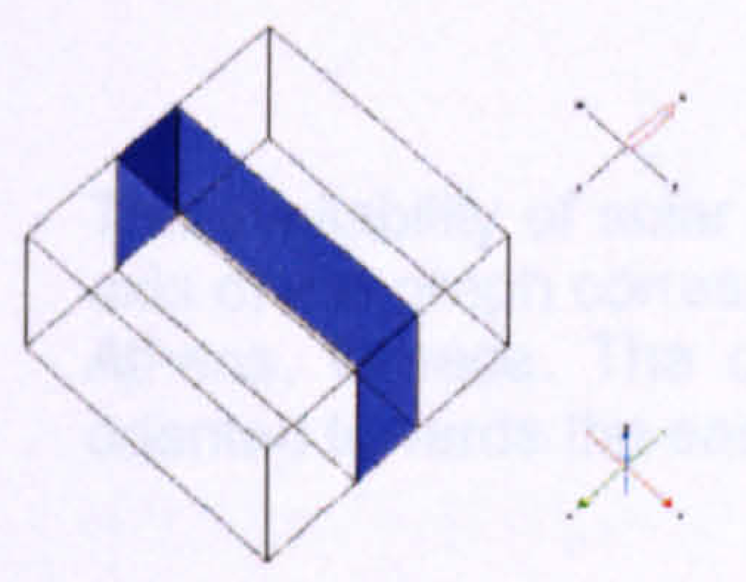	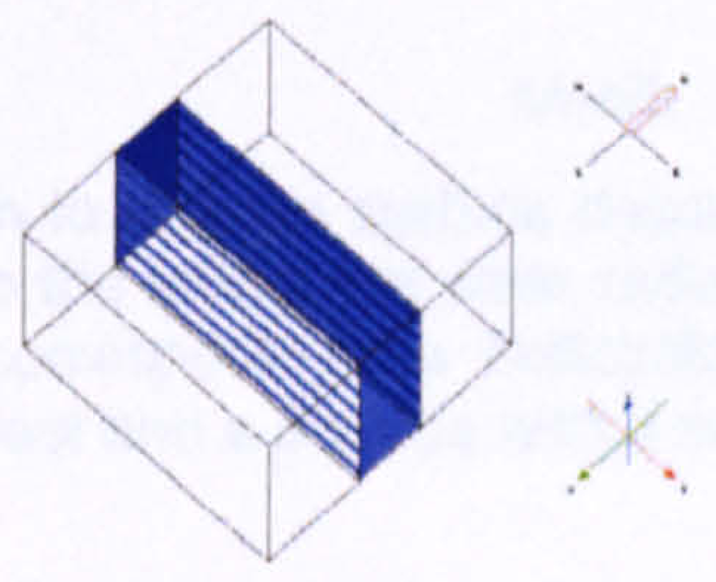	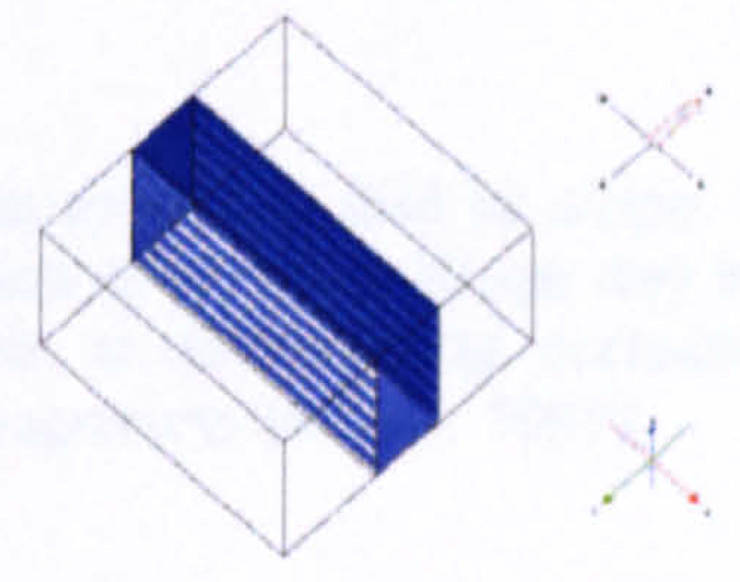
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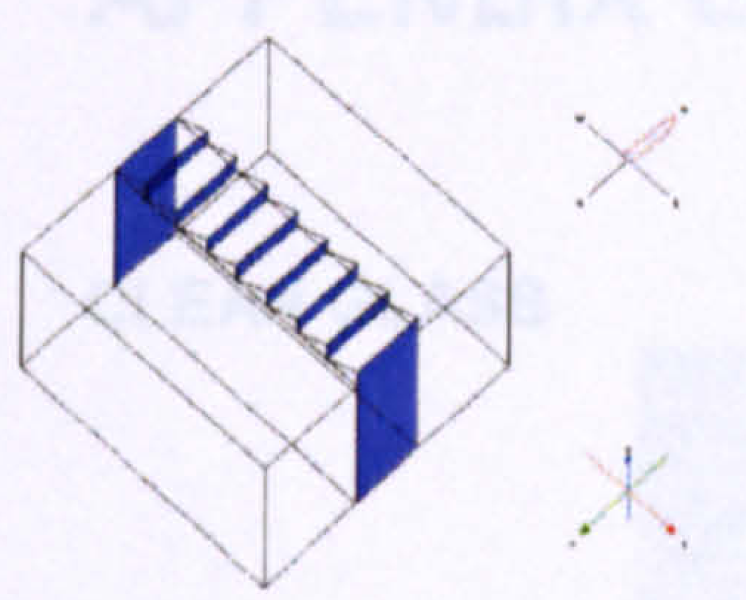	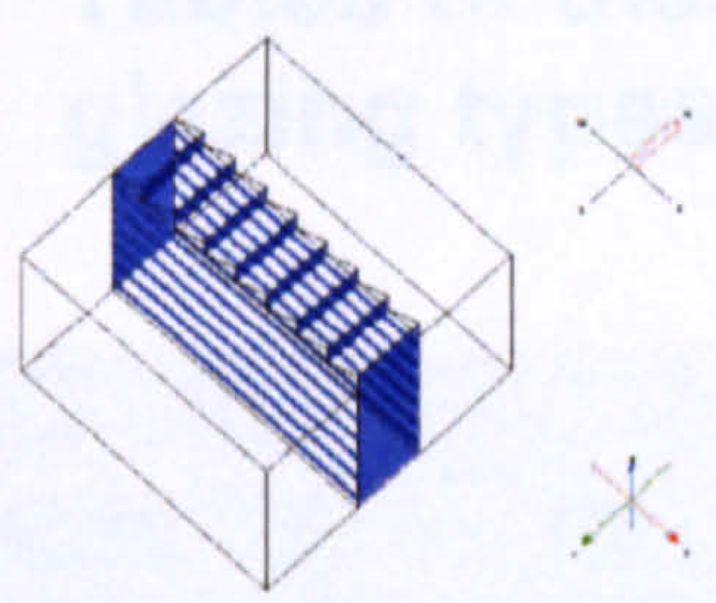	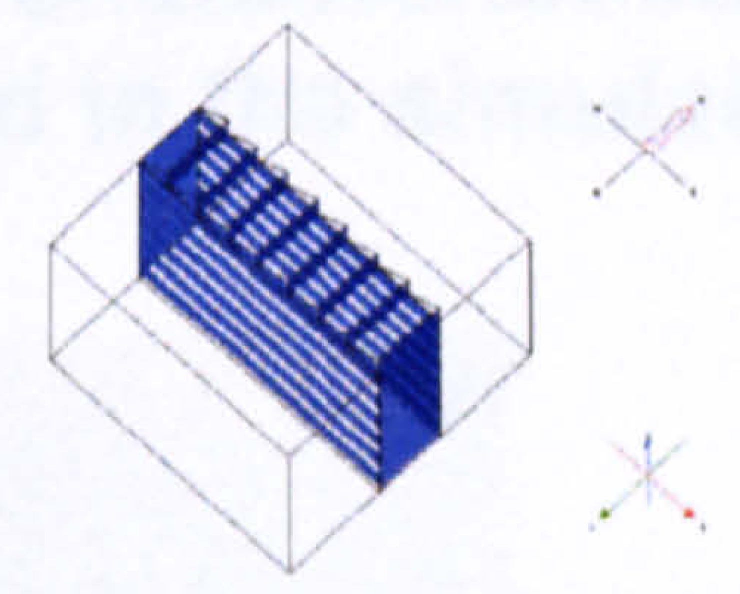
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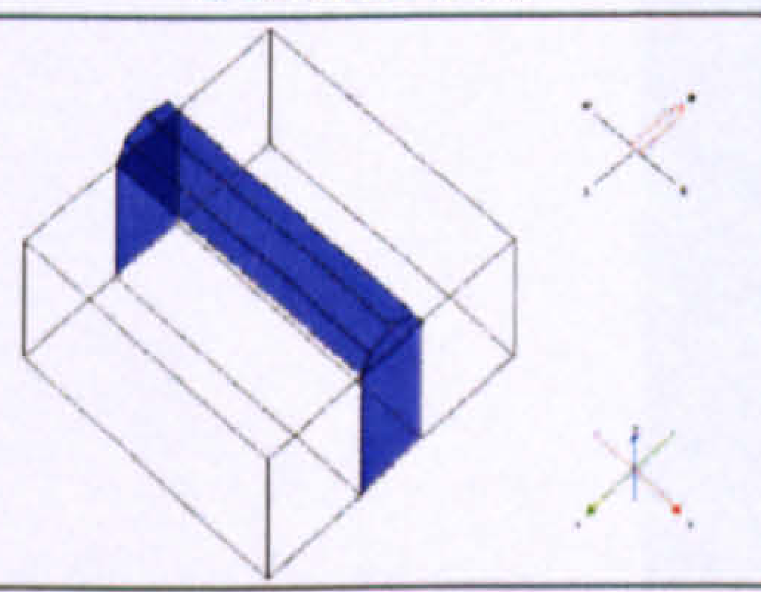
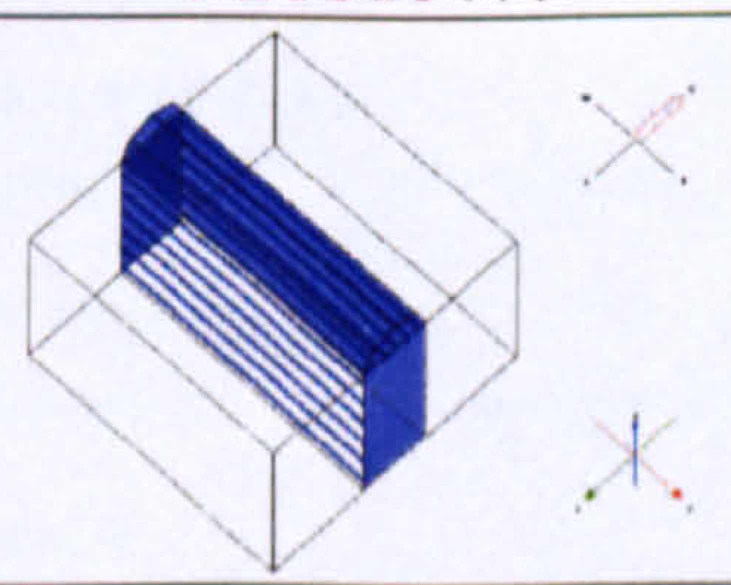
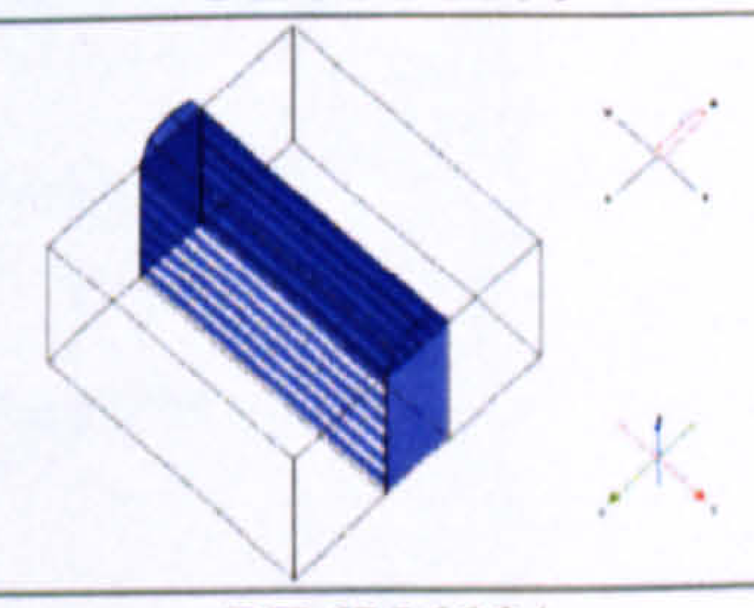
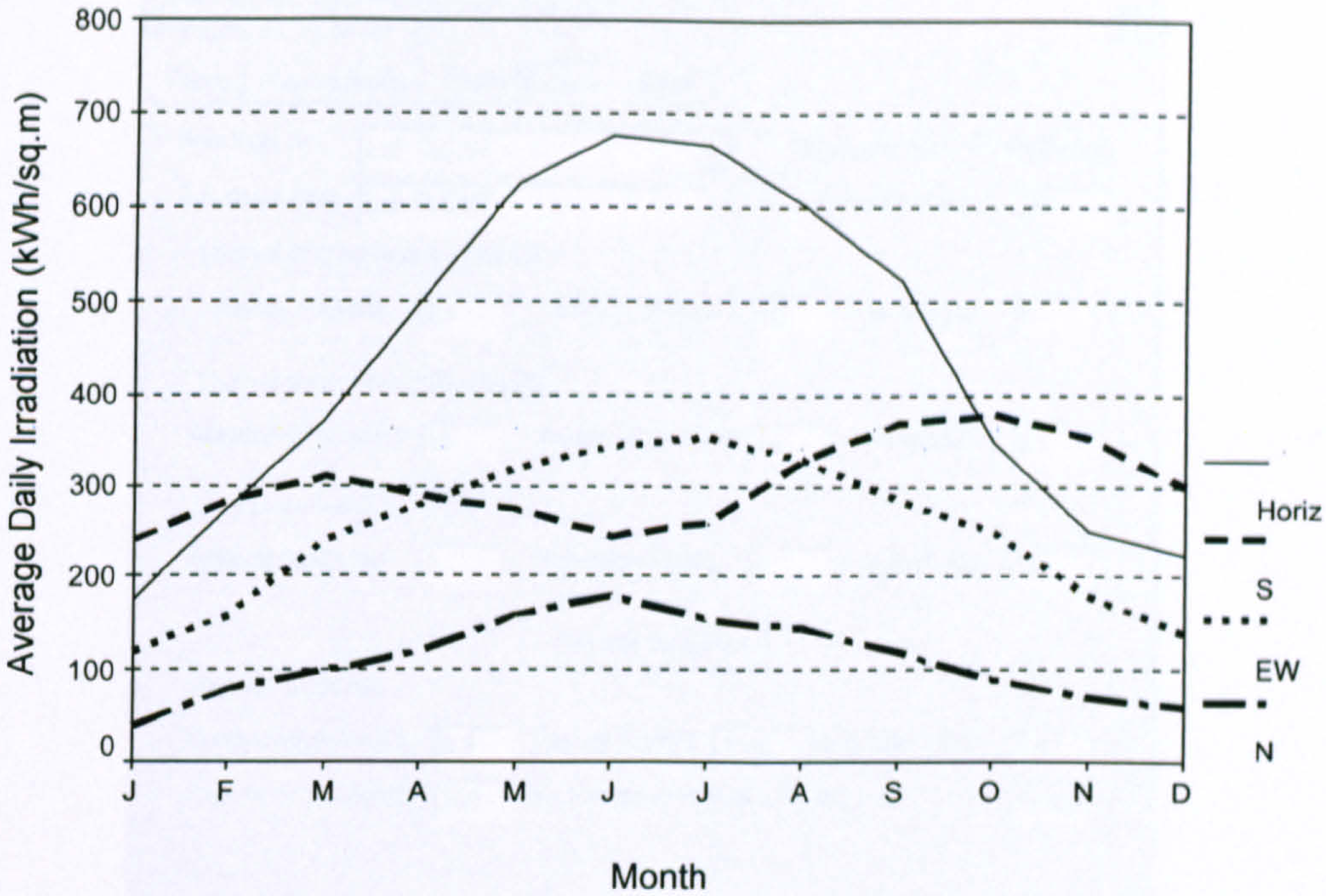
		
PE6V0%	PE6V30%	PE6V60%

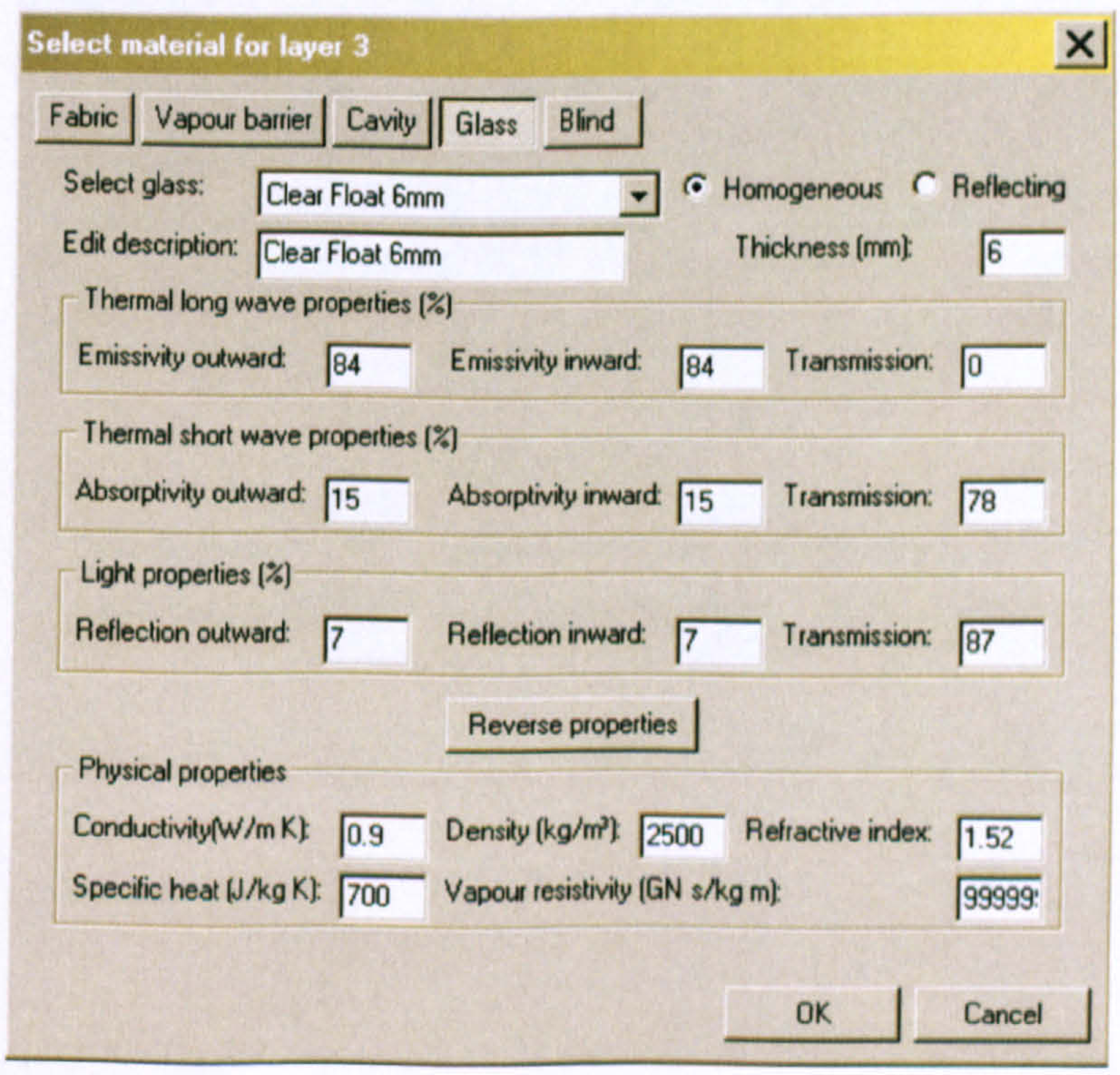
APPENDIX Ga Graph of available solar radiation in a given surface for Athens



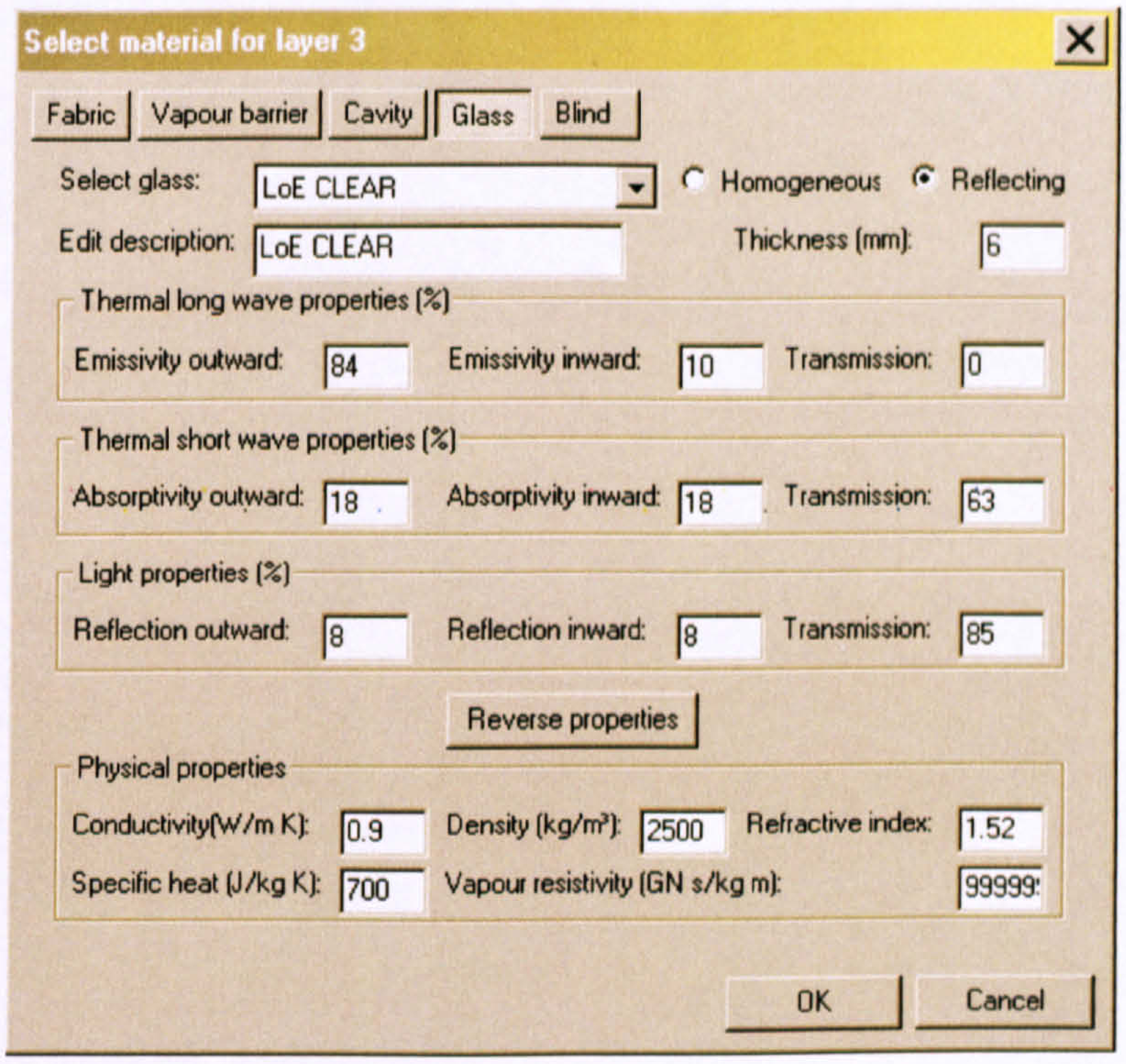
The availability of solar radiation to a given surface depends on its exposure and its slope. The vertical axis of the graph corresponds to the amount of solar radiation available on an average day in kWh/m^2 in Athens, Greece. The curves correspond to a horizontal surface, a south-facing surface, a surface oriented towards the east and west and a surface with a northern exposure. [Lewis, 1997]

APPENDIX Gb Tables of thermal characteristics of glazing types used in the simulation

CLEAR GLASS



LOW-EMISSIVITY GLASS



REFLECTIVE GLASS