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Environmental Design in Contemporary Brazilian Architecture: The Research Centre of the National Petroleum Company, CENPES, in Rio de Janeiro

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Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/48420>

1. Introduction

This paper assembles the complete work of environmental design developed for the new research centre of the Brazilian Petroleum Company, Petrobras, in the tropical city Rio de Janeiro, in Brazil (latitude 22.53S). The main objective is to make clear the relationship between architectural solutions, environmental strategies and quality of space, by presenting the criteria and methods applied to the architectural concept and technical assessment of four complementary areas of environmental design: outdoors comfort, daylight and natural ventilation in buildings and, ultimately, the energy performance of air conditioned spaces.

Undertaken by members of the Laboratory of Environment and Energy Studies (LABAUT) from the Department of Technology of the Faculty of Architecture and Urbanism of University of Sao Paulo (FAUUSP), the environmental design of the new research centre of Petrobras was a comprehensive project of research pro-design related to the environmental performance of contemporary buildings in one of the Brazilian's main cities, Rio de Janeiro.

The design project was the object of a national architectural competition held in 2004. The programme of activities is an extension of the existing research centre, including laboratory rooms, offices, a convention centre, restaurants, greenhouse spaces and other special facilities (e.g. energy generation and model testing of petroleum platforms). The total built area of the extension of the Petrobras Research Centre in Rio de Janeiro encompasses 66.700,78 m², built on 193.290,65 m² site at the Guanabara Bay in Rio de Janeiro (see figure 1),

resulting in a plot ratio of 34,5% [1]. Completely built in 2010, this research centre is the first building complex of its size and complexity in Brazil to integrate environmental principles at the very early stages of the design. However, it should be noticed that the environmental agenda was not a particularity of the second phase of the Petrobras Research Centre. Comfort issues including thermal comfort were already regarded in the conceptual ideas of the architect Sergio Bernardes's for the first phase of the Petrobras research centre from the 1970s [2].

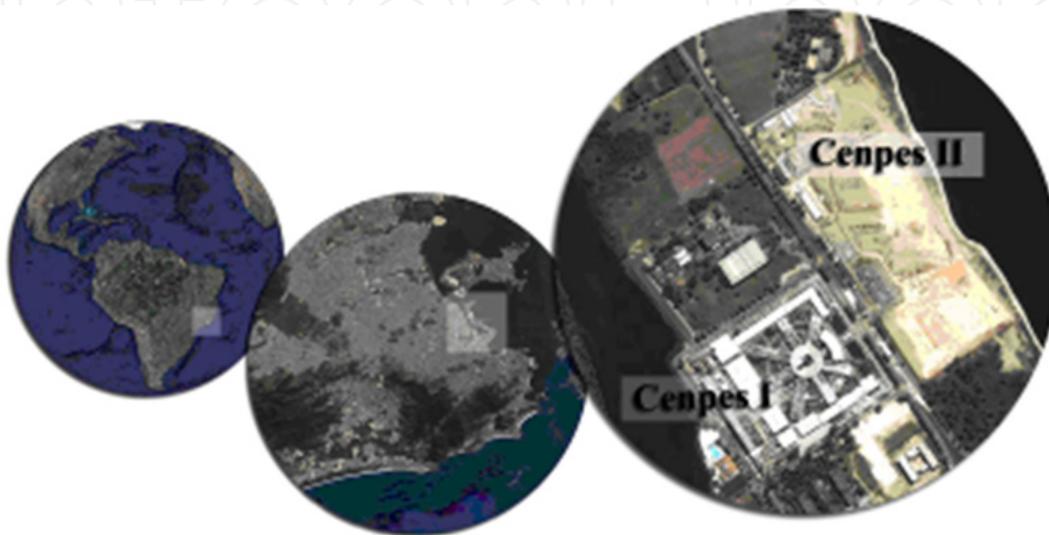


Figure 1. Site location of the Petrobras Research Centre in the Guanabara Bay of Rio de Janeiro.

Alongside a series of functional requirements, the design brief aimed for environmentally responsive solutions related to the comfort of the occupants and buildings' energy efficiency, in which the use of daylight, natural ventilation and vegetation were mandatory. Moreover, the brief's environmental agenda included issues associated with water consumption and the environmental impact of building materials. A list of 10 items summarises the environmental brief, involving building's design and building services: 1. buildings' orientation according to solar radiation, 2. buildings' form according to principles of bioclimatic design, 3. appropriate materials to local environmental conditions, 4. window wall ratio (WWR) according to local environmental conditions and good use of daylight, 5. protection against solar radiation, 6. natural ventilation in buildings, 7. good use of daylight, 8. low environmental impact materials, 9. rain water harvesting and re-use of grey water and, 10. vegetation for local environmental benefits, such as ecological niches and biodiversity [1]. Those strategies had a rather generic approach, with no pre-established quantitative criteria or benchmarks, opening up the possibility for the creation of a bespoke environmental reference in the context of Brazilian contemporary architecture.

The winning architectural scheme was the proposal from Zanettini Arquitetura S.A., (co-authored by José Wagner Garcia), which was informed by creative contributions from the various complementary areas, including structural, mechanical and electrical engineering and landscape and environmental design, resulting in a truly conceptual holistic design proposal. The local warm-humid conditions of Rio de Janeiro had a major influence on the

architecture of the winning design project, which was inspired in one hand by the local bioclimatic modernist architecture (specially from the period between 1930's and 1960's) and on the other hand, by contemporary environmental principles and methods as well as the possibilities of current construction technologies.

In terms of internal thermal environmental conditions the new buildings of the research centre encompassed totally naturally ventilated, mixed-mode and full-time air conditioned buildings as a function of buildings' use and the consequent environmental requirements. The naturally ventilated ones are the Operational Support Building and Utilities Centre all designed based on the architectural typology of the factory building. The main air conditioned and mixed-mode buildings are: the central Building (approximately 36.000 m²), the Laboratories (approximately 33.000 m²) and the Convention Centre (approximately 6.500 m²), being those three functions located at the core of the architectural composition.

Apart from influencing the architectural design, the local climatic conditions also played an important role in re-establishing some of the basic environmental performance criteria, such as the definition of comfort parameters, energy consumption targets and daylighting levels, based on the warm-humid climate of Rio de Janeiro. As the architectural design progressed, environmental assessment evolved from the interpretation on principles and simplified analytical work to advanced simulation procedures, carried out over the first 9 months of the total design period which lasted 22 months (from November 2004 to September 2006), covering the integral part of the architectural design concept). Construction began in September 2006 and was completed in 2010.

Looking at the first stages of the design of the winning project for the Expansion of the Petrobras Research Centre in Rio de Janeiro, design of the architectural proposal designed by Zanettini Arquitetura S.A., co-authored by Arch. José Wagner Garcia, and supported by a diversified consultancy team, this work presents the environmental concepts and some of its qualitative and quantitative performance aspects, highlighting the role of the Environment and Energy Studies Group of the *Faculdade de Arquitetura e Urbanismo, Universidade de São Paulo* (Faculty of Architecture and Urbanism of the University of São Paulo).

The environmental studies of the expansion of Petrobras Research Centre in Rio de Janeiro had four main objectives: assess the thermal comfort in the open spaces created by the horizontal disposition of buildings on site; maximize the benefits of daylight, assess the thermal performance of free running buildings where natural ventilation was required as a function the programme; and finally assess the performance of architectural solutions for air-conditioned buildings, where active cooling was a design premise.

The new buildings of the expansion were classified in two groups: one which the main the spaces had to be naturally ventilated, being these the *Operational Support Building* and *Utilities Centre*, and the other where the artificial control of the thermal conditions by means of active cooling systems was a design premise, being these the *Central Building* (an office building), the *Laboratories* and the *Convention Centre*. In addition, three other buildings of the

research centre had active cooling as a functional requirement: the two restaurants and the *Visualization Centre (Núcleo de Visualização e Colaboração, NVC)*, (see figure 2) [1].

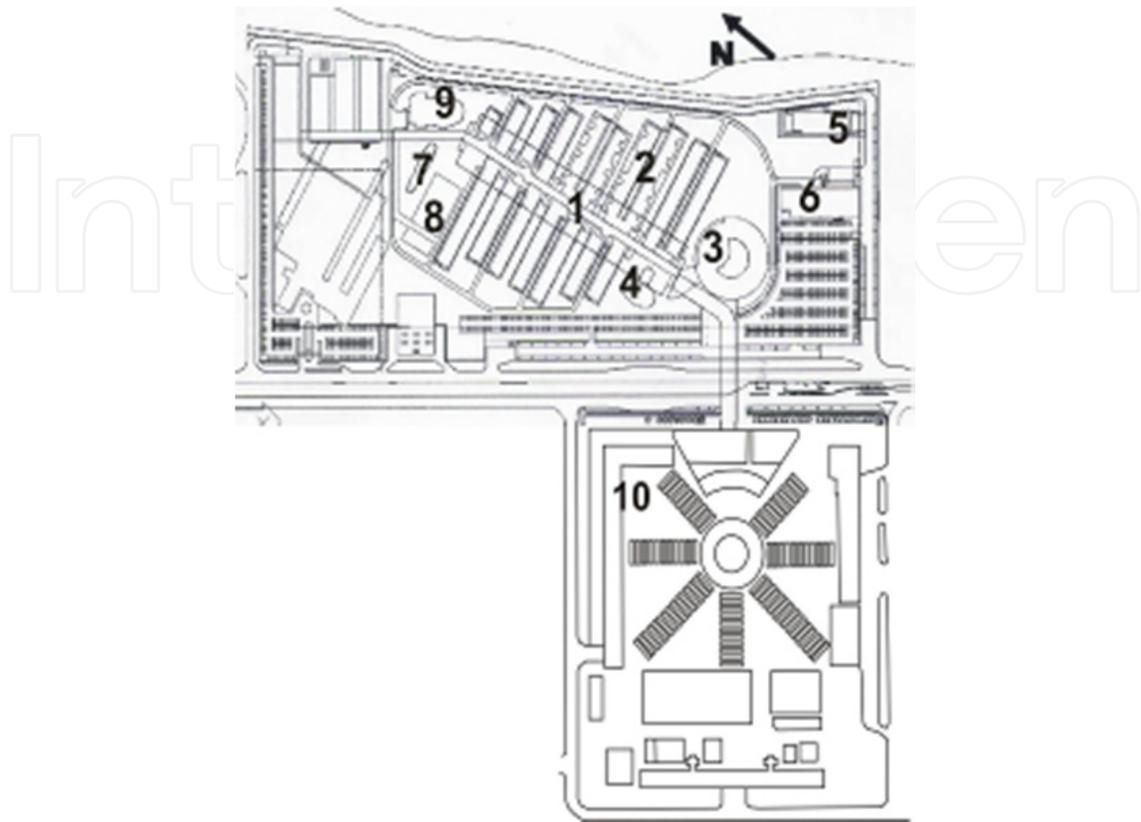


Figure 2. CENPES site planning, including the 1st phase of the Research Center towards the south and the expansion with new buildings on the north part of the site facing the bay, as presented in the winning proposal.

The initial requirement for active cooling in all office spaces of the Petrobras research centre for all year round could be associated with the air-conditioning cultural of working spaces (artificial cooling is an unquestioned factor in commercial buildings in most Brazilian cities, being definitely a common practice in Rio de Janeiro), rather than a climatic driven need. Challenging the supremacy of air conditioning in the context of office spaces in Rio de Janeiro, the efficiency of natural ventilation and the introduction of the mixed-mode strategy were critically evaluated for the various typologies and conditions of working environments within the new buildings of the research centre, being ultimately recommended in some particular cases. Initially a simplified analysis of the local climate suggested the possibility of natural ventilation in a typical office space for approximately 30% of the working hours over the year, which justified a more detailed analysis of the mixed-mode strategy for the final design proposal [3].

2. Environmental concept

The preliminary climatic diagnosis highlighted the importance of shading and light colors as well as the possibility of natural ventilation as the main passive strategies to reduce heat

gains in buildings and improve thermal comfort both indoors and outdoors. Analysis were based in a reference climatic year, with hourly data, encompassing readings from 2000 to 2004 of the meteorological station situated at the International Airport of Rio de Janeiro, situated within 2Km from the site of the Petrobras Research Centre. Air temperatures were high, more than 29°C for 10% of the year, and below 20°C, for 10% of the year as well, combined with high relative humidity rates, more than 70% in 66% of the year [4].

In this context, the search for adequate building environmental strategies started at the concept stage, addressing thermal comfort in buildings and open spaces, daylighting, acoustics and the specific issue of cooling demand. A horizontal architectural composition of multiple buildings derived from the core objective of creating meeting areas in semi-outdoor spaces, With buildings connected by transitional spaces, site planning and architectural form were defined to respond to need of protection from solar orientation, versus the exposure to natural ventilation and views towards the bay. Double roofs and various shading devices, high-level openings and open circulation routes are some of the defining architectural features which are found in all key buildings of the expansion of the Petrobras Research Centre in Rio de Janeiro.

At the masterplanning scale, the main environmental strategy was to position the different functions of the programme in separate low-rise buildings, keeping people at the ground level, or close to it and in contact with the external environment. As buildings were interspersed by transitional spaces on a predominantly horizontal occupation of the site, a series of open and semi-opened areas of different environmental qualities, including sunny and shaded areas (or partially shaded), exposed to various wind directions, as well as different landscape projects were created between, around and within buildings [5].

The value of such transitional spaces to the overall design concept was primarily related to the possibility of comfortable outdoor spaces protected from the all year round inhibiting solar radiation of Rio de Janeiro, available for leisure, social interaction and working activities, in other words, introducing the outdoors experience in the daily routine of the occupants and visitors of the Petrobras Research Centre in the Guanabara bay. Furthermore, environmentally the transitional spaces also give the benefit of reducing the impact of solar gains in the thermal performance of buildings' internal spaces (being some of them artificially cooled). In summary, the main transition spaces of the complex are associated with the three main buildings: the terraces from the Central Building, the gardens between the wings of Laboratories and the central open atrium of the Convention Centre, which is the main access to the expansion of the Research Centre.

The building cluster formed by the main office building (the Central Building), the laboratories and the convention centre was conceived to be the core of the masterplan of the extension of the research centre (see figure 3) laboratories were allocated in parallel wings facing the north-south orientation, on the two sides of the main office building (which then looks at east and west towards the bay).

The emphasis given to the efficiency of space and functionality, specially with respects to the laboratories and their connections to the rest of the research centre, was a fundamental to the site planning of buildings both in the first phase as in the expansion of the Petrobras Research Centre, as it was the importance given to the transitional spaces in the overall environmental quality of the masterplan. Whilst in the first phase, the laboratories follow and radial displacement on the site, in the expansion project, parallel rows of laboratories oriented north-south are attached to the long linear main central building, as shown previously in figure 2.

The north-south orientation to the laboratories was chosen given the relatively minor exposition to the direct solar radiation, therefore the most favorable conditions to achieve good daylight (specially from the south) and minimize solar gains, considering that daylight was a fundamental requirement to the laboratories, where cellular office cells were designed to be naturally ventilated.

The north-south orientation of the laboratories' wings was also important to allow the penetration of the predominant south-east wind into the open and semi-open areas of the complex through the patios – the semi-open spaces between two parallel laboratory wings, whilst creating appropriate conditions for the installation of photovoltaic cells on the exposed areas of the roof of laboratories.



Figure 3. Physical model of the new masterplan for the expansion of the Research Center. Source: Zanettini Arquitetura S.A.

In the case of the Central Building, the orthogonal position in relation to the wings of laboratories resulted in the east-west orientation, which brought the challenges of providing solar control on the facades whilst allow for views and daylight. On the other hand, apart

from giving the opportunity of views towards the bay, the east orientation facilitated exposure to the prevailing wind from south-east (comparable to the sea breeze) at the terrace level, where semi-open spaces totally protected from the sun were design to encourage outdoors working activities, leisure and social interaction. On the opposite orientation, the west façade looks at the first buildings of the Research Centre, built on the 70s.

Architecturally, the shading of windows and semi-open spaces coupled with the use of light colors on the external facades (primarily white) were primary strategies in response to the local climatic conditions. As a result, a series of opened circulation areas inside and between buildings, shaded from the direct sun but exposed to wind, alongside internal environments of diffuse daylight and protected views of the surroundings qualify the architecture of the buildings placed at the core of the new masterplan: The Central Building, Laboratories and Conventional Centre.

However, it is important to notice that the environmental qualities and the related architectural solution of the double roofs in the main office building and the laboratories were modified with the design development. In the case of the Central Building, the original permeable structure gave place to a more robust and closed roof (see figures 4 and 5), whilst in the laboratories, the space dedicated to capture daylight was taken by systems in response to the need for highly specialized technical installations (see figures 6 and 7). Despite the major changes in the design, in both cases the second roofs kept the original role of extra solar protection. The consequent differences in performance will be explored in the forthcoming topics.

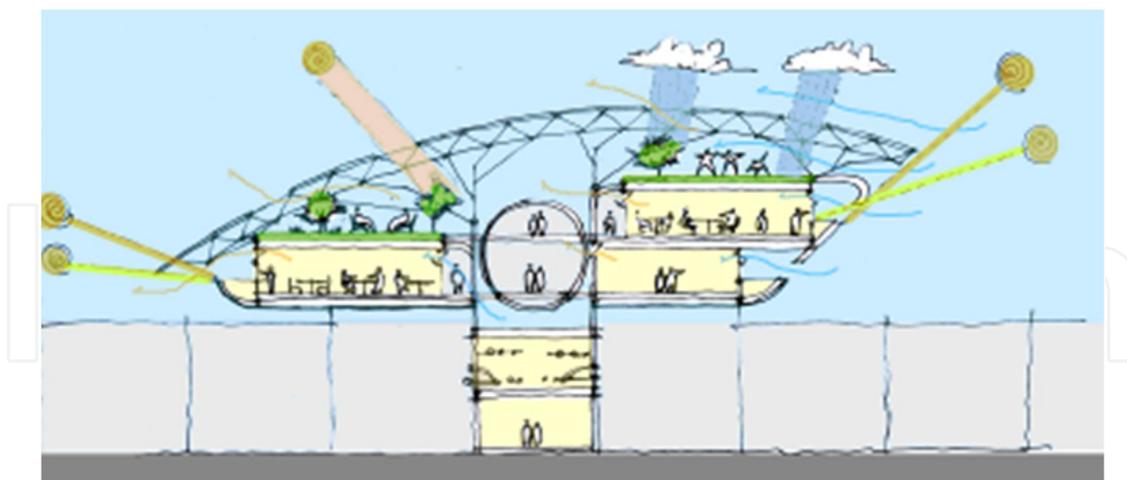


Figure 4. Conceptual sketch of the Central Building with the permeable screen roof filtering sun, light and air flow creating environmental diversity.

In addition, the two utility buildings, Operational Support and Utilities Centre, follow the factory-like building typology, in which daylight and natural ventilation by stack effect are intrinsically related to the roof design and its orientation in relation to the sun and the winds (see figure 8).

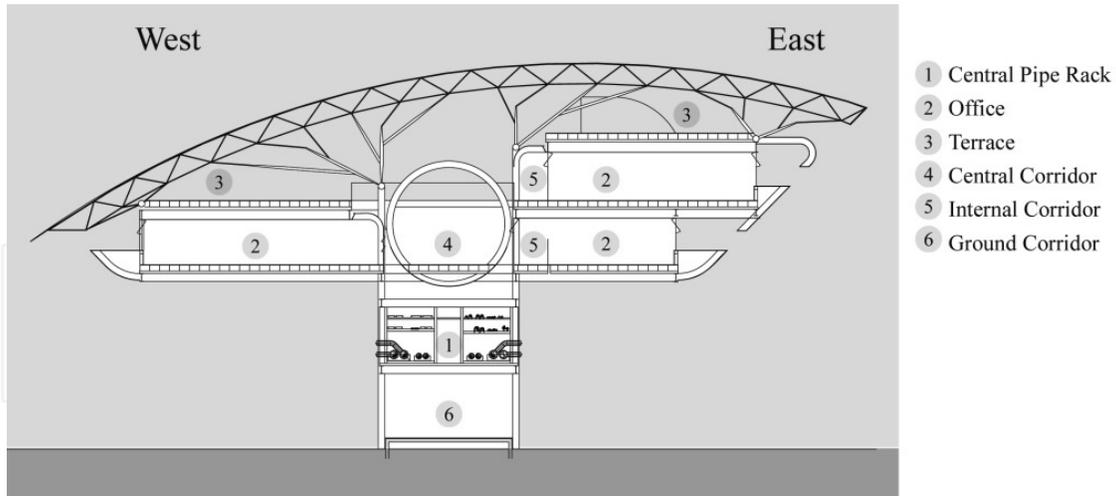


Figure 5. The final design of the Central Building with the insulated metal sandwich roof offering a higher protection against the sun and the rain.

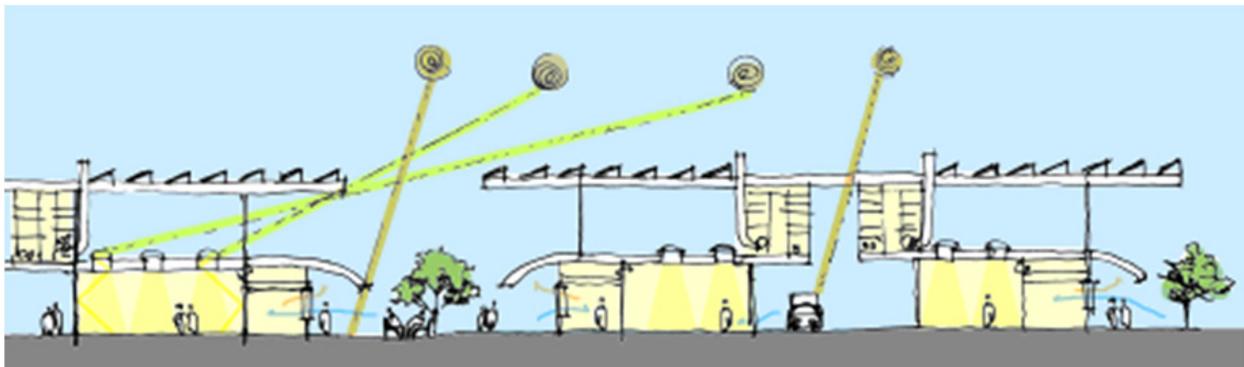


Figure 6. Conceptual sketch of the Laboratories showing the original concept of the double roof shading skylights.

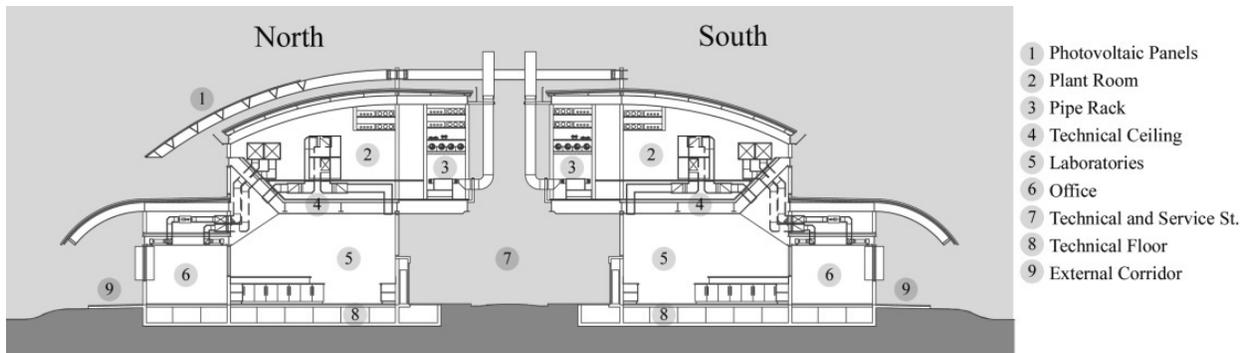


Figure 7. The final design of the Laboratories with the space between the two roofs taken by the technical systems.

3. Thermal comfort in open spaces

Considering the attractive scenery of the Guanabara Bay, in Rio de Janeiro, and the intention to promote an environment for encounters and enjoyment in outdoor spaces, the architectural premises brought a horizontal composition, with buildings connected by open

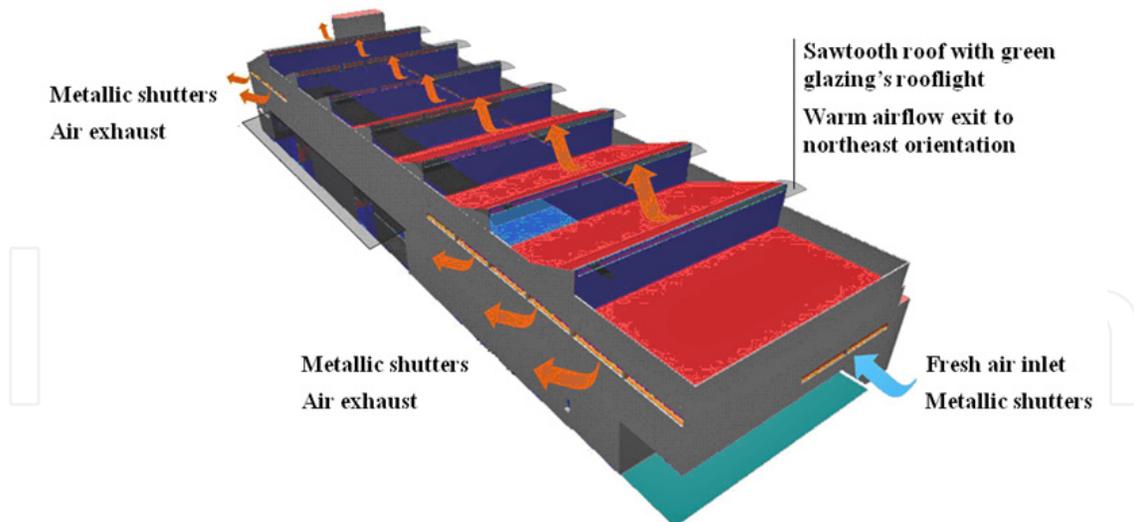


Figure 8. Design concept of the typical naturally ventilated factory- type building for services and utilities.

spaces and transition spaces between outdoors and indoors. Given the warm-humid characteristics of the local climate, the transitional spaces followed the principle of protection against the impact of solar radiation, but exposed to wind. In this respect, as shown in figure 9, simulations of air flow around and between the buildings has shown lower velocities particularly near the eastern edge of the laboratory buildings, but better conditions in centre of the patios as well as in the central void of the conventional centre.

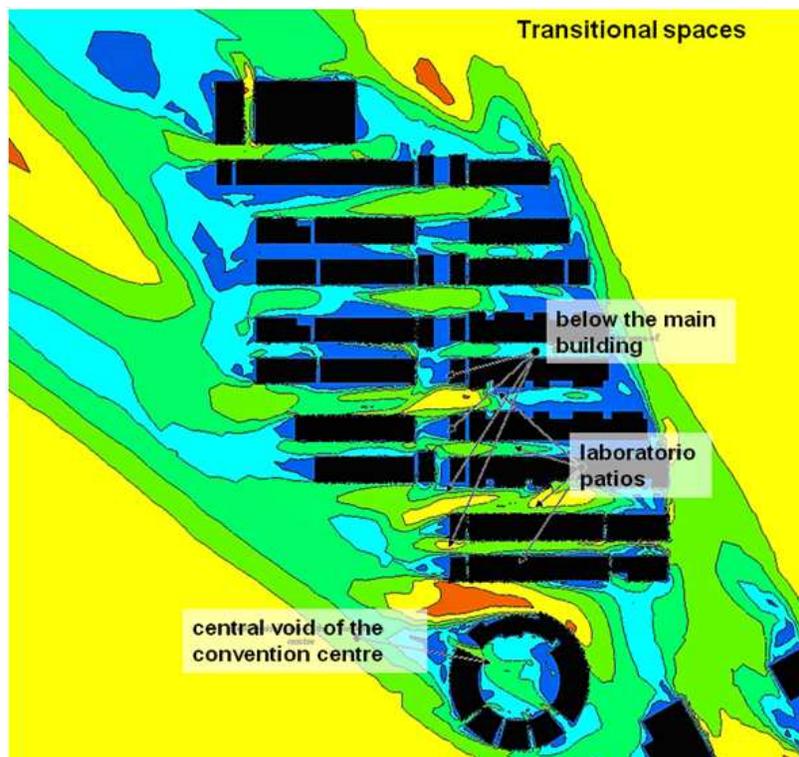


Figure 9. Simulation of air flow around and between the buildings of the new masterplan. Data about air speed was one of the fundamental variables to the prediction of thermal comfort in the open spaces of the masterplan.

The predictions of thermal comfort in outdoor spaces were established using the Outdoor Neutral Temperature (T_{ne}), presented by Aroztegui [6], which considers as reference the concept of Neutral Temperature (T_n) introduced by Humphreys [7], who defined Neutral Temperature (t_n) as the room temperature considered thermally neutral to a given population, observing the local conditions. The author presents a linear ratio between mean monthly temperature (t_{mm}) and Neutral Temperature (t_n), valid indoors in situations with low air speeds and mean radiant temperature close to air temperature.

$$T_n = 17.6 + 0.31 \cdot t_{mm} \quad (1)$$

Where: t_n = Neutral Temperature [$^{\circ}\text{C}$]; t_{mm} = mean monthly temperature [$^{\circ}\text{C}$]

It is important to notice that the equation for the calculation of the Neutral Temperature is valid for the value range 18.5°C - 30.5°C , considering individuals in sedentary activity and wearing light clothing. For different human activities, the following corrections can be applied: light work ($M=210\text{W}$), -2.0°C ; moderate work ($M=300\text{W}$), -4.5°C ; heavy work ($M=400\text{W}$), -7.0°C .

Aroztegui [6] proposed the Outdoor Neutral Temperature based on the same variables of the Neutral Temperature for internal spaces previously defined by Humphreys, to which variables related to sun irradiance and wind speed were incorporated. With respect to sun irradiation, the direct component should not be the only factor, but also diffuse irradiance and surrounding reflections. Regarding wind, the author highlights the need for simplifications, as variables associated with wind are difficult to value, as it is affected in space and time by random accidents at pedestrian level. Looking at other references, Givoni's Index of Thermal Stress (ITS) [8], is based on an empirical equation for indoor neutral temperature, that takes also into account variables that are characteristics of outdoor.

To establish the sweat rate in sedentary activity, considering mean conditions for the individual and the surrounding characteristics (with relative humidity ranging from 35% to 65%), the following equation for outdoor neutral temperature was established:

$$t_{ne} = 3.6 + 0.31 t_{mm} + \{100 + 0.1 R_{dn} [1 - 0.52 (v^{0.2} - 0.88)]\} / 11.6 v^{0.3} \quad (2)$$

Where: t_{ne} = Outdoor Neutral Temperature [$^{\circ}\text{C}$]; t_{mm} = mean monthly temperature [$^{\circ}\text{C}$]; R_{dn} = normal direct solar irradiance [W/m^2]; v = wind speed [m/s].

Outdoor neutral temperature is estimated for a mean monthly temperature, corrected to a 50% relative humidity situation. Therefore, in the context of this work, the formulation of the new effective temperature was used to correct the mean monthly temperature values to an equivalent value of a 50% relative humidity situation. This means that, instead of using only the air mean monthly temperature value, this value was considered in terms of the New Effective Temperature, which considers the air temperature and also air humidity, providing equivalent temperature values, having as reference a 50% relative humidity situation.

According to ASRHAE [9], the New Effective Temperature (TE^*) is the operative temperature of an enclosure at 50% relative humidity that would cause the same sensible

plus latent heat exchange from a person at the actual environment, and it can be calculated by the following equation.

$$TE^* = t_o + w \cdot I_m \cdot LR \cdot (p_a - 0.5 \cdot p_{sTE^*}) \quad (3)$$

Where: t_o = operative temperature [$^{\circ}C$]; w = skin wetness [dimensionless]; I_m = index of clothing permeability [dimensionless]; LR = Lewis relation; p_a = vapour pressure [kPa]; p_{sTE^*} = saturation pressure of the new effective temperature [kPa].

The Operative Temperature (t_o) is the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non uniform environment. It is numerically the average of bulb temperature (t_{bs}) and mean radiant temperature (t_{rm}), weighted by their respective heat transfer coefficients (h_c and h_r). ASHRAE defines the equation for the Operative Temperature as follows [9]:

$$t_o = h_r \cdot t_{rm} + h_c \cdot t_{bs} / (h_r + h_c) \quad (4)$$

Where: t_{rm} = mean radiant temperature [$^{\circ}C$]; t_{bs} = dry bulb temperature [$^{\circ}C$]; h_r = radiant exchange coefficient [$W/m^2 \ ^{\circ}C$]; h_c = convective exchange coefficient [$W/m^2 \ ^{\circ}C$].

In this work the calculation of TE^* adopted the proposed equations by Szokolay [10], according to which the new effective temperature is given by lines in the psychrometric chart, crossing the curve of relative humidity of 50% for the given temperature [11]. These lines inclination equal to $0.023 \cdot (TE^* - 14)$, if $TE^* < 30$, and $0.028 \cdot (TE^* - 14)$, if $TE^* > 30$. Knowing the operative temperature and absolute humidity of a specific location, the new effective temperature was calculated through iterative process.

In this process, the New Effective Temperature is the mean temperature of all the hours from the previews thirty days. Assuming a tolerance range of $\pm 2.5^{\circ}C$ to the outdoor neutral temperature, at least 90% of the users would be satisfied with the thermal environment conditions. Assuming a tolerance range of $\pm 3.5^{\circ}C$ the satisfaction percentage drops down to 80%. In this research, the more restrictive range was applied, working with a satisfaction index superior to 90% of all users.

Three typologies for outdoor environments were studied configuring nine possible different environmental conditions, as shown in table 1 [11], in order to quantify the impact of different degrees of exposure to sun and wind in the overall thermal comfort in open spaces.

	rv	r*v	rv*	r*v*	r	r*	v	v*	-
cold	7,6%	14,5%	0,1%	0,1%	0,0%	0,0%	28,8%	0,4%	0,0%
comfort	57,0%	75,4%	42,4%	54,1%	0,3%	1,1%	68,8%	78,3%	1,7%
hot	35,4%	10,1%	57,5%	45,8%	99,8%	98,9%	2,4%	13,2%	98,3%

Table 1. Comparative results of the considered configurations

The key outdoor environments studied in this analysis were: the open central atrium of the convention centre, the patios of semi-enclosed gardens between the laboratories and the

terraces at the rooftop of the main office building, at 10 meters high, (see figures 10 to 12) being these three areas for mid and long-term permanence, also being some of the major circulation routes between buildings¹.



Figure 10. View of the open atrium of the Convention Centre.



Figure 11. The gardens between the two laboratory wings. Images of the still “immature” landscape.

Technical studies proved that in the central atrium of the convention centre, when exposed to the sun, one will be in comfort condition approximately for half of the time. When shaded, this figure goes up to nearly 85% of the time, showing a major improvement of outdoors thermal comfort, as seen in table 2 (see figure 10). Aiming for even better results, more and wider apertures between the multiuse rooms, which connect the central atrium to the immediate surroundings of the building, would increase the air flow in the open centre.

¹ All the analytical assessments were done considering the period of occupancy set by Petrobras (from 7am to 6pm), during weekdays of the whole year.



Figure 12. View of the terraces at the roof top of the Central Building, from the west to the east terrace.

Regarding the patios between the laboratories, considering total exposure to direct solar irradiation when the wind speed is lower, the predicted comfort conditions are identified only for 13% of the time. This percentage increases to 23% when 90% of incident solar irradiance is blocked by tree shading. On the other hand, when the wind speed is higher, the hours in thermal comfort raise to 67.5% of the time in the spots with direct solar irradiance, increasing to 98% of the time when the sun is blocked by the trees, as shown in tables 3 and 4 (see figure 11).

Considering the terraces at the rooftop of the main office building (the Central Building), the insulated sandwich metal roof, specified in the final design, provides a high percentage of time in comfort conditions (77%), against the metallic screen solution (64%), proposed in the

Month	cold	comfort	hot
January	0,0%	74,7%	25,3%
February	0,0%	82,3%	17,7%
March	0,0%	93,4%	6,6%
April	0,0%	91,5%	8,5%
May	0,0%	90,5%	9,5%
June	0,0%	100,0%	0,0%
July	0,0%	91,8%	8,2%
August	0,0%	96,3%	3,7%
September	0,0%	83,6%	16,4%
October	0,0%	82,2%	17,8%
November	0,0%	72,7%	27,3%
December	0,0%	83,5%	16,5%
Year	0,0%	86,9%	13,1%

Table 2. Thermal comfort at the open central area of the convention centre (shading)

January	0,0%	7,5%	92,5%
February	0,0%	13,6%	86,4%
March	0,0%	21,5%	78,5%
April	0,0%	21,1%	78,9%
May	0,0%	22,5%	77,5%
June	0,0%	46,6%	53,4%
July	0,0%	28,1%	71,9%
August	0,0%	39,7%	60,3%
September	0,0%	22,7%	77,3%
October	0,0%	18,6%	81,4%
November	0,0%	17,4%	82,6%
December	0,0%	19,5%	80,5%
Year	0,0%	23,2%	76,8%

Table 3. Thermal comfort at the open areas between the laboratories (low mean wind speed and shading)

Month	cold	comfort	hot
January	0,0%	100,0%	0,0%
February	0,0%	100,0%	0,0%
March	0,4%	99,6%	0,0%
April	0,6%	99,4%	0,0%
May	1,3%	98,7%	0,0%
June	5,9%	94,1%	0,0%
July	3,0%	97,0%	0,0%
August	7,9%	92,1%	0,0%
September	0,5%	99,5%	0,0%
October	0,0%	100,0%	0,0%
November	0,0%	100,0%	0,0%
December	0,0%	100,0%	0,0%
Year	1,8%	98,2%	0,0%

Table 4. Thermal comfort at the open areas between the laboratories (high mean wind speed and shading)

conceptual stage, as shown in tables 5 and 6. However, it should be noticed that the thermal performance of the metal screen roof, coupled with local shading strategies (such as small trees, green wired structures, umbrellas, etc), results in a percentage of hours in comfort in the terraces which is verified to be very close to the predicted results for the case of the sandwich metal roof (75%), as seen in table 7 (see figure 12).

Interestingly enough, although the percentage of hours in comfort is fairly close in both cases (insulated sandwich metal roof versus screen roof), the conditions related to discomfort show a significantly different performance. The discomfort in the case of the

metal screen with local shading devices are associated with feeling “cold” for 15% of the time, due to slightly high wind speeds, and feeling “hot” for 10%. In the case of the insulated sandwich metal roof, the total hours of discomfort are practically due to feeling “hot”. Despite the fact that the sandwich metal roof provides less time in discomfort, it has a distribution curve of thermal conditions tending to a more extreme part of the “hot” zone, i. e. its values are closer to the limit of hot discomfort. On the other hand, the metal screen solution with shading devices presents values closer to better comfort situations, i.e. they are located in the central part of the comfort zone.

Month	cold	comfort	hot
January	1,6%	71,9%	26,5%
February	1,4%	66,8%	31,8%
March	0,0%	78,9%	21,1%
April	0,0%	77,3%	22,7%
May	0,0%	67,1%	32,9%
June	0,0%	85,0%	15,0%
July	0,0%	65,8%	34,2%
August	0,0%	76,4%	23,6%
September	0,9%	89,1%	10,0%
October	1,6%	79,4%	19,0%
November	0,4%	84,3%	15,3%
December	0,9%	83,1%	16,0%
Year	0,6%	77,1%	22,3%

(insulated sandwich metal roof)

Table 5. Thermal comfort at the rooftop area of the central building

Month	cold	comfort	hot
January	7,1%	64,8%	28,1%
February	9,5%	58,2%	32,3%
March	9,9%	55,8%	34,3%
April	10,0%	54,7%	35,3%
May	10,0%	64,9%	25,1%
June	12,3%	66,4%	21,3%
July	5,6%	68,8%	25,6%
August	7,4%	59,9%	32,7%
September	17,7%	61,8%	20,5%
October	19,0%	60,1%	20,9%
November	14,5%	67,4%	18,1%
December	10,4%	64,5%	25,1%
Year	11,1%	62,3%	26,6%

Table 6. Thermal comfort at the rooftop area of the central building (metal screen)

Month	cold	comfort	hot
January	12,6%	72,7%	14,7%
February	13,6%	69,5%	16,9%
March	12,8%	73,6%	13,6%
April	12,9%	72,1%	14,9%
May	15,2%	72,7%	12,1%
June	16,2%	80,2%	3,6%
July	6,9%	80,5%	12,6%
August	12,8%	75,2%	12,0%
September	23,2%	70,9%	5,9%
October	24,1%	70,0%	5,9%
November	16,5%	78,1%	5,4%
December	18,2%	71,4%	10,4%
Year	15,4%	73,9%	10,7%

(metal screen with local shading)

Table 7. Thermal comfort at the rooftop area of the central building

Without barriers in the rooftop area, and since the wind speed at 10m is higher than at the ground, the wind speed in rooftop areas is more significant. Nevertheless, the cold discomfort periods caused by the wind could be reduced by adopting local wind breaks in the more affected areas of the rooftop. Moreover, given the hot-humid climatic conditions throughout the year in Rio de Janeiro, theoretical discomfort for “cold” can be challenged by real-life practice and be simply solved considering occupants adaption through clothing.

At first sight, comparing the insulated sandwich metal roof solution and the metal screen one, without other designing strategies, both present similar thermal comfort performance. But the metal screen solution has a higher potential to increase thermal comfort conditions, since local shading devices and wind brakes (if required) proved to increase comfort hours significantly. On the other hand, in the case of the insulated sandwich metal roof, in which almost all the situations of discomfort are hot ones, local solutions are not possible, since all solar irradiance is already blocked and it is difficult to induce, yet locally, an increment in the air speed.

Due to the possibilities of local solutions, the choice of metal screen provides a great diversity of environmental conditions, with different local figures of thermal radiation and air speed, which affect the thermal comfort sensation in open spaces. Providing environmental diversity, with areas of thermal sensation varying between slightly hotter to slightly colder, it is known that people can satisfy their comfort needs by choosing wherever they want to be, increasing even more the percentage of thermal comfort satisfaction. Nevertheless, in real practice, the possibility of creating a semi-open space protected from

the rain led to the adoption of the sandwich metal roof (see figures 7 and 8). Technical assessment led to a final solution composed by metallic screen at the edges of the roof (shading the windows), sandwich metal panels in the main part of the roof, with strips of green glass along the roof surfaces and a central opening for air exhaustion placed along the entire length of the roof, In order to improve daylight and ventilation on the terraces.

Besides the results about the thermal comfort conditions in open spaces of the three buildings at the core of the expansion of the Research Centre, the study of insolation and wind speed in such areas have also informed the landscape design as a whole. Regarding the creation of shadows, the areas less shaded by buildings (or permanently exposed to the sun) have received a higher protection by the landscape than those already shaded, in order to create favourable conditions to thermal comfort in open spaces between and around buildings, taking into consideration the routes of people as well as the adequate conditions for short and long permanence.

Furthermore, the location of the different *restingas* implanted in the open gardens between the laboratories, extending until sea shore of the site, was reviewed based on the diagnosis of air movement around the buildings. The *restinga* of sand, initially proposed for the southern garden, the most exposed to wind, was replanted to the northern garden, thus avoiding sand grains displacements to other open spaces. In the same token, the analysis of insolation and daylight availability in the terraces of the Central were important for the choice of species that would best adapt to the specific conditions of daylight and heat exposure.

The analytical studies of thermal comfort in open and semi-open spaces of the Research Centre verified the possibility of satisfactory comfort scenarios, especially due to the well-planned design of shading and access to air movement in such areas, in the warm-humid tropical climate of Rio de Janeiro.

4. Daylighting

In response to the design brief, daylighting should be prioritized and maximized in all interior spaces where there is no functional restrictions, in order to provide visual comfort with energy efficiency [1]. Given the specific warm-humid climate of Rio de Janeiro and the major impact of solar irradiation on buildings thermal performance, coupled with the typical partially cloudy and bright local sky conditions, the major challenge of taking maximum benefit of daylight was related to the need for solar protection and avoidance of glare. For this purpose, the building form, together with roof's and facades' components were designed and sized with precision to shade the direct sun, whilst capturing and redirecting daylight to the deeper parts of the interior spaces (see figures 13 and 14).

The design and assessment processes of daylighting focused on the three main building typologies of the research centre, where buildings' orientation and form had a significant impact on the daylighting performance: the linear north and south rows of laboratories, the

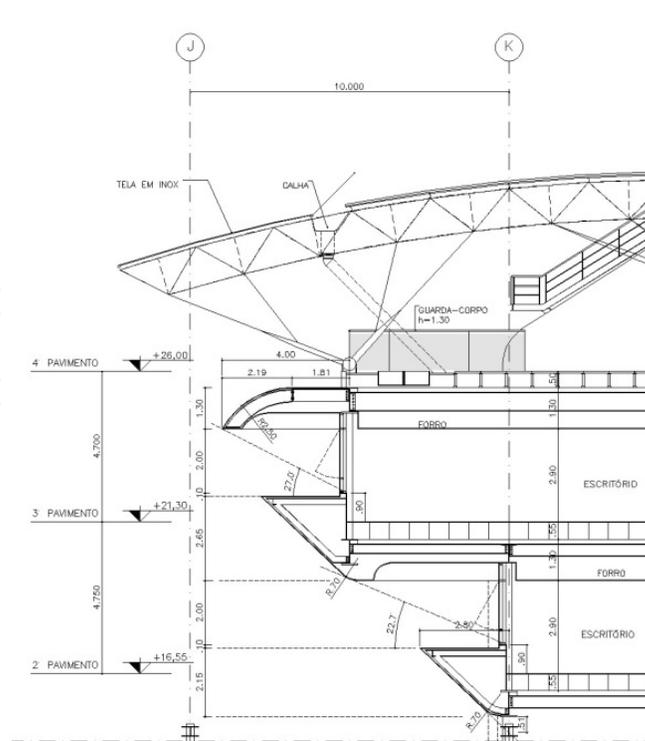


Figure 13. Central Building: design of the building’s east facade to provide total solar protection to the working stations.

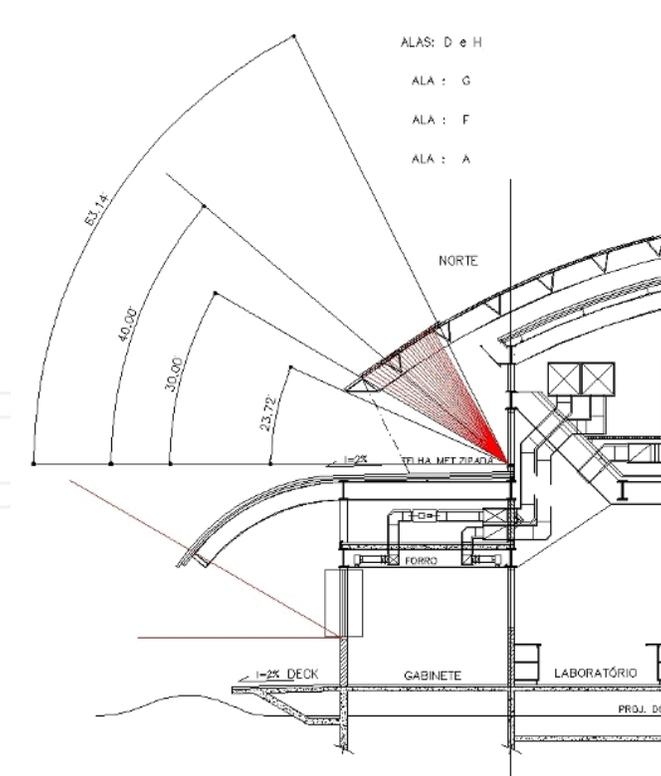


Figure 14. Typical north facing wing of laboratories: design of the shading device for the high-level window aiming to cut the direct solar radiation and redirect it as diffuse light to the deeper parts of the working areas.

multi-storey west and east facing office building, and the typical factory-like typology, in which the conflicts between natural ventilation, solar protection and penetration of daylight had a determining role in the design of the roofs. A number of in-depth simulation parametric studies were used to analyze architectural design possibilities for solar protection and penetration of daylight in all three cases [12].

In order to estimate internal daylight performance, Brazilian Standard NBR 15215 -3 calculation method was adopted [13]. Quantitative reference parameters in lux, from Brazilian Standard NBR 5413 [14], were complemented by Germany Standards DIN 5034, Daylight in interiors [15], DIN 5035, Artificial lighting of interiors [16] and LEED guidelines [17], adopting performance criteria as follows:

- a. Uniformity: above 66%;
- b. Daylight Factor: above 2%;
- c. Illuminance Levels related to work planes: above 265 lx;
- d. Daylight Factor and illuminance Levels should be reached on 75% of work plane areas, at least.

Computer simulation parameters for daylight assessment:

- a. CIE overcast sky luminance distribution;
- b. Unobstructed external horizontal plane illuminance: 13.250 lx²;
- c. Floor, wall and ceiling reflectance: 0.35; 0.60; 0.85;
- d. Work plane height: 0.70m (offices); 1.00m (utility buildings);
- e. Glass transmittance: 0.89 (general); 0.69(main office building and factory sheds).

In the main office building, the terraces (designed to hold social and working activities) showed areas with daylighting levels higher than 300 lx, nearly corresponding to a Daylight Factor (DF) of 2%. In the working environments close to the east facade facing the bay, the predominant DF identified was over 2%, despite the shading device, allowing appropriate levels up to the point of circulation between working stations, of approximately 2.50 meters deep. Further than this point, DF was below 2%, revealing the need for supplementary artificial lighting. In the west façade, facing the first phase of the Research Centre, the figures for the DF were over 2% in almost the whole area close to the openings, of about 5.5 meters deep. On the other hand, in the deeper plan areas (between 5,50 and 13.00 meters from the facade), the values of DF were predicted to be over 2% in 20% of the floor area (at working height) and 1.5% in 30% (see figures 13, 15 and 16).

² In parallel to the development of this project, ISO and CIE launched the Standard General Sky, presenting 15 sky relative luminance distribution types, including CIE Standard Clear Sky and CIE Standard Overcast Sky. Unfortunately, there was not enough measurement data to feature Brazilian sky in accordance with ISO/CIE 15 types. Hence, CIE Standard Overcast Sky was adopted to calculate values of DF. However, unobstructed external horizontal illuminance was established taking into account Brazilian climate conditions. The unobstructed external horizontal illuminance parameter (13.250 lx) adopted on computer simulations, reports 80% of annual occurrence. Increasing the unobstructed external horizontal illuminance parameter, the annual occurrence decreases, and the autonomy of daylight can be estimated.

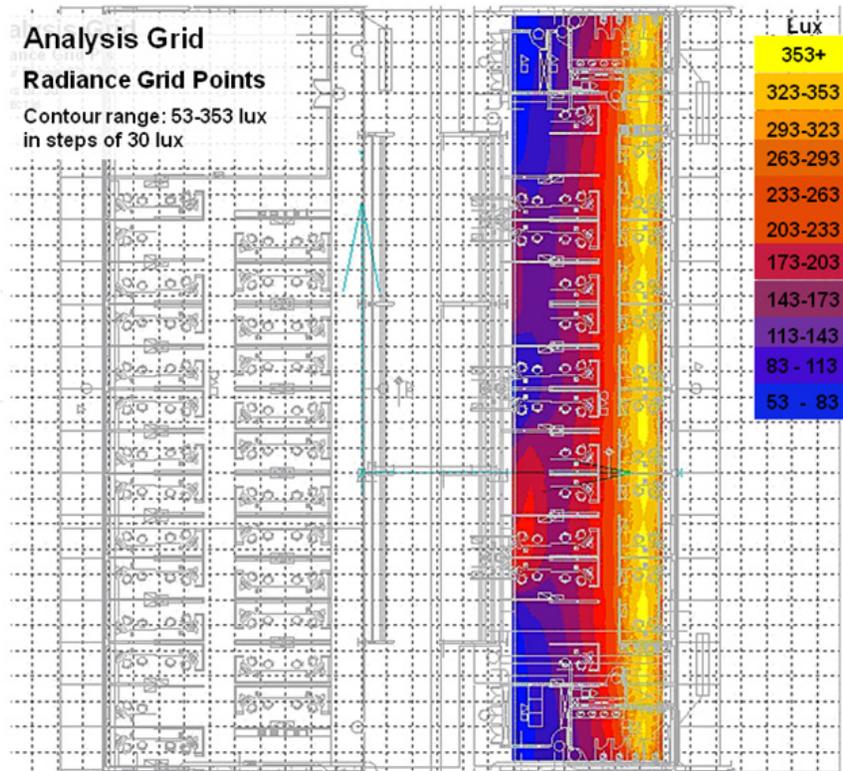


Figure 15. Central Building: daylight distribution on the 2nd floor of the east facing offices (relatively narrower plan in relation to the west facing offices).

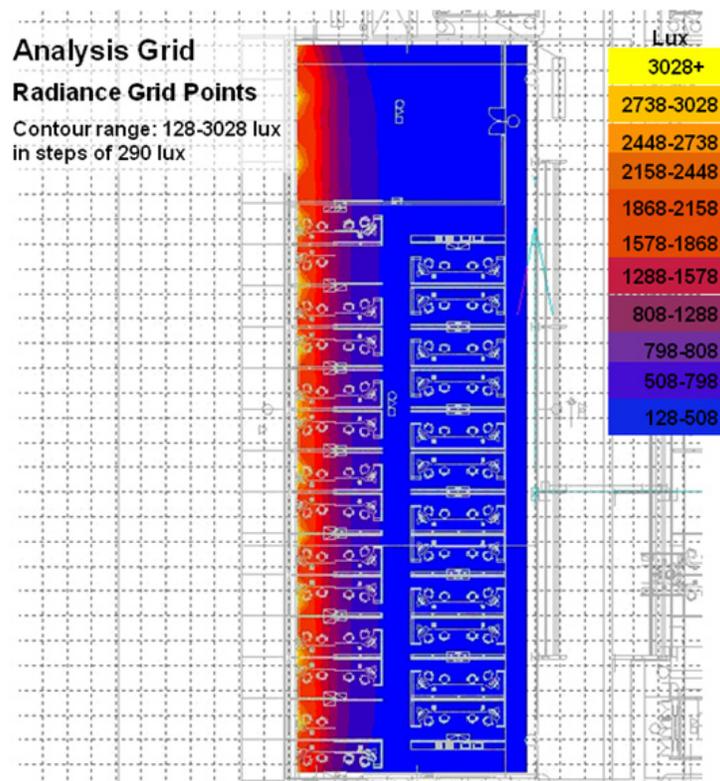


Figure 16. Central Building: daylight distribution on the 2nd floor of the west facing offices (the deepest plan area of the building).

In the laboratory buildings of north and south orientations, the performance of daylight in the two main working areas: the main (and bigger) working space and the contiguous office cell, showed minimum values of DF of approximate 2% in 75% of the main working plan of the south facing laboratories and 70% in the case of the north orientation. In the office cells the result was the same in both cases, being 50% (see figures 14, 17 and 18). The overhangs placed over the high level windows of the north facing laboratory buildings to block the direct solar radiation didn't compromise daylight performance, as it incorporates horizontal louvers which redirect diffuse light into the deeper areas of the main working laboratory room. In the south facing laboratories, the high-level window was kept with the maximum view of the sky to maximize daylight penetration, being shaded only on the side vertical plans against the early morning and late afternoon sun.

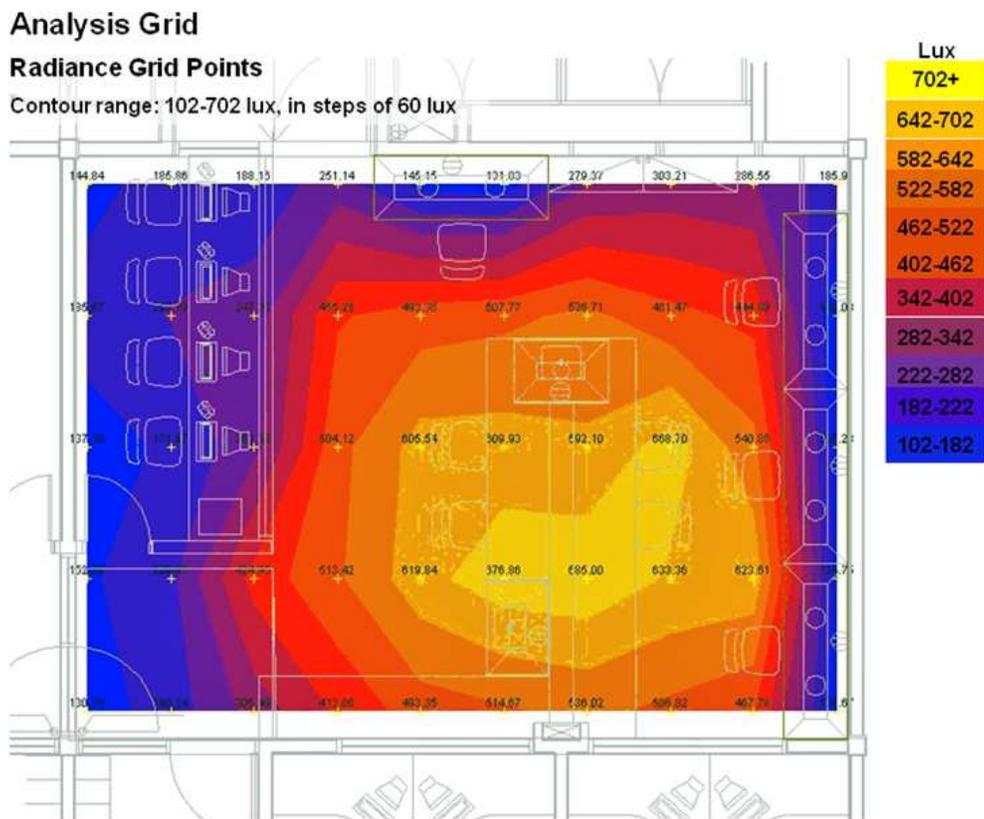


Figure 17. Laboratories: distribution of daylight in the typical south facing rooms.

In the sawtooth roof buildings (the factory type), characterized by top daylight, the minimum illuminance levels established by the national standard [14] were satisfied. However, changes in the design of the shed component in one of the buildings were needed to decrease the initially predicted illuminance levels. For that purpose, a decrease in the height of the shed and the reduction of over 50% of the sheds were tested, not just to reduce daylight (and the risk of glare), but also to cut down critical thermal loads.

Considering the adopted criteria, the illuminance level 265 lx is achieved with the Daylight Factor of 2%, found as a minimum value in most of the working plans in the laboratories and in the main office building. Although this value is close to the recommendation for

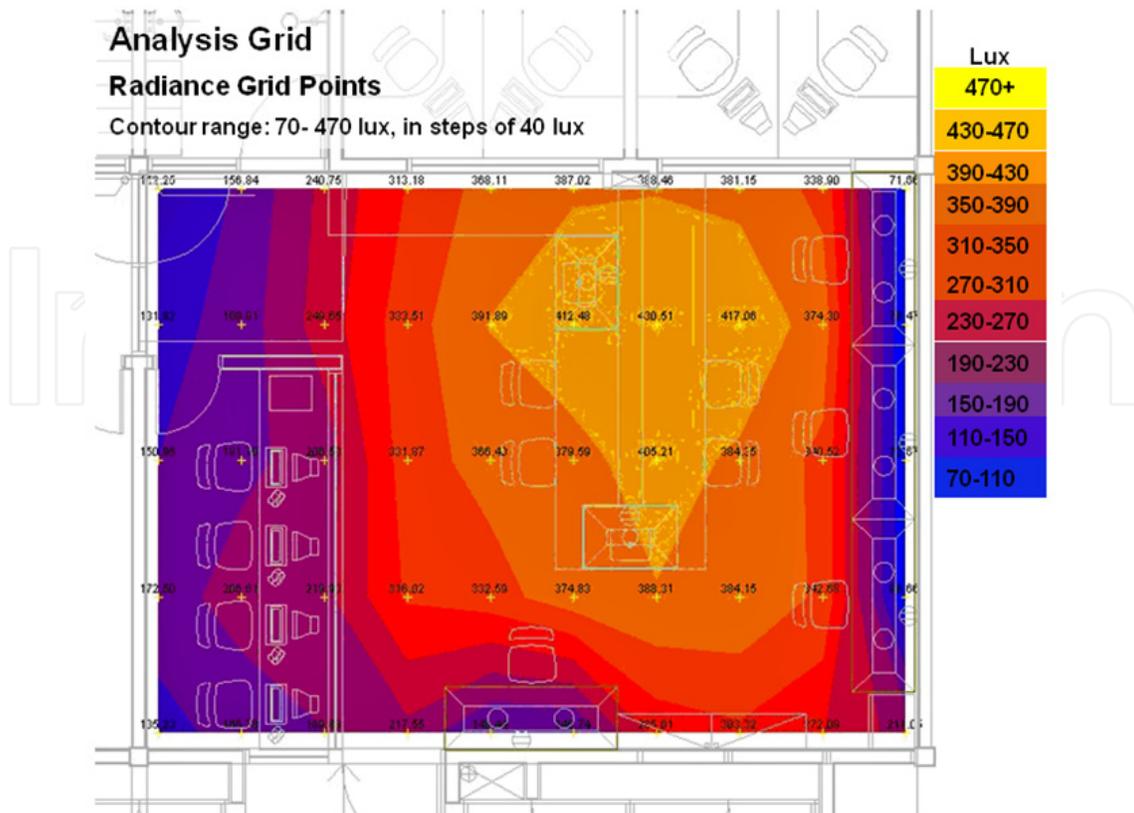


Figure 18. Laboratories: distribution of daylight in the typical north facing rooms.

reading rooms (300 lx), prescribed by the Brazilian Standard NBR 5413, it does not comply with the requirements for office activities, where the advised nominal illuminance is 500 lx [14]. Nevertheless, 500 lx could be considered to be high in the context of contemporary offices and the related work conditions, harming the visibility of computer screens. Adjusting Brazilian Standards guidelines and visual task needs, the complementary artificial lighting was adopted, placing supplementary luminaries over restrict areas controlled by the user. This strategy allows estimated energy savings of approximately 40% to 45% of artificial lighting, taking into account the Research Centre usual working hours between 7 am to 4 pm, during 5 days a week [12]. Almost all main office areas and laboratory rooms presented well balanced daylight distribution. Yet, the uniformity below 0.66 was identified in some places, such as in the office building second floor of the west facing wing of the main office building, where uniformity resulted in 0.35, indicating the need for supplementary artificial lighting, to adjust lighting levels to the task requirements around the room.

In summary, the outcomes of daylight uniformity were:

- Main office building, 3rd floor rooms, west orientation : 0.82 – 0.88;
- Main office building, 2nd floor rooms, east orientation: 0.82 – 0.88;
- Main office building, 2nd floor rooms, west orientation: 0.35 – 0.75;
- North oriented laboratories: 0.94;
- South oriented laboratories: 0.94.

Daylight Factor and Uniformity calculations provided artificial lighting design optimization. By means of isolines plotted on work planes, one could map each room and identify natural lighting availability inside the building, detecting zones and establishing the proper strategy for each one [12]. In this sense, artificial light keeps up with natural light variations, adjusting lighting levels and distribution in order to improve luminous environment quantity and quality, intending good visibility and visual comfort.

The daylighting analysis made use of concept of Daylight Autonomy [12], to predict periods only on account of natural light providing the proper visual task lighting level. Although the minimal value of 2% for the Daylight Factor is adopted by some international standards to consider a well-daylit space, regarding tropical countries, daylight availability can be increased due to high sky luminance conditions, consequently, the minimal Daylight Factor value can be decreased. On this basis, minimal value of 1.5% for DF was considered accepted in the context of this work, whereas the minimal of 2% remained as an initial reference. Being so, by maintaining the same criteria, external illuminance parameter was increased to reach the same internal illuminance value related to DF 1.5% and 2%. In essence, beyond the performance indicators, quality of daylight in most of the working areas, including daylight distribution, views, visual communication and absence of contrast and glare, was achieved with the design of the façade's components in relation to the orientation and building form.

5. Naturally ventilated buildings

The main natural ventilated buildings in the extension of the Research Centre were two: *Operational Support Building* and *Utilities Centre*. In addition, both the main office building and the laboratory buildings have spaces optimized to be naturally ventilated for a percentage of the year (see topic: *Air conditioned buildings, in the sequence*). The assessment of the naturally ventilated internal spaces involved a set of analytical work developed with the support of advanced computer simulations of thermal and computer fluid dynamics, according to the following procedures [19]:

- a. elaboration of a 5 year weather file (1998 - 2004) with hourly data from the Tom Jobim International Airport station [4];
- b. identification of the critical summer month (February 2003) and a summer reference design day for in-depth assessments of heat flow through the building envelope;
- c. establishment of comfort parameters for naturally ventilated internal spaces;
- d. definition of base cases including building's thermal zoning, occupation profile, construction materials and internal thermal loads;
- e. advanced computer simulations of fluid dynamics (carried out with the software CFX 5.7) to determine air flow around buildings, pressure coefficients, air velocity on the openings of buildings' envelope and convection exchange coefficients;
- f. thermal dynamic simulations (carried out with the software TAS v.9.0.5) in order to quantify buildings' thermal performance and, consequently, estimate the potential number of hours in comfort;

- g. quantification of thermal loads for air-conditioned spaces;
- h. elaboration of design guidelines for a better environmental and energy performance of buildings.

In the typical warm-humid climate of Rio de Janeiro, the thermal performance of naturally ventilated buildings is dependent on the provision of efficient shadowing strategies, alongside enhanced cross ventilation and possibly external thermal insulation (to be tested on a case by case scenario). However, the ultimate success of naturally ventilated spaces will depend on the definition of the comfort band and its acceptable conditions.

At the time of the project (2004-2005) there were two national buildings' standards related to the general internal environmental conditions of working spaces: NR- 15 [20] and NR 17 [21]. The first one refers mainly to extremely hot environments, such as factories, and recommends resting periods related to people's exposure to above certain indoor temperatures, whereas the second one says that the environment must be adequate to the psycho-physiological characteristics of the workers and to the nature of the task. For working spaces in which intellectual demand and constant attention are required, NR-17 recommends the following design parameters: effective temperature between 20°C and 23°C; air relative humidity not inferior to 40%; air speed not superior than 0.75 m/s. Even though NR-17 applied theoretically to all environments of interest in this work, its parameters were impossible to be attained in a free running mode, in any time of the reference year, given its narrow limits.

Aiming to maximize natural ventilation, the adaptive comfort model adopted by ASHRAE [22] and created by De Dear [23] was adopted here. It brings an empirical model which includes acclimatization, clothing options, behavior patterns and tolerance to climatic variability (based on the New Effective Temperature (TE^*), seen in *Thermal comfort in open spaces*) (see figure 19).

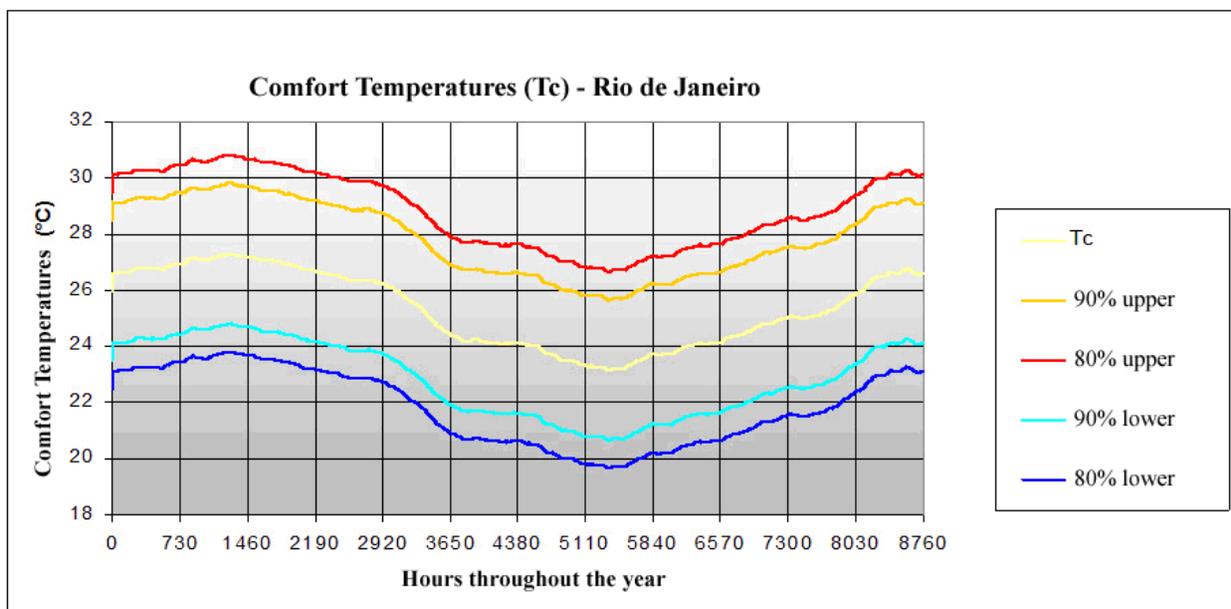


Figure 19. Comfort zone for the climate of Rio de Janeiro, created after De Dear's adaptive model [23].

For naturally ventilated internal spaces, dry bulb temperature, relative humidity and mean radiant temperature extracted from the simulations' results are used to calculate TE* for each hour, which is assessed in relation to the comfort zone. Comparing the TE* figures calculated for each hour of the reference year with the limits of the adaptive comfort zone created for the climate of Rio de Janeiro, one can observe that 50% of occupation time are in accordance with the acceptable thermal comfort conditions [19]. In other words, in a hypothetical scenario where the internal conditions are equivalent to the calculated TE*(for the external climatic conditions), comfort would be obtained for 50% of the occupied hours, which was then considered as a reference for the performance of the naturally ventilated environments.

The thermal performance of buildings and the potential for natural ventilation were determined by advanced thermal dynamics' computer simulations with the software TAS. The simulated environment was divided in a number of thermal zones, in which the influence of neighboring rooms is taken into account. In that way, several thermal phenomena can be evaluated in terms of simultaneity, location and interaction. Building modeling was carried out in two stages: geometry characteristics, and materials specification and occupation schedules.

Preliminary analytical studies showed that the sawtooth roofs of the factory-type buildings facing southeast in order to get the minimum direct sun to the maximum diffuse light, incurred in negative impacts on the natural ventilation of the internal environments, as the southeast coincides with the direction of prevailing winds. For this reason, the shed elements of the sawtooth roofs were re-designed changing the position of the opening for ventilation and including a solar and wind protection device (see figures 20 and 21). Without changing the original orientation of the roof (the best one to minimize solar gains), the new solution prevented the unfavourable effect of the prevailing wind on the air outlet of the stack effect, simultaneously taking advantage of the negative pressure generated to maximize the exhaustion of the internal air flow. In addition, thermal insulation was proved to be beneficial in the buildings' envelop and external solar protection was included on the windows and roof openings of all main buildings. The specification of materials and building components used in the thermal simulations are shown in Table 8.

The factory-type building form played a decisive role in the success of the passive strategies, since the double and triple floor to ceiling heights and the sawtooth roof favoured natural ventilation through stack effect, whilst bringing diffuse daylight into the deeper parts of the floor plan with protection against solar radiation. Shading and ventilation were fundamental strategies for the achievement of satisfactory thermal comfort conditions in the naturally ventilated buildings, followed by external insulation coupled with internal thermal inertia of the buildings' envelop. In the case of interior environments with higher internal heat gains, mechanical ventilation had to be introduced, especially in the hot periods of the year (from December to February). This was the case of the changing rooms in the *Operational Support Building*, where the mechanical ventilation had to provide up to 15 air changes per hour. The mechanical ventilation proved to have a positive impact also in the distribution of air flow within the environments, reaching with more homogeneity the occupied zone.



Figure 20. The Operational Support Building, one of the factory type buildings featuring triple floor to ceiling heights and shed structures in the roof for daylight and stack ventilation.

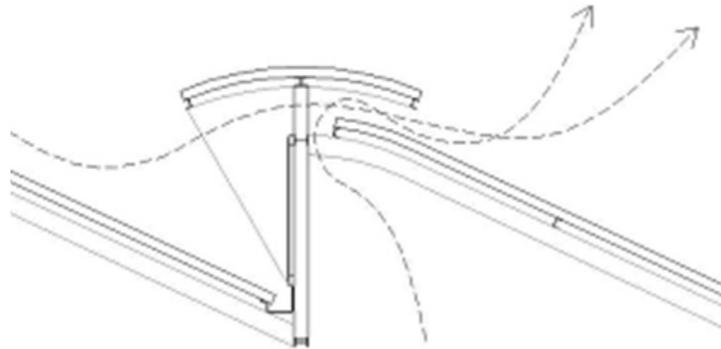


Figure 21. Design of shed showing the ventilation aperture on the back of the shaded glazed area.

Preliminary solution	Final solution
EXTERNAL WALL	
150mm concrete (d=1,200kg/m ³) U = 1,77 W/m ² °C	ceramics + cement + 25mm gypsum +200mm air gap + 120mm concrete (d=2.500kg/m ³) U = 1,63 W/m ² °C
FLOOR	
Ceramics + cement + 150mm concrete (d=2.200kg/m ³) + steel +1000mm air gap + 12,5mm gypsum U = 0,82 W/m ² °C	Ceramics + cement + 100mm concrete (d=2.500kg/m ³) + steel +1000mm air gap + 12,5mm gypsum U = 0,85 W/m ² °C
GLAZING	
6mm clear single glazing U=5,73W/m ² °C	8mm clear single glazing U=5,66 W/m ² °C
CEILING/ROOF	
aluminium + 50mm rock wool + aluminium (metallic sandwich panel) U=0,58 W/m ² °C	

Table 8. Materials and building components applied in the thermal dynamic simulations of the naturally ventilated factory type buildings

Looking at the yearly percentage of comfort hours in the naturally ventilated environments, the highest performance was found in the changing rooms in the Operational Support Building, featuring approximately 60% of the yearly occupation hours within comfort conditions (considering the hours found in “cold” conditions are insignificant) (see table 9). In addition, it was estimated that the addition of the mechanical system would increment the number of air changes per hour could raise the hours in comfort to 75% (an increase of 65% comparatively to its performance before the implementation of the initial architectural modifications) [19]. On the other hand, the lowest performance was in the kitchen of the same building marking 51% of hours in comfort (see table 10). In conclusion, it can be said that the results of the thermal performance of the naturally ventilated internal environments (seen in number of hours within the comfort zone) shows the adequacy of the architectural response to the specific warm-humid conditions of the climate of Rio de Janeiro.

Daily occupation 5am-7pm						
Month	PDD = 20%			PDD = 10%		
	Cold	Comfort	Hot	Cold	Comfort	Hot
January	0.0%	32.8%	67.2%	0.0%	20.6%	79.4%
February	0.0%	32.3%	67.7%	0.0%	24.7%	75.3%
March	0.0%	47.9%	52.1%	0.0%	34.2%	65.8%
April	0.0%	47.9%	52.1%	0.0%	34.2%	65.8%
May	0.0%	49.5%	50.5%	0.0%	38.1%	61.9%
June	2.0%	87.0%	11.0%	8.1%	65.8%	26.1%
July	1.6%	76.2%	22.2%	3.8%	59.4%	36.8%
August	7.3%	76.7%	16.1%	15.5%	56.4%	28.2%
September	0.3%	76.3%	23.3%	4.0%	57.0%	39.0%
October	0.0%	60.3%	39.7%	0.3%	42.9%	56.8%
November	0.0%	47.6%	52.4%	0.6%	31.5%	67.9%
December	0.0%	44.4%	55.6%	0.0%	29.5%	70.5%
Year	1.1%	58.5%	40.4%	3.2%	42.6%	54.2%

Table 9. Operational Support Building: Percentage of predicted yearly hours in comfort in changing rooms.

Daily occupation 5am-7pm						
Month	PDD = 20%			PDD = 10%		
	Cold	Comfort	Hot	Cold	Comfort	Hot
January	0.0%	21.4%	78.6%	0.0%	8.4%	91.6%
February	0.0%	25.0%	75.0%	0.0%	9.3%	90.7%
March	0.0%	38.8%	61.2%	0.0%	19.1%	80.9%
April	0.0%	38.8%	61.2%	0.0%	19.1%	80.9%
May	0.0%	45.1%	54.9%	0.0%	21.3%	78.7%
June	0.0%	93.3%	6.7%	0.0%	66.4%	33.6%
July	0.0%	70.8%	29.2%	0.0%	41.6%	58.4%
August	0.0%	81.8%	18.2%	0.0%	56.7%	43.3%
September	0.0%	63.3%	36.7%	0.0%	39.3%	60.7%
October	0.0%	46.1%	53.9%	0.0%	23.5%	76.5%
November	0.0%	32.4%	67.6%	0.0%	16.7%	83.3%
December	0.0%	34.6%	65.4%	0.0%	16.8%	83.2%
Year	0.0%	51.3%	48.7%	0.0%	29.8%	70.2%

Table 10. Operational Support Building: Percentage of predicted yearly hours in comfort in kitchen of the Operational Support Building.

6. Air conditioned spaces

This work looks at the thermal performance of the specific areas within the air conditioned buildings which have the potential to be naturally ventilated for parts of the year: the office cells of the laboratories and the working spaces of the main office building. The assessment of the air conditioned and mixed-mode spaces followed the main procedures described for the analysis of the naturally ventilated environments, with the inclusion of some specific studies:

- a. in addition to the annual performance assessment, specific studies were developed for the critical summer month of the weather file (February 2003), aiming to analyze the maximum thermal loads and the heat flows through the building envelop;
- b. comfort parameters different from the ones used for the natural ventilated buildings were established for the air conditioned spaces;
- c. thermal dynamic simulations: were first carried out with the software TAS without the air conditioning mode, in order to determine the potential number of hours in comfort;
- d. subsequently, the loads for the air conditioning and mixed-mode strategies were simulated;
- e. finally, the results were analysed and changes were proposed in the architectural design, materials and criteria of operation of buildings in order to increase the naturally ventilated hours and improve comfort conditions, where possible, and reduce cooling loads where air conditioning was necessary either for part or the total time of the year.

With respects to the thermal comfort parameters for air conditioned spaces, air conditioning settings were established based on the international standard ISO 7730 [24] and the correlated regulations ISO 7726 [25], ISO 8996 [26] and ISO 9920 [27], and compared with the Brazilian national regulations.

ISO 7730 estimates the predicted percentage of dissatisfied people (PPD) in a given thermal environment and recommends a PPD value inferior to 10%. However, such design parameters are limited to the following conditions: dbt between 10 °C and 30 °C, rh between 30% and 70% and air velocity under 1 m/s. Within the context of the national standards, as previously presented for the naturally ventilated buildings at the time of the project there were two buildings' regulations concerning the internal environmental conditions in general working spaces, NR- 15 [20] and NR 17 [21]. For the air conditioned spaces, there were two other national standards: NBR 6401 [28] and the *Orientação Técnica sobre Padrões Referenciais de Qualidade do Ar Interior* (Technical Orientation on Air Quality Standards) by the National Sanitary Supervision Agency, ANVISA [29]. In both cases, the recommended ranges for dry bulb temperature (dbt) and relative humidity (rh) are: dbt = 23–26°C and rh = 40–65%; dbt_{max} = 26.5–27 °C and rh_{max} = 65%; dbt_{max} = 28 °C and rh = 70% (for access areas); and considering air velocity at 1.5 m ($v_{a,1.5m}$) = 0,025- 0,25m/s. Based on the previous references, exploratory studies considered combinations of dbt, rh and v_a for a PPD inferior to 10%, assuming:

- a. Metabolic rate (M) for sedentary activity (ISO 8996) $M = 70 \text{ W/m}^2$ (1.2 met);
- b. Clothing thermal resistance I_{clo} (ISO 9920) of 0.5 clo (shirt with short sleeves, light trousers, underwear, socks and shoes);

- c. mrt (mean radiant temperature) = dbt, since the envelopes are shadowed and/or insulated. Therefore (ISO 7726) $t_o = t_{bs}$; and
- d. $v_a < 0.25$ m/s for light or sedentary activities during summer, if $t_o < 26$ °C (ISO 7730; ASHRAE 55). Above 26 °C, air velocity should be under 0.8 m/s.

In summary, the recommended air-conditioning settings considered dbt = 26 °C, rh = 65% and $v_a = 0,1$ m/s, complying with ISO 7730 and the Brazilian national regulations, what resulted in higher air temperatures than those frequently adopted by the current Brazilian practice.

A mixed-mode strategy, alternating natural ventilation and active cooling was suggested for the office cells of the laboratory buildings and the specific areas of the main office building, where a minimum of 30%³ of the occupation time was found to be within thermal comfort conditions in the free-running mode. The parameters adopted in this assessment for the mixed-mode strategy were:

- a. window opening at $t_{bs}=20$ °C, with a gradual increase in the natural ventilation rate;
- b. window closing and air-conditioning activation at $t_{bs}>26$ °C, keeping an indoor t_{bs} of 26 °C ou 24 °C (according to the comfort criteria established for each occupation area); and
- c. window closing when external wind velocity $v_a \geq 5.0$ m/s, as found in the ventilation assessments as the threshold for acceptable internal air velocities.

A comparative analysis of thermal performance and energy efficiency of the various solutions was carried out according to the following criteria:

- a. the periods of comfort during the free running mode were determined by the adaptive comfort model [22, 23], for a dissatisfaction index of 10% and 20%; the percentage of hours of “comfort”, “warm” or “cold” was calculated for each thermal zone during the occupied time;
- b. the maximum thermal load was established by the highest load of the design reference day, and it was provided to inform the sizing of the air-conditioning system; only the internal loads were considered (regardless of the air exchange loads in the coil). It is worth to notice that the thermal loads’ values of the annual assessments which exceed the simulations of the reference day are never superior to 5% of the occupation period; therefore, the recommendations for the sizing of the air-conditioning system follow the reference day recommendations;
- c. a profile of annual loads created based on the frequency of occurrence (both accumulated and by intervals) of thermal loads during the year; and
- d. a profile of cooling loads of the selected spaces was also created for the reference day.

³ This value is based on a general cost-benefit analysis for European projects, since there are no benchmarks for tropical climates or for the Brazilian economic reality [30]. Although the figure of 30% was taken as a reference, it could not be a benchmark, since economic criteria including air-conditioning running costs as well as the associated costs of operable façades have to be considered in the definition of such a target.

Preliminary parametric investigations were carried out for a typical office cell of one of the laboratory buildings to provide an overview of the possibilities and limitations of a mixed-mode approach in such spaces (see figure 22). The test-room was in the most exposed side of the laboratory buildings, with one exposed façade towards the west, however with openings shaded, opaque surfaces with light colour finishing and with a maximum occupancy of two people. Simulation parameters included north and south orientated offices, and the possibility of users' control of both windows for natural ventilation and the air-conditioning system. The specification of materials applied in these simulations are described in table 11.

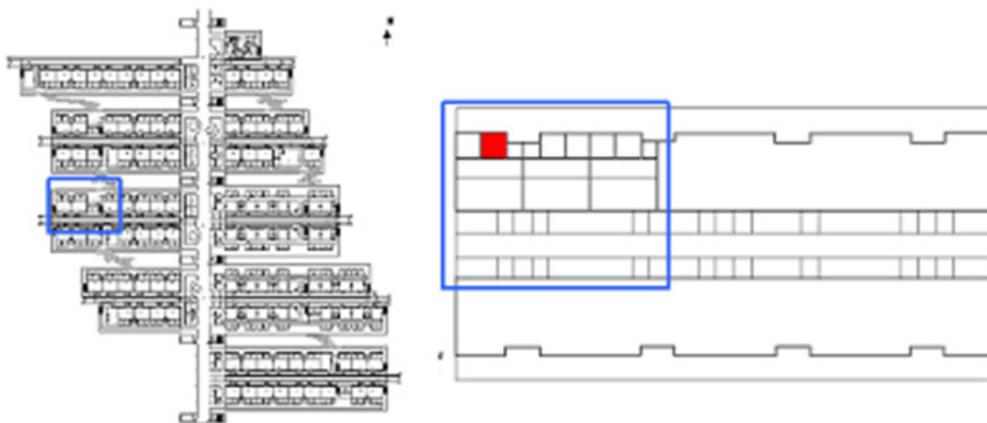


Figure 22. Location of the laboratory used as the first base-case for the thermal assessment.

Occupancy parameters	Elements	Materials	U value (W/m ² °C)
2 people + 15 W/m ² equipment load + 12 W/m ² lighting	Windows	Aluminum frame (5%) + transparent float glass (one sheet -6 mm)	5,73
	Door	Wood (3cm)	
	Walls	Cellular concrete panel (15cm), no coat	0,90
	Floor	Concrete 2000kg/m ³ (15cm) + air cavity (50cm) + concrete 400 kg/m ³ (15cm) in contact with the soil	1,10
	Roof	Plasterboard (2cm) + air cavity (50cm) + concrete 400 kg/m ³ (15cm) + air cavity (100cm) + sandwich panel (15cm)	0,25

Table 11. Materials and building components applied in the thermal dynamic simulations of the typical office space of the Laboratories' office cells.

The results of the preliminary assessment indicated a potential annual period of natural ventilation ranging from 13% to 30%, higher values were found with the inclusion of thermal mass, adding thermal inertia to the internal spaces and considering the entire window as a ventilation aperture, opened for 24hrs during the days of thermal comfort conditions [3]. Excluding the hottest period of the year (from December to February), the performance of natural ventilation increases to 50% of the occupied hours. Based on such results, the mixed-mode strategy has proved to be a positive approach, especially for environments with low internal gains. Furthermore, regarding the set points of the air-conditioning system, the exploratory simulations showed a total reduction in thermal loads of 22% for set point conditions of 26 °C and 60% rh, compared to the scenario of 24 °C and 60% rh, therefore showing the significant impact of comfort standards on building energy efficiency, in the specific case of the Petrobras Research Centre [3].

More in-depth spaces of comparing different environmental control settings of the air conditioning system showed a even more significant impact in the final cooling demand of the spaces, apart from allow a longer period of natural ventilation. Looking at the the case of the east-facing working areas in the main office building, a change in the operation parameters from 26 °C and 65% rh to 24 °C and 50% rh reflected in 28% increase in the room's total annual loads. A higher impact was found for the laboratories' offices, marking 42%, and resulting in a decrease of one month in the natural ventilation potential period. However, the final simulations for annual loads considered the environmental scenario of 24 °C and 50%, as determined in the engineering design as an operation parameter for the cooling system, whereas the settings for the sizing of the cooling systems were 22 °C and 50%.

As a consequence of introducing hours of natural ventilation, in the case of the south-facing laboratories, the mixed-mode strategy led to a reduction of 10% in the total annual loads in comparison with the full air-conditioning mode, and a 50% decrease was found considering the maximum thermal loads. For the working areas in the main office building, the mixed-mode strategy was only not possible in the west-wing offices natural ventilation was not recommended due to acoustic issues related to the motorway that separates phase one and phase two of the Research Center⁴.

Regarding the specification of windows, transparent laminated double glazing windows with air filling (10+28+6 mm) were tested against transparent laminated 8mm single glazing. The double glazing has not presented significant benefits for the thermal performance of the offices of the laboratories, due to the periods of natural ventilation. Similar findings occurred for the east-facing rooms of the main office building. As opposed to that, in the

⁴ Natural ventilation in such spaces was only possible through the openings on the internal façade, adjacent to the central corridor, which proved to be insufficient, so that the west-wing offices were designed from the outset to operate on the air-conditioning mode [19].

case of the west-wing offices, which present fixed façades, as already mentioned, transparent double glazing was recommended for both façades in order to increase the efficiency of the air-conditioning system.

Regarding the specification of windows, transparent laminated double glazing windows with air filling (10+28+6 mm) were tested against transparent laminated single glazing (8mm). The double glazing has not presented significant benefits for the thermal performance of the offices of the laboratories, due to the periods of natural ventilation. Similar findings occurred for the east-facing rooms of the main office building (see table 12). As opposed to that, in the case of the west-wing offices, which ended up with fixed windows, transparent double glazing was recommended for both façades in order to increase the efficiency of the air-conditioning system.

office / room	total annual load (MWh)		
	clear single glazing	clear + green single glazing	
	26°C / 65%	26°C / 65%	24°C / 50%
east (mixed-mode)	58,8	57,0	79,1
west (full a/c)	62,9	61,8	81,3

Table 12. Total annual loads for the east and west office rooms, with different glazing types and air-conditioning settings.

The thermal performance of the working spaces of the main office building was strongly influenced by the big roof, a fundamental element of the design of such building, covering the terraces and the office floors. Different design solutions were tested for the roof, aiming to find a balance between daylighting and the thermal conditions of both the offices and the open spaces of the terraces (as seen in the *Thermal comfort in open spaces*). In comparison to the original design based on a metallic screen, permeable to air and light, the final solution of the insulated sandwich metal panels showed reduction of 20% in the cooling loads of the office areas located at the top floors, mainly due to a reduction in the solar heat gains through the open corridor between the two office wings (see Table 13).

With special concerns to the main office building, in spite of the environmental and energy assessment carried out, some architectural aspects, such as raised floors and insulated ceilings, resulted in internal environments similar to those from the commercial international standards (see Table 13). Alternatively, the working spaces of the laboratories, with reduced dimensions and relatively low thermal loads, additionally to internal thermal mass use, presented a comparatively higher performance, mainly due to the natural ventilation (see Table 14).

Preliminary solution	Final solution
EXTERNAL WALL	
25mm gypsum +50mm glass wool +25mm concrete, $d=2.200\text{kg/m}^3$ $U = 0,66 \text{ W/m}^2\text{C}$	25mm gypsum + 50mm rock wool +200mm air gap + aluminium $U = 0,43 \text{ W/m}^2\text{C}$
FLOOR	
raised carpet floor (metal+120mm concrete $d=2.200\text{kg/m}^3$ + 375mm air gap + metal + carpet) $U = 0,85 \text{ W/m}^2\text{C}$	
GLAZING	
6mm clear single glazing $U=5,73\text{W/m}^2\text{C}$	- 8mm clear single glazing, $U=5,66 \text{ W/m}^2\text{C}$ - 8mm green single glazing, $U=5,66 \text{ W/m}^2\text{C}$
CANOPY	
51mm metallic sandwich panel (EPS filling) $U=4,76 \text{ W/m}^2\text{C}$	Composition: perforated metal panel (40% void)+ metallic sandwich panel + 8mm green single glazing+ shed

Table 13. Materials and building components applied in the thermal dynamic simulations of the main office building: preliminary vs. final solution

Preliminary solution	Final solution
EXTERNAL WALL	
25mm gypsum +50mm glass wool +25mm concrete, $d=2.200\text{kg/m}^3$ $U = 0,66 \text{ W/m}^2\text{C}$	120mm celular concrete $d=2.500\text{kg/m}^3$ + plasterboard $U = 1,07 \text{ W/m}^2\text{C}$
FLOOR	
110mm concrete $d=2.200\text{kg/m}^3$ + 700mm air gap + 150mm concrete, $d=2.800\text{kg/m}^3$ $U = 1,38 \text{ W/m}^2\text{C}$	200mm aereted concrete $d=2.500\text{kg/m}^3$ + impermeabilization + cement + ceramics $U = 1,52 \text{ W/m}^2\text{C}$
GLAZING	
6mm clear single glazing $U=5,73\text{W/m}^2\text{C}$	8mm clear single glazing $U=5,66 \text{ W/m}^2\text{C}$
CEILING/ROOF	
gypsum +400mm air gap +110mm concrete, $d=2.200\text{kg/m}^3$ $U=1,82 \text{ W/m}^2\text{C}$	12,5mm gypsum +1530mm air gap + metallic sandwich panel $U=0,39 \text{ W/m}^2\text{C}$

Table 14. Materials and building components tested in the thermal dynamic simulations of the office cells of the Laboratories: preliminary vs. final solution

Regarding the thermal performance of building components, it was verified that, in general, U values close to $1,00 \text{ W/m}^2 \text{ }^\circ\text{C}$ and higher for the walls of both naturally ventilated and air conditioned spaces and modes, coupled with light external colours, give a good balance between heat losses and heat gains in the specific climatic conditions of Rio de Janeiro. On the other hand, the roofs had to be more insulated, given the intensity of solar radiation throughout the year, with U values between $0,25 \text{ W/m}^2 \text{ }^\circ\text{C}$ and close to $0,50 \text{ W/m}^2 \text{ }^\circ\text{C}$ in the great majority of the buildings, reinforcing the validity of the initial hypothesis of double roofs with extra shading and insulation for a better thermal performance of the internal spaces.

It must be noticed that the mixed-mode approach to the control of the internal thermal environments is a new concept in Brazil, where most air-conditioned buildings are sealed boxes with raised floors and insulated ceilings. Nevertheless, in the context of this project it is considered that the mixed-mode approach can bring economic and environmental benefits, introducing periods of natural ventilation and allowing for fluctuations in the internal environmental conditions within the limits of a given comfort zone, whilst also reducing the thermal loads of the air-conditioning periods. It also increases the user interaction with the exterior, fact which has proved to have positive psychological effects in the occupation of buildings [31].

Despite the technical reasoning that would support the use of a mixed-mode approach to internal environmental control, in the final design of buildings and systems, all environments in which air-conditioning should be necessary for any period of the year became fully air-conditioned main due to a established design culture. Notwithstanding, the specification of operable windows, coupled with an air distribution zoning in the office environments in both in the laboratories and in the working areas of the main office building (one fan-coil for each unity), granted the occupant with the possibility of choosing for periods of natural ventilation, if technically possible and desirable.

7. Final considerations

The challenge of bringing together design considerations about outdoors comfort, good daylight, the need and possibility of natural ventilation and energy efficient buildings' envelop was geared towards quality spaces for the occupants and visitors, rather than focusing only on energy efficiency issues. In this respect, the core objective of the environmental design approach was to create inviting open and semi-open spaces as well as comfortable internal spaces where the occupants are intuitively led to interact with means of controlling their own environmental conditions, ultimately achieving levels of environmental and energy performance beyond what was shown by the analytical predictions.

The potential environmental performance of the buildings that encompass the extension of the Petrobras Research Centre in Rio de Janeiro, which was firstly developed at the design level, has been put to test by its real occupation which took place in June 2010. An Initial and

informal feedback has confirmed the satisfaction of the occupants with the environmental quality of both naturally ventilated and air conditioned buildings, translated into internal visual communication and access to daylight, views towards the outside from all working spaces, physiological cooling through natural ventilation and inviting shaded transitional spaces.

Possibly, the positive response of the occupants about their working environments will maximize the use of natural ventilation in the working spaces where environmental quality can induce a better performance than the predicted in the simulations, since a more flexible and adaptable notion of comfort could be put in practice by the occupants as a consequence of the overall quality of the spaces. This could be the case of the office cells in the laboratories, for instance, where the relatively small internal loads, coupled with the internal thermal mass and operable windows facing the gardens could spontaneously lead to the preference for natural ventilation rather than the air conditioning system.

Overall, the environmental quality and performance potential achieved in the design of the extension of the Petrobras Research Centre in Rio de Janeiro define a new reference for future environmentally responsive buildings in Rio de Janeiro, exploring environmental attributes from outside the boundaries (and often limited) of energy performance standards.

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Acknowledgement

Thanks to: Anésia Frota, Anna Miana, Alessandra Shimomura, Bruna Luz, Cecília Muller, Gisele de Benedetto, Jose Cremonesi, Jose Ovidio, Luciana Ferreira, Marcia Alucci, Rafael

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Brandão and Rodrigo Cavalcante, for the support in the development of the environmental analytical work. The authors are also thankful to the architects from Zanettini Arquitetura S.A., especially to Siegbert Zanettini and Érika Bataglia for their collaborative work throughout the environmental assessments and, finally, to Petrobras S.A. for the support provided during the design project and authorizing the publication of the information presented in this text.

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