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# ANALYSIS OF CLIMATE VARIANCE INFLUENCE ON ENERGY CONSUMPTION IN A SEMICONDUCTOR CLEAN ROOM AIR-CONDITIONING SYSTEM

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***Abstract.*** *Climate variation plays and important role on the energy consumption of a clean room air-conditioning system when operating on a 24/7 regime. In order to analyze potential reductions of energy usage taking advantage of the climate characteristics, and its variability, the implementation of two different type of economizers were evaluate. Using Energy Plus software, the annually energy need of the system was simulate in three different conditions: (i) current configuration, (ii) enthalpy and (iii) dry-bulb temperature controlled economizers operating in the system. The comparison regarding the plant location among the actual address, São Leopoldo, Manaus and Gwangju, South Korea was made. The lowest consumption was achieved in cities with high climatic variation like São Leopoldo and Gwangju, with the enthalpy economizer reducing 41% chiller energy need, and 21% global energy usage. The consumption of the current configuration in Manaus, located in a hot climate zone, was 20.4% higher than São Leopoldo. Along the hot climate, the small climatic variation compromises the effectiveness of the economizers and no energy reduction was obtained when they were implemented. Comparing the economizer results with São Leopldo, the consumption was 52.6 % higher in Manaus. The highest effectiveness have been reach in Gwangju.*

***Keywords:*** *Economizer, Energy Consumption, Air-Conditioning, EnergyPlus, Clean Room*

## 1. INTRODUCTION

According to Whyte (2010) semiconductor production is only possible thanks to the use of clean rooms in the fabrication process. While these environments were firstly employed in the pharmaceutical industry, on the early days of the 20$^{th}$ century, their use in technological production processes began in the 50's decade. Given the small dimensions of a semiconductor, the smallest particle to naked eye represents a destructive threat for properly circuit operation. Terminating any possibilities of contamination during production of a semiconductor is the role of a clean room in the process. The temperature, humidity and especially the amount of particulate matter in the air inflated inside a clean room should be strictly controlled. Contamination control is done through high efficiency filters, known as HEPA or ULPA filters. The temperature and humidity control of the clean room are made through an air conditioning plant, also called HVAC systems.

The internal temperature and humidity set points are 23 ± 3 ºC and 50 ± 15% to this particular plant. In order to maintain the internal ideal conditions in its current location, the HVAC system is required to operate. This paper analyses and compares the implementation of two different kinds of economizers in order to suggest a solution to reduce the energy demand. In addition, a comparison regarding the location of the plant is also made given the different climatic conditions of each locality and its representativeness as industrial center of electronics.

## 2. METHODOLOGY

All the analysis were based on the current air-conditioning system operating in the plant, under its parameters established in the original project. To achieve the objectives proposed by this work, thermoenergetic simulations of the analyzed system were performed through EnergyPlus, a software that enables comprehensive analysis of the entire air conditioning system, allowing a close assessment of the actual operating condition and the influence of each of the performance variables. Seven main steps were followed to meet the proposed objectives for this study.

First, a virtual model of the clean room using the Google SketchUp 3D modeling application and the Legacy OpenStudio plug-in was made to generate an IDF file with the constructive data of the building, required for simulations in EnergyPlus. The second step was to create a virtual model of the HVAC system installed: chiller unit, cooling tower, pumps and fans, taking into account available data and information from its manufacturers' and manuals'. After all the modeling process, analysis of climate files (EPW) from São Leopoldo, Manaus and Gwanju were done to emphasize its different climatic conditions, which will be used as basis for a comparative study of energy consumption. Then, annual simulations were performed in the three different locations, and the impact of its climate in the operation of the original plant configuration. Through the preliminary results, a consolidation of the benefits and disadvantages of the currently HVAC system of the clean room in each of the selected cities was made. Later, the study of the HVAC system operation opportunities through the employment of an economizer in each location took place. The economizer system was divided into two scenarios. The first using a control made by the enthalpy difference and the second controlled by a fixed temperature. The final step consisted on a comparison study of the results along all the three cities and its different operations conditions proposed.

### 2.1 Building Simulated

The simulated environment is a set of five clean rooms used in semiconductor production. Four of those rooms are ISO 8 class, while one of them, AHU201 room, caters to a specific project need, which should provide a maximum concentration of 5,000 particles of 0.5 µm in diameter for each cubic meter of air. The total area of the plant consists on 9,500 square meters, which comprise offices, utility rooms and clean rooms. For simulation purpose, only the cleanrooms met by the refrigeration plant were considered, resulting in a total conditioned area of 5,597.76 square meters.

For loyalty between the real and simulated performance of the plant, it is essential that during the building modeling, its constructive features are entered correctly. Not only are the dimensions, shapes and arrangement important, but mainly the physical properties of each material used in the construction of the simulated environment. Figure 1 , illustrates the 3D model.

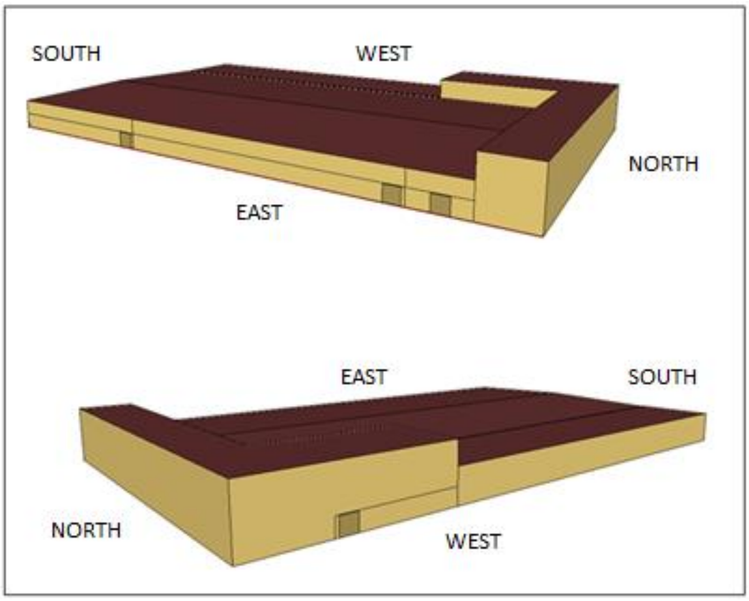


Figure 1. Plant simulation model

The thermal zoning modeling was divided into seven different zones, as seen in Fig. 2. Five of them are clean rooms served by air conditioning plant, as follows: AHU203, AHU201, AHU101, AHU202b and AHU202a. Each referenced cleanroom is served individually by an air handling unit (AHU). The other two patterned areas refer to utility room of the plant and the office area.

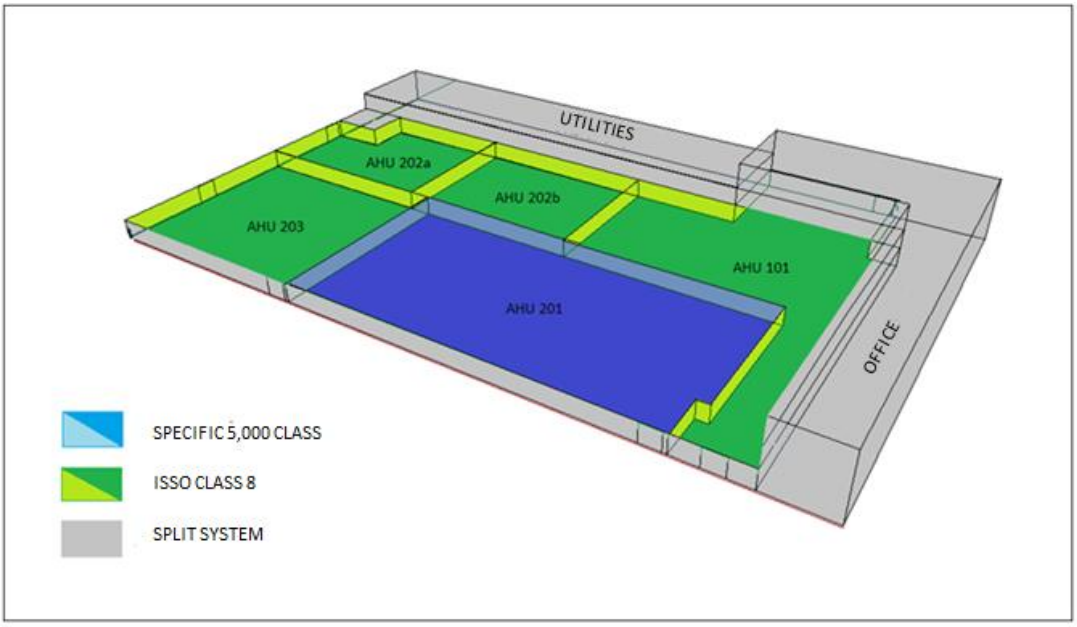


Figure 2. Thermal zone model division

The utility room houses the entire HVAC plant, except the cooling tower, located on its mezzanine. A Split air-conditioning system serves the office zone. As the objective is specifically to evaluate the performance of clean room operation through climatic variations, the air conditioning system of the offices was not modeled.

## 2.2 Weather Data

EnergyPlus requires EPW (EnergyPlus Weather) files to run all the climatic calculation. EPW files contemplates several features, including dry and wet bulb temperatures, dew point temperature, humidity ratio, wind speed and so for. These files include also the geographical position of every location. Unfortunately, not all cities, including São Leopoldo, have this data available. In the other hand, all main capitals in every country are available in the US Department of Energy EPW file library. Porto Alegre EPW file was chosen by the authors to run this simulation. The main reason for this choice was that São Leopoldo is located under the metropolitan region of Porto Alegre, only 25 kilometers distant from it, which means that discrepancies between the climates profiles tend to be irrelevant.

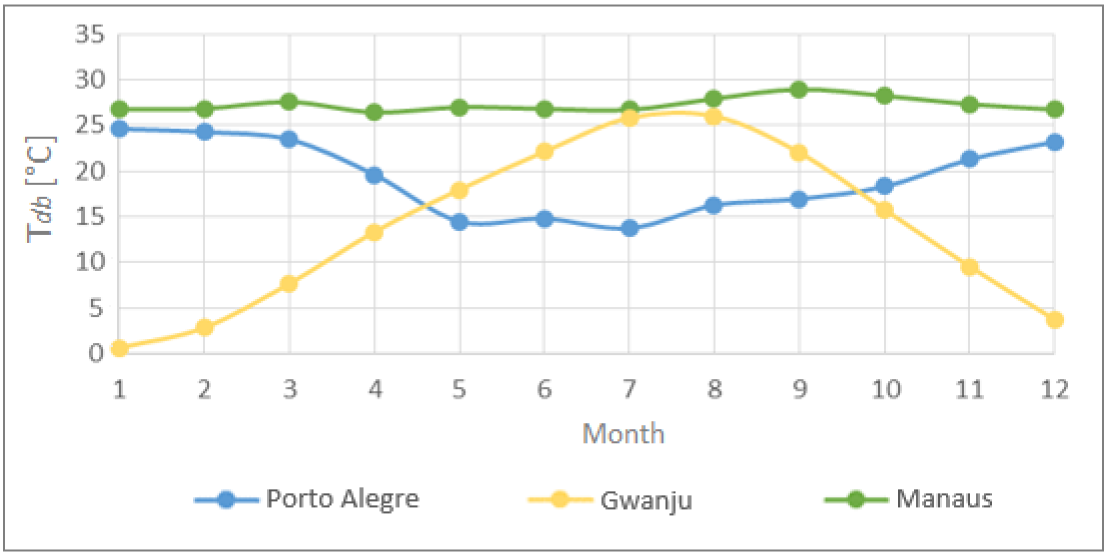


Figure 3. Dry bulb temperature profile

Figure 3 depicts the different temperature profiles in each city. The greater range of temperature occurs in the city of Gwanju, which presents during the winter months below 0 °C daily occurrences. On the other hand, Manaus temperatures are almost constant throughout the year. The city of São Leopoldo shows in the summer very similar monthly averages as found in Manaus, but comparing the winter periods, a considerable reduction of temperature from April to November can be observed.

### 2.3 HVAC System

The HVAC system consists of a chilled water circuit, a condensing circuit and a heating circuit, as shown in Fig 4. Although there are two chiller units installed, only one of them operates to reach thermal loads requirement. The second unit installed in the plant serves as a safety feature in case the main chilling unit to fail.

The chilling unit in operation in the circuit has a nominal capacity of 1406.74 kW and COP of 5.4 in this condition. A centrifugal compression unit provides the refrigerant compression. The condensing fluid used by the system is water.

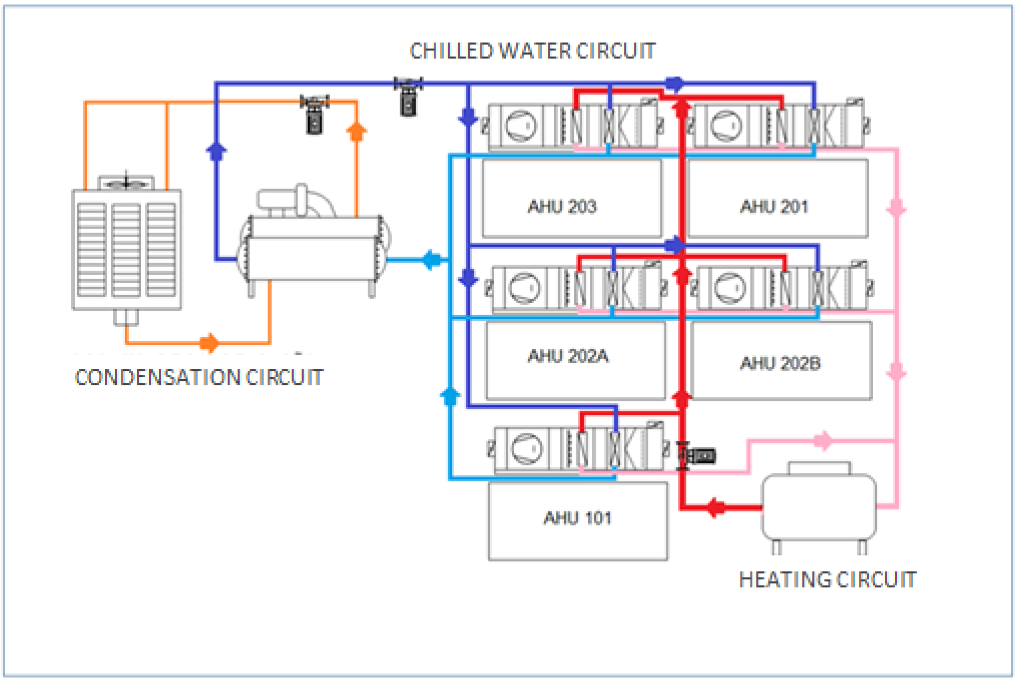


Figure 4. HVAC system layout

Five AHU units, positioned on the mezzanine utility room, provide air conditioning. Each of these units particularly meets one cleanroom. These units comprise two heat exchangers, one for air cooling with chilled water and other for air heating by steam. Filters are positioned in the airflow within the AHU. A centrifugal fan meets the air circulation requirements. The operating pressure of fans that circulate air through ducts is 1324 Pa. Two other fans are used to exhaust indoor air, with 780 Pa operating pressure, driven each one by a 33 kW electrical motor.

Centrifugal fans installed on each AHU are responsible to maintain the air circulation in the clean room. Fan operation pressure is 1324 Pa in each room. Table 1 shows the fan installed power on each room.

Table 1. Fan power by room

| **Room** | ***Fan power (kW)*** |
|---|---|
| AHU 203 | 74 |
| AHU 201 | 74 |
| AHU 101 | 37 |
| AHU 202a | 74 |
| AHU 202b | 74 |

### 2.4 Economizer

The basic concept of operation of an economizer is the use of a system of automatic dampers to increase the amount of outside air admitted when this air present a temperature or enthalpy smaller than the internal recirculated air. The ASHRAE Standard 90.1 provides for the compulsory use in most commercial air conditioning applications in the United States (Taylor and Cheng, 2010).

Recently, Aktacir (2011) showed that reductions in power demand in chiller units can be obtained with the use of economizers. At cool weather conditions, even free cooling can be achieved. Such cooling occurs when the temperature or enthalpy, used as control, is such that incoming air from the external environment have potential to cool the internal environment without the need of the chiller. The most important feature for the free cooling to take place refers to the local weather conditions. A detailed climate analysis can determine the potential for free cooling. While it is advantageous, the process of free cooling does not replace the mechanical refrigeration equipment. This happens because the weather conditions during the year vary. The best conditions for the process to occur happen in the winter months with low humidity in general, according to Olsen and Chen (2003).

The economizer systems were modeled within the Controller object, on EnergyPlus: Outdoor Air IDF file. Two types of economizers control were selected to perform the simulations, one for enthalpy difference of external and internal air (Differential Enthalpy), and another for dry bulb temperature fixed (Fixed Dry Bulb).

The model controlled by the enthalpy difference checks the outside air as compared with the enthalpy of the return air inside the room. When the enthalpy of the outside air is lower than enthalpy of the indoor air return, the economizer drives the stepper motors by initiating the opening of the dampers allowing a greater flow of outside air.

The economizer operation control made by dry bulb temperature set always acts when the temperature of the outside air reaches a certain temperature value. In this study, the dry bulb temperature set point used as an economizer for actuation is 21.5 °C. This temperature limit was chosen after the first simulation room in São Leopoldo, with its original setting. It was found an increase of 1.5 °C in the temperature of air blown into the room due to the energy dissipated by insufflation fans. As the internal temperature set point of the room is 23 °C, the admitted outside air should be as close to room temperature set point. In order to determine the optimum economizer operation, including free cooling schemes, the temperature limit of 21.5 °C was chosen since providing the temperature gain from the fan operation.

The use of economizers with both controls can bring an unwanted effect for the room, which is a variation of its internal enthalpy. This phenomenon is expected when using temperature control, since the sensors analyze only the values of this magnitude. For days of outdoor air temperature below the design set point, outside air will always be admitted. This air can contain higher levels of humidity, changing the internal enthalpy levels of the room, and thereby increasing the internal moisture. To work around this problem, the enthalpy economizers are used. However, these can, in certain situations present a similar behavior to controlled temperature. To days of harsh winter, with near zero temperature profile, humidity levels can be both low as high, which is a peculiar feature of each locality. For regions with rigorous and wet winter, the enthalpy drivers can end up admitting external air at low temperature but with higher levels of moisture in relation to internal and recirculated air. When this condition occurs, a variation in enthalpy can be observed within the air-conditioned environment. This variation is not desired because with it, varying humidity levels will be present in the environment and can cause discomfort to the occupants or even problems in production processes developed.

The object responsible for simulating the economizer operation in the IDF file used does not allow controlling the economizer actuation period throughout the year. For the enthalpy control, there are possibilities of lower and upper limits, while for the temperature control only the upper limit was available. Lack of minimum temperature limit may be a problem on winter season. On cold season the air can be so cold it requires heating. This heating will increase the energy demand and decrease the effectiveness of the economizer system. Therefore, an enthalpy change within the environment can occur when simulated regions with winters with low average temperature and humidity.

## 3. RESULTS AND ANALYSIS

A comparative study seeking to reduce demand for cooling energy was held between the cities during 8760 hours of system operation. It’s important to clarify that when comparing the energy reductions achieved, a distinction must be made. On a partial analysis, focused on chiller demand, a great cutback was achieved. However, when comparing reductions on a global plant energy need, those reductions were smaller. The reason for this relays on the fan system of the clean room,which require a certain amount of positive pressure inside its environment and air exchange rates are quite high when compared to regular commercial building. When simulated in its original HVAC system configuration, fans consumption represents a mean value of 58% of all energy required for any location studied in this paper, as seen on Fig 5.

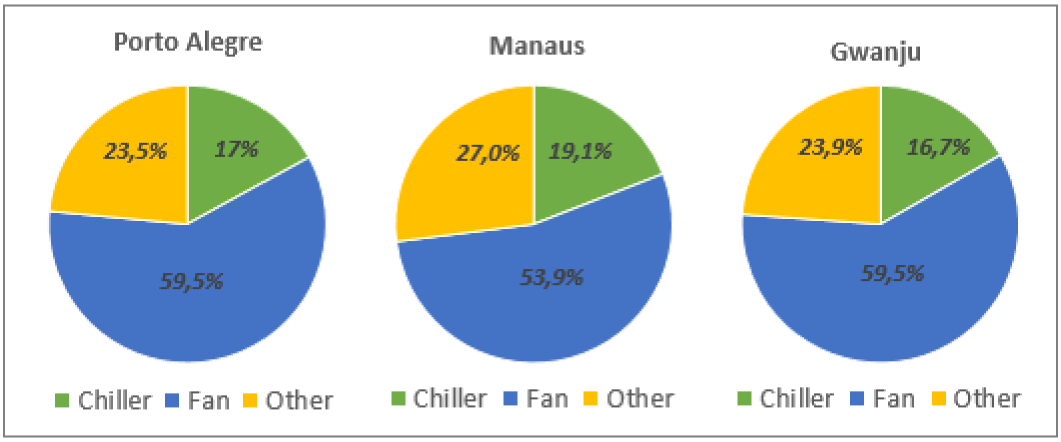


Figure 5. Energy percentage share comparisons in Porto Alegre, Manaus and Gwanju

Table 2 presents the constant fan consumption and its impact on a global demand analysis in Porto Alegre along all three different simulated system layouts. Important to note that the share increase in percentage terms on power demand from fan when applying the economizer systems, while the actual consumption is constant. Gwanju and Manaus also have the exactly same energy demand for fan system, since the airflow requirement is the same for all locations.

Table 2. Energy consumption component and its percentage share in Porto Alegre

| Component | Original [kWh] | Share [%] | Enthalpy Economizer [kWh] | Share [%] | Temperature Economizer [kWh] | Share [%] |
|---|---|---|---|---|---|---|
| Chiller | 854,140.05 | 17,0 | 501,683.18 | 12,3 | 509,993.76 | 12,4 |
| Fans | 2,988.945.00 | 59,5 | 2,988,945.00 | 73,4 | 2,988,945.00 | 72,7 |
| Others | 1,177,326.52 | 23,5 | 581,323.57 | 14,3 | 611,396.63 | 14,9 |
| Total | 5,020,411.575 | | 4,071,951.74 | | 4,110,335.38 | |

Table 3 presents the energy consumption by chiller only. Manaus appears with the biggest demand, thanks to its steady temperature profile, well over 27 °C yearly average values. This climate characteristic also plays an important role on the inefficiency of the economizer system proposed. No sensible improvements were achieved in this location.

Table 3. Chiller energy consumption for each location

| **Location** | **Original System (kWh)** | **Enthalpy Economizer (kWh)** | **Temperature Economizer (kWh)** |
|---|---|---|---|
| São Leopoldo | 854.140,05 | 501.683,18 | 509.993,76 |
| Manaus | 1.059.442,19 | 1.058.589,31 | 1,059,340.14 |
| Gwanju | 837.354,54 | 435.452,25 | 442.388,63 |

Economizer usage appears to be effective in Gwanju and São Leopoldo. In South Korea, enthalpy and temperature economizer are responsible for 48% and 47% respectively. Winter in Gwanju has a lower mean temperature when compared to the south of Brazil, making the economizer actuation in Korea better in terms of energy reduction. São Leopoldo was able to reduce 41% and 40% for enthalpy and temperature controlled systems. A lower reduction compared to the Asian case, but an amazing advantage when compared nationally. Enthalpy economizer working in São Leopoldo would save 53% compared to Manaus operation.

In terms of the overall energy consumption, fans systems have an important role. Table 4 presents the reductions found with the implementation of the proposed solutions.

Table 4. Global energy consumption for each location

| Location | Original System (kWh) | Enthalpy Economizer (kWh) | Temperature Economizer (kWh) |
|---|---|---|---|
| São Leopoldo | 5,020,411.57 | 4,071,951.75 | 4,110,335.39 |
| Manaus | 5,544,335.70 | 5,539,954.64 | 5,543,666.33 |
| Gwanju | 5,025,842.24 | 3,998,616.30 | 4,030,123.90 |

Reductions achieved on the chiller units and its adjacent equipment's reflects straight to global energy need reduction were economizers were effective. In average, São Leopoldo and Gwanju operating with any economizer controlled system were able to achieve 20% energy reduction.

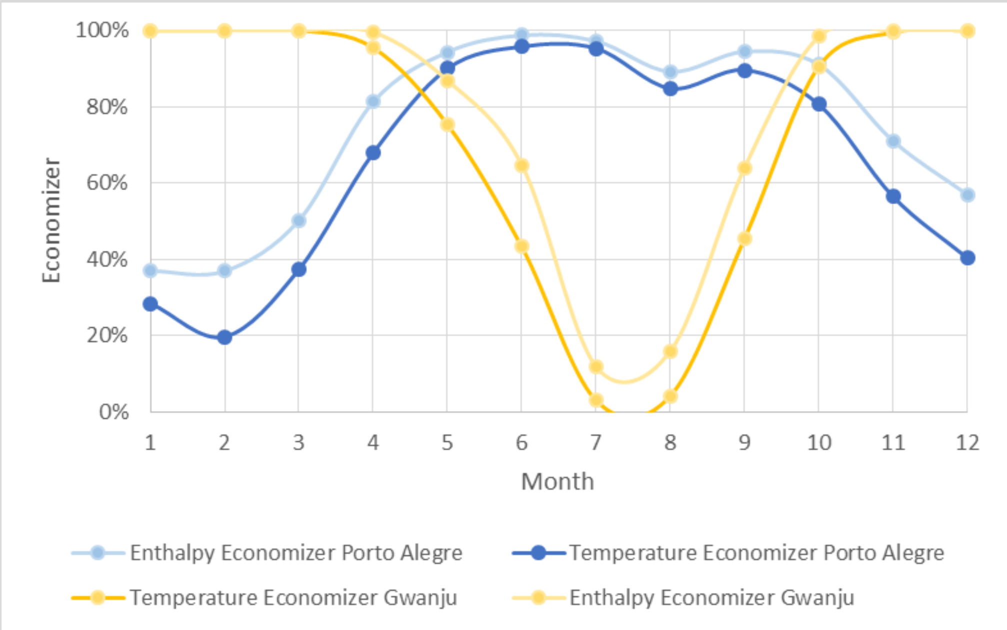


Figure 6. Economizer actuation

Figure 6 depicts economizer percentage of actuation. In both situations, enthalpy controlled actuation showed a higher performance compared to temperature systems. As the enthalpy of the outdoor air is directly dependent on the dry bulb temperature and specific humidity, a decrease in air humidity levels, even if it presents a low temperature, contributes to a greater reduction in the enthalpy than the temperature only.

## 4. CONCLUSIONS

Porto Alegre and Gwanju with its large temperature range throughout the year, showed consistent consumption reduction for cooling when operated with the use of economizers. The city of Manaus did not significantly reduced its consumption with the use of both economizer systems. Manaus has a constant temperature profile throughout the year, registering an average of 27.4 ºC. The minimum average monthly temperature recorded in Manaus happens in April, 26.4 ºC. This average is high compared to the dry bulb temperature limit used for controlling the economizer. Combining medium to high temperature and high humidity levels in the region cause annual average enthalpy to reach values of 73 kJ/kg also preventing the operation of the enthalpy economizer, since the enthalpy of the inner room is 62.3 kJ/kg. The greatest reduction by use of economizer occurred in the city of Gwanju when using an enthalpy control system. The effectiveness in the implementation of energy-saving feature was due to low levels of specific humidity of the region and the low temperatures found in winter period, making the average annual external air enthalpy of 35.6 kJ/kg, against internal annual average room in this locality, 44.2 kJ/kg. Still, with monthly minimum and maximum temperatures of 0.62 °C and 26 °C respectively, both saving systems were effective in reducing consumption. The city of São Leopoldo presented climatic conditions with similar behavior as the temperature range. The minimum and maximum monthly temperatures in São Leopoldo were 14.8 °C and 24.6 °C, respectively, which provide the conditions to the performance of the controlled temperature economizer. São Leopoldo has shown an average annual enthalpy of the outside air of 48.7 kJ/kg, which is lower than the 52.7 kJ/kg annually within the clean room. Although the enthalpy difference is 7%, it was sufficient for the effective performance of the enthalpy economizer. The internal enthalpy difference for the three sites is due to the high tolerance of the setpoints of temperature and humidity (23 ± 3 ºC and 50 ± 15%).

When compared to the original operation project between Gwanju and São Leopoldo, this one has the lowest energy requirement. By using the economizer system, the city of Gwanju shows a 48% reduction in consumption when using enthalpy control. In a national scenario, the traditional industrial center of electronics in Manaus had the worst performance in energy consumption for operation of a clean room. The city of São Leopoldo has a reduction of 53% in energy demand of the chiller specifically, and a 27% reduction in overall energy requirements when compared to Manaus.

Although the study did not faithfully reproduce the constructive and operational characteristics of the building analyzed, the results showed that the original design of the clean room installed in southern Brazil has less need for power consumption compared to Manaus and Gwanju, traditional industrial poles, making São Leopoldo an attractive option for the installation of this kind of company. The analysis also showed that for regions with temperature range and variations of psychometric condition, significant power consumption reductions can be achieved by implementing economizer system. Energy savings achieved with an economizer can entail costs in the filtration system of the clean room. As a larger amount of external air is admitted, the levels of contamination from this air will be greater, saturating the filter media at a much lower than expected time period for operation with the maximum volume of outside air original design.

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