# CONSUMOS ENERGÉTICO E HÍDRICO NO INSTITUTO SUPERIOR TÉCNICO

## UMA ANÁLISE EXPLORATÓRIA NO PAVILHÃO CENTRAL, PAVILHÃO DE CIVIL E TORRE NORTE

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DISSERTAÇÃO PARA A OBTENÇÃO DE GRAU DE MESTRE EM

**MESTRADO INTEGRADO EM ENGENHARIA CIVIL**

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# 1 INTRODUCTION

Economic, social and environmental sustainability is a worldwide project. The development of these dimensions should respond to current needs without compromising future generations (Sustainable Development Goals, 2019). In this context, the management of energy and water resources should be carried out with a focus on sustainability. More than the financial and resource economy, a more balanced relationship between human activities and nature is sought.

Lower energy consumption should be achieved to reduce greenhouse gas emissions (UNFCCC, 2008). In addition, the EU aims to reduce the energy dependence. The energy dependence rate was 55% in 2017 (Eurostat, 2019). In order to achieve these goals, it is important to take action on buildings because they represent 40% of EU energy consumption.

Measurements should also be taken for water savings as this resource is increasingly limited in the context of growing population.

In *Instituto Superior Técnico* (IST) a commission named *Campus Sutentável* was created to promote sustainability through efficient management of resources. This same mission was included in the IST masterplan in 2015 (IST,2019).

# 2 LITERATURE REVIEW

## 2.1 ENERGY AND WATER VARIABLES

Building activity was the main variable that explained the variance of energy consumption of Taiwan (Wang, 2016) and Australia (Khoshbakht et al., 2018) Universities. Depending on the building use, for example, research, engineering, sciences and health, the energy consumption was different. The building dimension, the number of occupants, the outdoor air temperature and the construction solutions where also found to be related to energy consumption (Bourdeau et al., 2018; Deshko & Shevchenko, 2013; Bonnet et al., 2002).

The literature on water resource is scarce in university buildings. Deshko & Shevchenko (2013) reported that the type of activity, the number of students/m$^2$ and the climate influenced water consumption. The influence of building area and type of use were also studied as predictors of water consumption in the *Université de Bordeaux* (Bonnet et al., 2002). Other authors and institutions, suggested water cost (Velazquez et al., 2013), water equipment efficiency (University of California, Berkeley, 2010) and cultural aspects (University of Colorado Boulder, 2006) as predictors of water consumption.

## 2.2 ENERGY AND WATER-SAVING RETROFIT MEASURES

Energy and water-saving retrofit measures were analysed in some countries and in particular in Portugal, IST. From the 27 studies reviewed, 13 investigated the energy performance of IST buildings. The other studies were distributed through Europe and Asia.

Most of the studies where performed in Italy and Spain. The year of construction of the university buildings varies between 1927 and 2010, but were predominantly built in the 60’s and 90’s. Some articles analysed the implementation of a small group energy retrofit managements (for example, Semprini et al., 2016 and Sesana et al. 2016). The others iterated measures with multi-objective algorithms to minimize global cost and energy consumption, and maximize thermal comfort of users (Ascione et al., 2017; Niemalä et al.,2016). The results are shown in Figure 2.1.

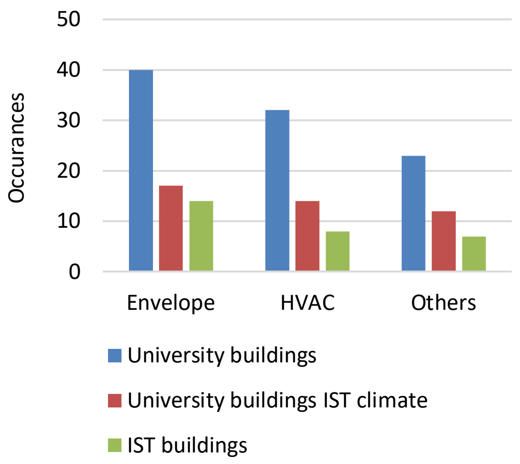


**Figure 2.1 Energy retrofit measures according to envelope, HVAC and others.**

Measurements regarding the envelope were the highest followed by HVAC. Inside the envelope category, the most studied measure was the improvement of windows, which reflects its importance on the energy performance of the buildings.

Regarding to water-saving retrofit measures there was less research in university buildings compared to energy. The majority of the studies come from public documents of water management strategies, such as Stanford University (2003) and University of California, Berkeley (2017). In IST, only one study was found about one water audit in Pavilhão Central. Measurements were divided trough the 5 R principle suggested by Afonso (2011). The results are presented in Figure 2.2.

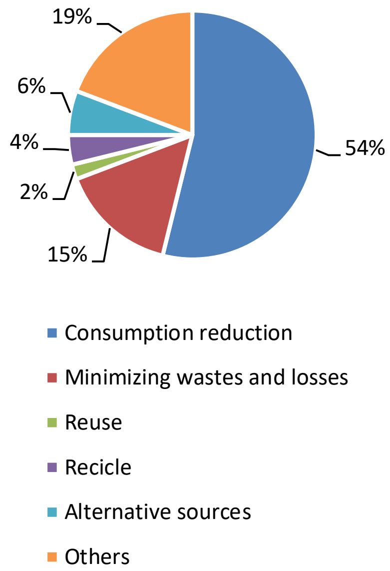


**Figure 2.2 Water-saving retrofit measures in university buildings, including IST.**

Most measures were about reducing the consumption, essentially, by installing more efficient hydraulic equipment. 'Others' represents the second category with most analyses since they have included the measure of rising awareness on the university community for the importance of water conservation. This measure is said to glue all the other water-saving retrofit measures (Stanford University, 2003).

# 3 CASE STUDY

## 3.1 ENERGY AND WATER VARIABLES

The 'Pavilhão Central' (Figure 3.1), 'Pavilhão de Civil' (Figure 3.2) and 'Torre Norte' (Figure 3.3). were the buildings selected for the study. The three buildings have the particularity of having been built in different years, are examples of the users activity in IST and combine 43% of the total infrastructure area of the Campus.

**Figure 3.1 'Pavilhão Central'.**

**Figure 3.2 'Pavilhão de Civil'.**

The U-values and solar factors of the case study buildings are presented in Table 3.1. The 'Torre Norte' has the lower U's-values of the external walls. More than 70% of the external envelope, has external walls with a U of 0,25, window with a U of 2,71 and a solar factor of 0,46. Based on these results, the 'Torre Norte' has the best thermal performance, while the 'Pavilhão de Civil' has the worst envelop performance.

**Figure 3.3 'Torre Norte'.**

The 'Torre Norte' has the lower U's-values of the external walls. Body B of the 'Torre Norte', which contains more than 70% of the external envelope, has external walls with a U of 0,25, window with a U of 2,71 and a solar factor of 0,46. The 'Torre Norte' has the best thermal performance, while the 'Pavilhão de Civil' has the worst envelop performance.

**Table 3.1 U-values and solar factors of the case study buildings.**

| Building | $U^{\dagger}$ Walls [$W/m^2$ °C] | U Roof [$W/m^2$ °C] | U Window [$W/m^2$ °C] | $g^{\ddagger}$ Window |
|---|---|---|---|---|
| 'Pavilhão Central' | 1,10-2,23$^{\dagger\dagger}$ | 1,67-2,42 | 1,89-5,30 | 0,22-0,76 |
| 'Pavilhão de Civil' | 1,01-4,37 | 1,14-1,14 | 5,77-6,01 | 0,56-0,85 |
| 'Torre Norte' | 0,25-1,00 | 0,40-0,93 | 2,71-5,84 | 0,29-0,95 |

$U^{\dagger}$, U-values; $g^{\ddagger}$, solar factor; $^{\dagger\dagger}$minimum and maximum values.

The 'Pavilhão Central' is the critical case of primary energy having the highest absolute and by unit of area consumptions (Figure 3.4).

For water consumption, the 'Pavilhão de Civil is the critical case due to the previous reasons (Figure 3.5).

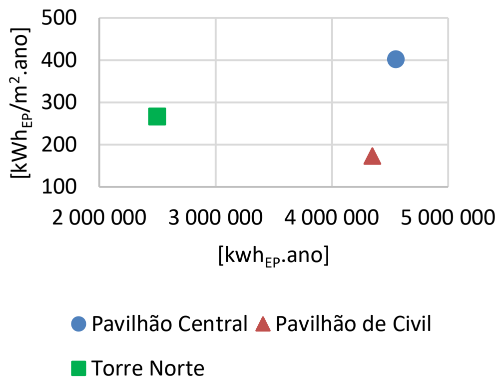


**Figure 3.4 Primary energy consumption of the case study buildings.**

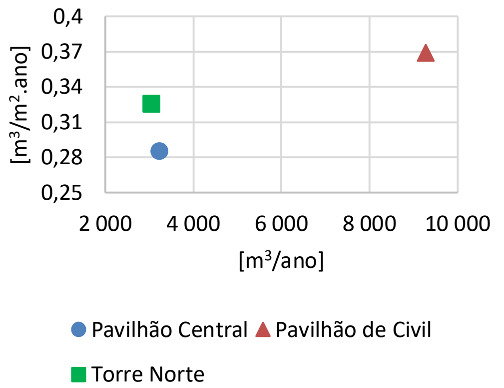


**Figure 3.5 Water consumption of the case study buildings.**

Time real electricity data has being monitored by Campus Sustentável since 2014. Figure 3.6 shows daily electricity consumption of 'Pavilhão Central', 'Pavilhão de Civil' and 'Torre Norte'.

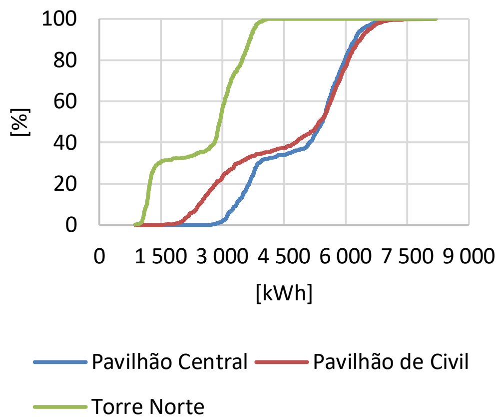


**Figure 3.6 Cumulative relative frequency of diary electricity consumption.**

The distribution of daily electricity consumption of 'Pavilhão Central' reveals a high degree of similarity with the 'Pavilhão de Civil', although the latter has about 2.5 times the area of the former. Differences occur on non-working days, when the 'Pavilhão Central' records higher consumption than the 'Pavilhão de Civil, due to the uninterrupted operation of the Data Centre.

## 4 METHODOLOGY

Multiple linear regression, neural networks and regression with ARMA errors were performed using the SPSS 25 software.

The daily electricity was modelled based on meteorological and occupancy variables for the selected buildings. The meteorological data included daily mean temperature, radiation, relative humidity, wind, and daily precipitation. The occupancy variables were the day of the week and a classification of the days by class day, exams day, students holidays, holidays and the period where 'Campus Alameda' was closed in August.

In regression models, the non-working days were excluded from the analysis due two reasons: (1) in one of these days the HVAC system is shut down and therefore, the electricity does not depend on the meteorological variables, which could affect the regression coefficient and (2) there are two normal distributions for daily electricity consumptions as shown in Figure 3.6. One is for weekdays and the other for the non-working days, which violates the assumptions of the regression models.

Besides that, the regression models were divided into the heating and cooling seasons. As shown in Figure 4.1, the relation was non-linear because low temperatures increase the heating demands and very high temperatures increases the cooling demands. Therefore, for modelling this pattern through a linear relationship the data was split in two climate seasons. Six regression models were developed, one for each building and one per each heating or cooling seasons. All the assumptions were verified and outliers were eliminated.

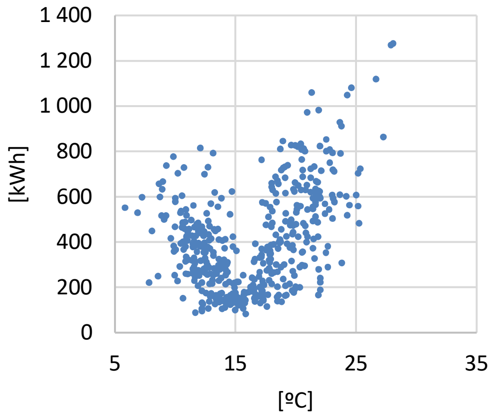


**Figure 4.1 HVAC consusumption and outside temperature in 'Pavilhão Central'.**

Daily electricity consumptions were also modelled through artificial neural network, called multilayer perceptron. Seventy per cent of the data was for training and 30% for testing. Again, 6 models were built as for the regression models.

Finally, regression models with ARMA errors were used to introduce the effect of time on the analysis. We considered that the consumption of electricity on one day depends on the consumption of the day before. It was also introduced in the model a seasonal component to model the pattern that the electricity on a specific day depends on the same day of the week before. Therefore the errors from the regression models were modelled through a $(p,d)(PQ)_7$ with p,d,P and Q less or equal to one. The order of these parameters were estimated through an iteration method until minimizing the Bayesian Information Criterion (BIC). For these models, the variables included the class day, exam day, students holidays, holidays and IST shut down in August. The temperature was forced to be linear through a transformation of the electricity consumption, i.e., the temperature minus the temperature that minimized both heating and cooling demand. At the end, three regression models were built, one for each building.

# 5 RESULTS AND DISCUSSION

## 5.1 MULTIPLE LINEAR REGRESSION

The results of the regression models for the heating season are presented in Figures 5.1. The results for the cooling season is presented in Figure 5.2.

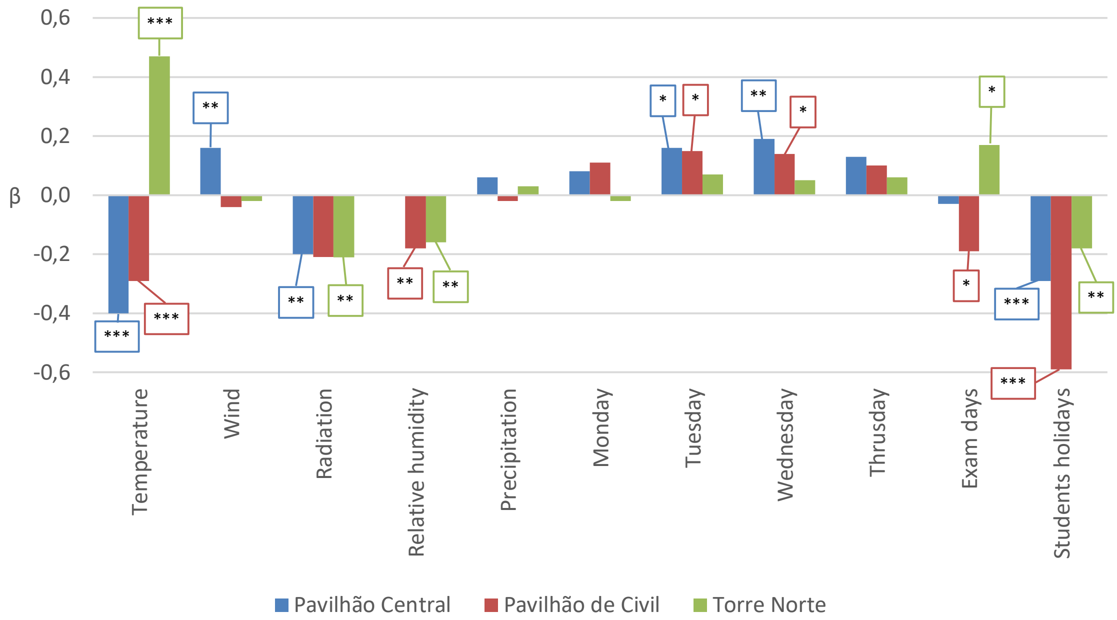


**Figure 5.1** ***β* coefficients for the heating season, *p < 0,05; **p < 0,01; ***p < 0,001.**

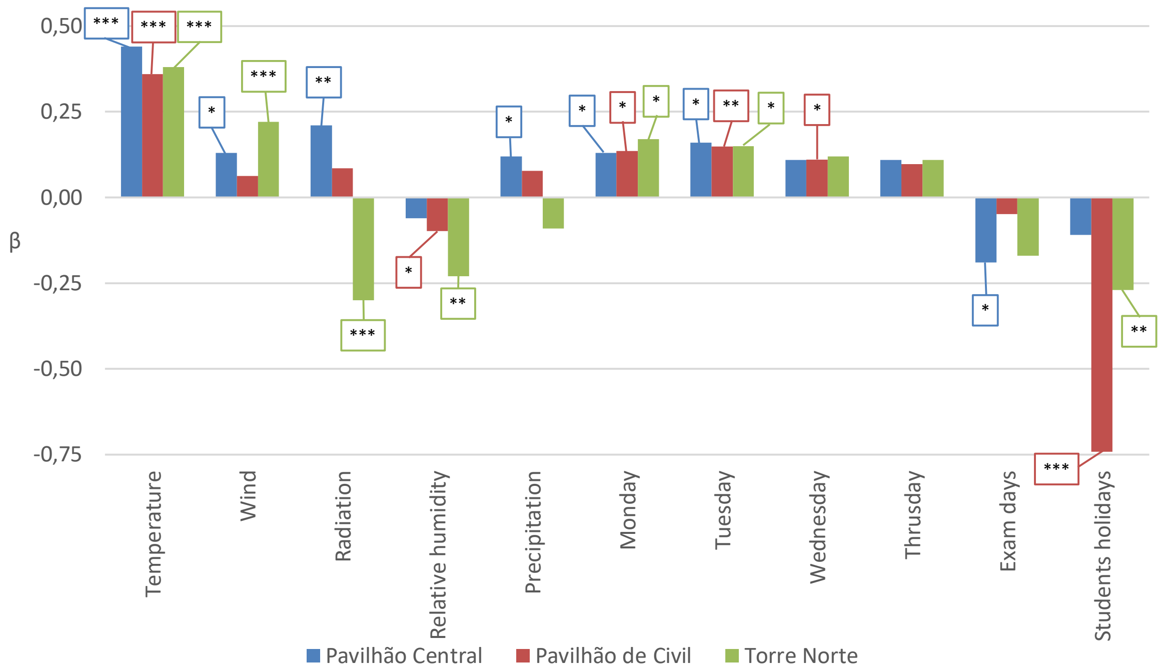


**Figure 5.2** ***β* coefficients for the cooling season, **p* < 0,05; ***p* < 0,01; ****p* < 0,001.**

Aside from spurious relationships, it is possible to observe that the predictors have a similar effect on the electricity consumption in both seasons. The main difference stands for consumptions in school days and student holidays relative to examination days. These differences are related with the percentage of spaces dedicated for students. In the heating season, the $R^2$ were 0,34, 0,43 and 0,36 on 'Pavilhão Central', 'Pavilhão de Civil' and 'Torre Norte', respectively. In the cooling season, for the same order, the $R^2$ were 0,42, 0,61 and 0,27. It is worth noting that events on 'Centro de Congressos of Pavilhão de Civil' were only statistical significant on the cooling season. This is because the cooling needs are constant in this space all the year, mainly due to high occupancy and equipment intensity. Hence, this high-energy dissipation combined with high outside temperatures increased substantially the cooling needs compared to the heating season.

## 5.2 Artificial Neural Networks

The interpretation of synaptic weights of the artificial neural network is complex (IBM Corp., 2017). However, it is possible to perform sensitivity analysis in order to verify the importance of a certain predictor. The temperature was the most important explanatory variable of the electricity consumption for all buildings and seasons. This is because the relationship between temperature and electricity consumption is non-linear. Marçal (2015) and Silva (2008) stated that Pavilhão de Civil and Torre Norte HVAC systems do not have the capacity to guarantee the thermal comfort of the users. Therefore, from a certain temperature and above the HVAC system operates on always on a certain level. This, combined with users behaviours, make the relationship between electricity and temperature non-linear. In the heating season the $R^2$ were 0,52, 0,61 and 0,51 for 'Pavilhão Central', Pavilhão de Civil' and 'Torre Norte', respectively. By the same order, $R^2$ were 0,52, 0,68 and 0,37 in the cooling season. It is noteworthy that, besides non-linearity, these models account for interaction between explanatory variables that maximizes the capacity of the model in describing the variance of the electricity consumption. For example, high radiation and high temperature interact and maximize the cooling needs. Another example is the interaction between temperature and occupancy predictors. The interaction between the users and the HVAC system is not the same for an outside temperature with different levels of occupancy.

## 5.3 Regression with ARMA Errors

The introduction of the autocorrelation patterns of daily electricity consumption enable high adjustment level from the statistical models. Temperature was statistically significant in all buildings. The $R^2$ was 0,88 for 'Pavilhão Central', 0,92 for 'Pavilhão de Civil' 0,91 for Torre Norte. These models were used for prediction, but a high adjustment does not mean prediction capability. The Figure 5.3 illustrate the quality of modelling for 'Pavilhão Central'. Besides the graphical predictability analyses, the MAPE was calculated for the three models.

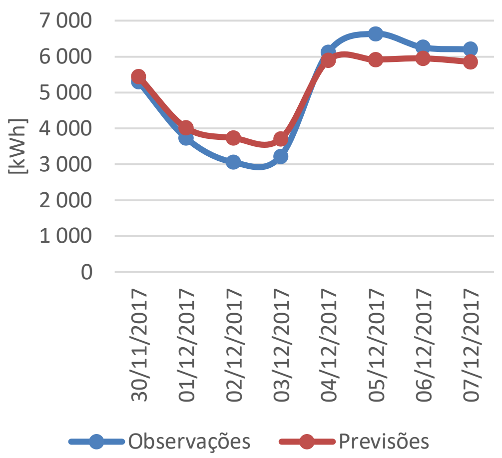


**Figure 5.3 Observed and estimated values of the regression model with ARMA errors for 'Pavilhão Central'.**

This parameter by itself is not a good performance tool, but it allows comparing different models (Makridakis et al., 1998). The MAPE for 'Pavilhão Central', 'Pavilhão de Civil' and 'Torre Norte' were, respectively, 10,32%, 8,76% and 12,95%. Therefore, the model with better prediction was for 'Pavilhão de Civil' and the worst was for 'Torre Norte'.

## 6 FINAL REMARKS

### 6.1 CONCLUSIONS

Among the energy retrofit measures, the improvement of the envelope, especially of windows and walls, HVAC and lightning system efficiency improvement and the use renewable energy were the most relevant. The most common water-saving retrofit measures were the water consume reduction, through more efficient equipment, increase users' awareness of water consumption and detection and correction of water losses. It should be noted that water losses have a high impact on consumption and that user awareness complements all other water-saving retrofit measures. The number of studies focusing on energy rationalization was higher than the ones for water savings, because energy was the main cost of university campuses management.

In the IST buildings, the most studied energy retrofit measure was the improvement of windows, which reveals its impact on the energy performance of buildings in this climate. It should be noted that this interpretation is based on the premise that researchers analysed the more appropriate types of measurements. This is just not applicable for the authors who investigated the optimal package of measures through multiobjective analysis as Ascione et al. (2017) and Niemalä et al. (2016). The goals to optimize were to (1) minimize life cycle cost, (2) minimize energy consumption and (3) maximize user comfort.

The selection of the buildings for analysis was accounted to include the various construction periods and solutions of the 'Campus Alameda'. However, each building has its own energy consumption patterns and should be addressed individually. Besides the availability of dimensioned drawings and constructive solutions of the buildings under analysis, it was concluded that 'Pavilhão de Civil' presented the worst thermal behaviour and 'Torre Norte' the best.

Based on the graphical analysis, 'Pavilhão Central' is the 'critical building' in terms of energy consumption and 'Pavilhão de Civil' is the 'critical building' in water consumption.

The multiple linear regression allowed concluding that the impact of the meteorological variables on the consumption of electricity is similar in the buildings under analysis, for both heating and cooling seasons. The difference in the adjustment of the quality of the models is related to the occupation variables, more precisely, with the academic moment. This variable is more explanatory of the electricity consumption as higher the percentage of spaces dedicated to students. Thus, the adjustment of the models was increasing towards 'Torre Norte', 'Pavilhão Central' and 'Pavilhão de Civil'. We also found that the impact of events at the 'Centro de Congressos' of 'Pavilhão de Civil' is only statistical significant on the cooling season. The managers of this building should be aware of these results.

The artificial neural networks allowed concluding that the relationships among meteorological variables and electricity consumptions are not linear. There are interactions among predictors that explains the variance of the electricity consumption. For example, for the same temperature with different academic moments the heating or cooling needs are different.

Finally, the regression models with ARMA errors revealed a high adjustment and prediction quality for a week of electricity consumption. However, it should be noted that these models require the use of numerical software to model the series of errors. In addition, the developed regression models with ARMA errors need the average daily temperature prediction series to predict future electricity consumption. In addition, the model parameters should be readjusted with new data. For these reasons, regression models with ARMA errors are not user friendly.

## 6.2 FUTURE WORK

Data collected in this study and the modelling of energy consumption of 'Pavilhão Central', 'Pavilhão de Civil' and 'Torre Norte' should be used in the management of IST, aiming to reduce consumption, ensuring comfortable conditions for the users and extend the life span of the buildings. The results revealed that IST has a strong potential for energy savings in renewable energy, improve glazing, opaque surroundings, equipment and building management. Continuous work could validate this and other previous studies and provide data to the scientific community on energy and water consumption in university buildings. Importantly, it will be the support of the Portuguese Government and the European Union to increase funding and improving economic policy to encourage and support energy and water-saving retrofit measures in universities. However, as IST has limited funds to implement all energy retrofit measures, it is important to outline the financial advantageous strategy. Such approximation was first suggested in an audit report of the IST by quantifying the energy retrofit measures in terms of investment (levels 1 to 5) and application (immediate, short term, long term or program).

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