Thermal Model Development of Modular Data Centers for Calibration and Multi-Objective Optimization

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Abstract

The use of containerized Modular Data Centers (MDCs) is an ongoing emerging trend within the industry and is gradually increasing, due to growing demand for cloud services. Consequently, the energy impact of these system is increasing significantly. Compared to traditional data centers, modular data centers are standardized, rapidly fabricated and quickly deployed. The purpose of modular data centers is to store and process data for telecommunications, Internet providers or IT companies. The aim of this thesis is to improve energy performance of four remote MCDs distributed across Portugal. As data center equipment generally generates enormous amounts of heat, HVAC systems are permanently required to cool down the data center space. This study develops and calibrates thermal models for the data center facilities based on real time temperature and energy consumption measurements in the software EnergyPlus. Two locations were successfully validated for time periods of three weeks with only minor discrepancies between measured and simulated values. Based on these calibrated solutions, two multi-objective optimization models were created with the software jEPlus. The models merge six individual optimization solutions, such as free-cooling or shading devices. The purpose is to determine the best combinations of solutions that minimize investment costs and energy costs. Results for solutions with highest investment costs show significant energy cost savings and energy consumption reductions (15.2% and 13.3%) for both models in a tri-rate time energy tariff compared to the calibrated cases (simple tariff). However, solutions with low investment costs can still substantially reduce energy consumption and costs.

Keywords: Modular data center, building energy simulation, building calibration, multi-objective optimization

1 Introduction

The development of society is creating an increasingly intensive usage of Internet, social media and cloud-based computing. The current social habits generate massive amount of information, such as videos, audios, emails, status updates, news or tweets. This big data needs to be stored and processed continuously in facilities named data centers.

Facilities for Information and Communications Technology (ICT) consume gigantic amounts of electricity, representing around 1.5% to 2% of the world's consumed energy in 2014 with a growth rate of about 12% per year [1], [2]. Data centers can consume 100-200 times more electricity as normal office spaces and must run nonstop 8760 hours per year. Global electricity demand from data centers is expected to be two to three times higher in the year 2020 compared to the year 2007. Recent scenarios anticipate that worldwide data center energy consumption will reach 507.9 TWh by the year 2020 [2] with an average data center efficiency. Implementing efficient technologies may decrease this number by 12.4% and could counteract the increasing demand for cloud-based connectivity.

A more recent evolution on the data center construction market since 2007 [3] is a type called Modular Data Centers (MDCs). These containerized modules are especially meaningful for remote or temporary installations. In 2012, this type of build represented less than 5% of the total market, but it has been projected to increase rapidly with a proposed growth of more than 20% until 2020 [2]. Often standard shipping containers with ISO standards are used as the enclosure for those data center units. Their advantages are a rapid fabrication, a robust envelope, lower construction costs, an easy transport and a quick deployment that saves time and costs compared to regular brick and mortar data centers [4], [5].

The research problem of this thesis is to improve energy efficiency of different operating remote Modular Data Centers (MDCs), due to their significant energy consumption caused by high and steady cooling needs. Typically, those MDCs are containers equipped with Information and Communication Technology (ICT) equipment such as servers or other communication systems whose power capacity is transformed into heat. This heat needs to be removed by HVAC systems to ensure a controlled atmosphere (temperature, humidity and dust). In this thesis, the facilities are used for telecommunication purposes and are distributed throughout four locations in Portugal. The objective of this work is to create and validate a thermal simulation model of the MDCs only based on real time measurements in a first step. Information about ICT equipment and air conditioning settings are not available. This reconciliation of model outputs with measured data is known as calibration. A calibrated model allows the forecast and estimation of cooling needs depending on climatic conditions. Consequently, in a next step the performance of a calibrated thermal model may be improved by employing appropriate solutions embedded in a multi-objective optimization (MOO) problem.

2 Methodology

Figure 2-1: Approach of the thesis

The methodology of the thesis is illustrated in Figure 2-1. As preparation for the model development, measurement data, weather data and additional facility *data are processed*. In a next step, thermal simulation *models are development* in the software EnergyPlus. Then, simulations *models are calibrated* with manual and automated calibration methods. Additionally, sensitivity analysis of the calibrations is performed. The fourth stage contains *model optimization*. First, individual solutions to increase the energy performance are explored. Second, multi-objective optimization models are created, to *evaluate* the best combinations of solutions.

3 Thermal Model

3.1 Characterization of the Facilities

The four MDCs are entirely located in Portugal and are distributed around the following places: Montalegre, Cinfães, Salvaterra de Magos and Mourão. The geographic allocation is presented on the map in Figure 3-1.

Figure 3-1: Facilities location distribution throughout Portugal [6]

In this study are analyzed two different geometries of MCDs. The large container size (6058 x 2438 x 2591 mm) is used in Cinfães and Salvaterra de Magos, whereas the small size (3029 x 2438 x 2591 mm) is deployed in Montalegre and Mourão. In the photos in Figure 3-2 are shown the two different geometries. The limits of ASHRAE class A1 for the space climate are applied: 18°C to 27°C dry-bulb temperature and within 20% to 60% relative humidity [7]. The electricity and temperature measurements are extracted from the Watt-IS online platform in a CSV file format.

The cooling equipment for a large container consists of two DX PTAC (Packaged Terminal Air Conditioner) units with each 6.36 kW total cooling power and a COP of 3.63. In contrast, a small container is equipped with only one PTAC unit with 6.36 kW and an additional Split unit of 5 kW with a COP of 2.75. The COP is calculated as gross cooling power capacity divided by electrical power input (compressor and condenser fan power). Still, the actual COP is varying depending on the environment conditions. The cooling units are mounted on the exterior walls, as shown in Figure 3-2. In both systems, the condensers are cooled by outside air. The PTAC units are equipped with damper and fans that allow the use of outdoor air (free-cooling with economizer) to cool the space. The PTAC units have a sensible heat ratio (sensible capacity divided by gross cooling power capacity) of 0.89 as MDCs typically have low moisture removal. It may be assumed that the split systems are only additional units to increase total cooling capacity for the small containers if necessary. Colors of the container envelopes are

Figure 3-2: Data center geometries: large 20 ft. container (left) and small 10 ft. container (right)

white/grey to keep the absorptivity and a heating-up as low as possible.

3.2 Model development

To facilitate the modeling process with EnergyPlus (v8.4.0), two additional programs are used to create the model geometry (SketchUp) and to create the weather file (Elements). Elements (v1.0.6) is an effectual program that is developed to create or modify existing weather files (EPW) for EnergyPlus. The Legacy OpenStudio Plug-in for SketchUp is an useful tool to create the building geometry for the EnergyPlus input files [8]. It is possible to draw 3D-Models and convert the geometric points automatically in an arranged EnergyPlus input file. EnergyPlus is one of the most used programs in the field of building energy simulation [9]. It is used as the main analysis tool in various research papers addressing a broad range of problems related with energy and environmental performance of buildings. The entire modeling workflow is visualized in Figure 3-3.

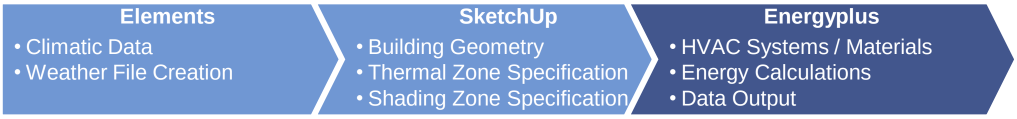

Figure 3-3: Workflow of Model Design

Weather files for the four locations in this study are modifications of existing TMY (Typical Metrological Year) weather files, which are generated with the Excel based software CLIMAS-SCE [10]. Since the facility data (energy consumption and temperature) have been measured recently in 2016 and 2017, the use of TMYs is not appropriate for thermal models that need to be calibrated the most precisely as possible with hourly values. Thus, the available weather files are corrected to recent weather data. The temperature, humidity and wind speed data is acquired from the NNDC Climate Data [11] that provide hourly measurements of nearby weather stations of the study locations. As the weather stations are still with some distance from the case study containers, the NDCC temperature values are scaled in Elements Software. Scaling is performed according to monthly min/max temperature profiles of Meteoblue database of each location [12] to achieve more precise results in a final step. The solar radiation data (global-, direct-, diffuse horizontal irradiance) is obtained from CAMS radiation service [13], which provides recent hourly values.

The container envelope is implemented in one thermal zone that is also created within SketchUp. The geometries (large and small) are shown in Figure 3-4. The containers have a floor area of 14.78 m^2 and 7.39 m^2 respectively. Both models are designed with doors (2.10 x 0.96 m). The material layers of the containers consist of metal layer and insulation layer. The insulation layers are based on cellular glass [14]. The insulation thickness of 0.02 m results from iteration in manual calibration. Moreover, the value is chosen assuming that the containers have small insulation thickness. The U-Values of the walls, roof and floor are 1.54, 1.57 and 1.45. It may be noticed that the constructions have a very low thermal mass performance and the cooling load profile follows the daily external temperature profile as the internal heat gains are constant. Therefore, it is important to have accurate weather files. However, the internal mass of the servers and thus, a possible internal temperature delay is not considered in this simulation.

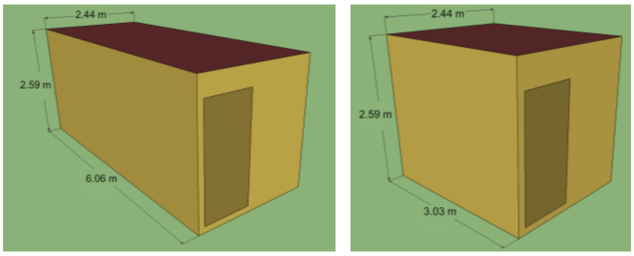

Figure 3-4: 3D-Geometry of large (left) and small (right) container models in SketchUp

The internal gains are only composed of the ICT equipment and are assumed to be constant over time. The baseline total energy consumption (least amount of cooling) is supposed to be at night in a winter month. A start value of 20% for cooling power of the total energy consumption is assumed and iteratively slowly decreased. The difference of total energy and cooling energy equals ICT equipment power. The preliminary ICT equipment power values of the containers are the following: 5200 W for the large containers, 1500 W (Mourão) and 1100 W (Montalegre). Internal gains by lights are neglected, as there is no occupation of the containers. The value for the infiltration rate for all containers in the design phase has been set to 0.5 ACH (Air Changes per Hour) as recommended by CIBSE Guide A4-13 for air-conditioned buildings with moderately tight building envelope [15]. Infiltration rates are highly uncertain, thus a common strategy used in EnergyPlus is to assume fixed infiltration rates.

The HVAC system is chosen based on a unitary DX cooling system without ducts. Since EnergyPlus is limited to one HVAC unit per thermal zone, the two identical PTAC units are modeled as one large unit in case of the large containers. The small containers are modeled without the additional Split system first. The cooling coil COP is fixed on 3.63 based on actual system's specifications. The temperature set points are set to 21°C (large container) and 23°C (small container), based on the average measured indoor temperatures. The design supply air temperature is set to 14°C, sensible heat ratio is set to 0.80 and supply fan delta pressure is set to 444 Pa.

4 Calibration

In this study, calibration is a two-stage method. First, a manual calibration based on an iterative subjective approach is performed. Second, automated calibration based on parametric analysis and optimization is completed.

4.1 Manual Model Calibration

Manual model calibration approaches mostly rely on iterative pragmatic intervention by the modeler. It includes "trial and error" approaches, which are based on an iterative manual tuning of the model input parameters. The sources of uncertainty and limitations in building energy models can be classified and applied to this study: scenario uncertainty (climate conditions), physical uncertainty (building envelope and material properties, internal gains, HVAC systems operation and control settings), model inadequacy (model assumption, simplification in the simulation model algorithm) and observation error (metered data accuracy, sensor accuracy).

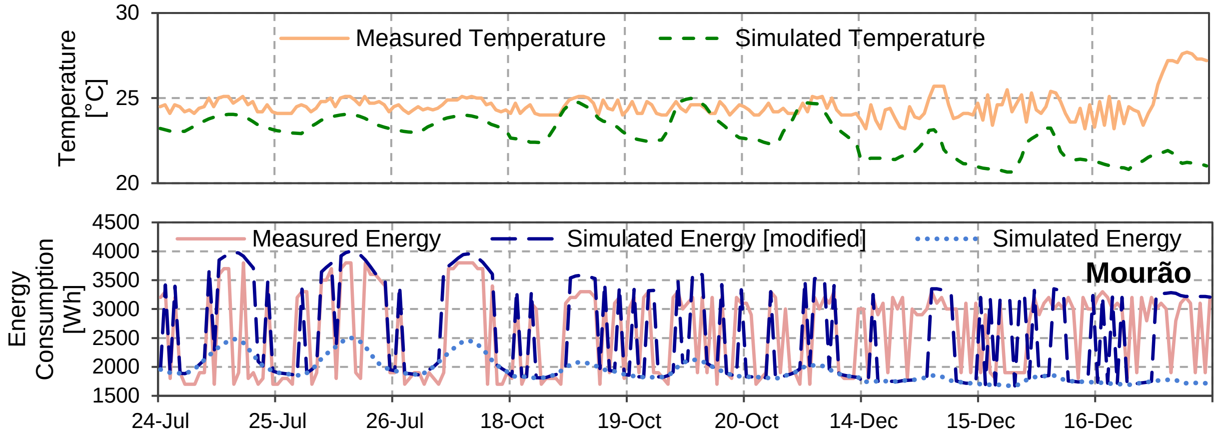

Figure 4-1: Manual calibration result for Mourão, measured and simulated temperature and energy consumption (with post-simulation modification)

Regarding results of the large containers, measured and simulated energy consumption profiles and temperature curves for both locations are most closely corresponding. However, the small containers have several load peaks in the measured energy consumption, which may be caused from switching on and off the AC split units that are not modelled by EnergyPlus. Post-simulation modifications try to integrate these load peaks, as shown in Figure 4-1 for Mourão. Still, results of measured energy and simulated energy (modified) are not similar. Consequently, automated calibration is only performed for the two large containers.

4.2 Automated Model Calibration

Two methods are used in this study for automated calibration: parametric analysis and evolutionary algorithms. The parametric analysis is a method in which series of simulations are run by software and systematically changes the value of parameters associated to one or more design variables. Modifying simultaneously several variables is the approach to explore distinctive design options. jEPlus (v1.7.0) [16] is a software package developed for creating parametric analysis around EnergyPlus.

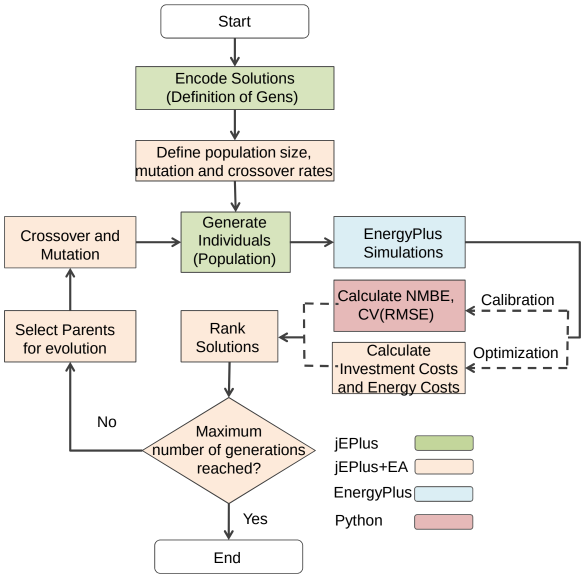

Figure 4-2: EAs procedure for calibration or optimization

Evolutionary algorithms (EAs) can be also used to perform model calibration. EAs are a class of optimization algorithms inspired by the Darwinian evolution theory. jEPlus+EA is an extension software for jEPlus that allows performing optimization problems. The program applies the genetic algorithm optimization method NSGA-II (Nondominated Sorting Genetic Algorithm II). Before starting the optimization process in jEPlus+EA, the user must define the decision variables (gens) and the optimization problem in a jEPlus project. The software encodes the different genes to a solution space (chromosomes). Once the jEPlus project is set, the jEPlus+EA tool can then be coupled with jEPlus. The flowchart of the EAs procedure for calibration or optimization is illustrated in Figure 4-2. EAs are also applied for optimization in the next chapter. In this study are used two metrics to assess the performance of the automated calibration: Normalized Mean Bias Error (NMBE) and the Coefficient of Variation of Root Mean Square Error (CV(RMSE)). The reference values for hourly calibration metrics are based on the ASHRAE Guideline 14. The report states a tolerance of 10% for NMBE and 30% for CV(RMSE). In this study, the container temperature error and energy consumption error between measurements and simulations are summarized to a sum error.

Table 4-1: Calibration Parameters

Parameter	Value Range	Unit
Temperature Set point	20.0 / 20.5 / 21.0 / 21.5 / 22.0 / 22.5 / 23.0	°C
COP	3.4 / 3.5 / 3.63 / 3.7	-
ICT Equipm. Power	5100 / 5200 / 5300	W
Infiltration Rate	0.1 / 0.2 / 0.4 / 0.5 / 0.6 / 0.7	ACH
Insulation Thickness	0.015 / 0.020 / 0.025 / 0.030 / 0.040	m

Simulated total energy consumption and operative temperature are compared to measured hourly total energy consumption and interior temperature. Total size of the solution space with the calibration parameters of Table 4-1 is 2520, thus simulations are executed remotely on the jEPlus Simulation Sever (JESS). Simulation run period covers three weeks in total for both locations with each week of a different month. The results of the parametric analysis can give a total picture of all possibilities, including the solutions with the lowest error indices. However, the method is very time consuming and resource demanding, especially for complex building simulations. Thus, in a next step, calibration is performed based on EAs to decrease simulation time. The objective is to find the two solutions with the best trade-off of both error indices.

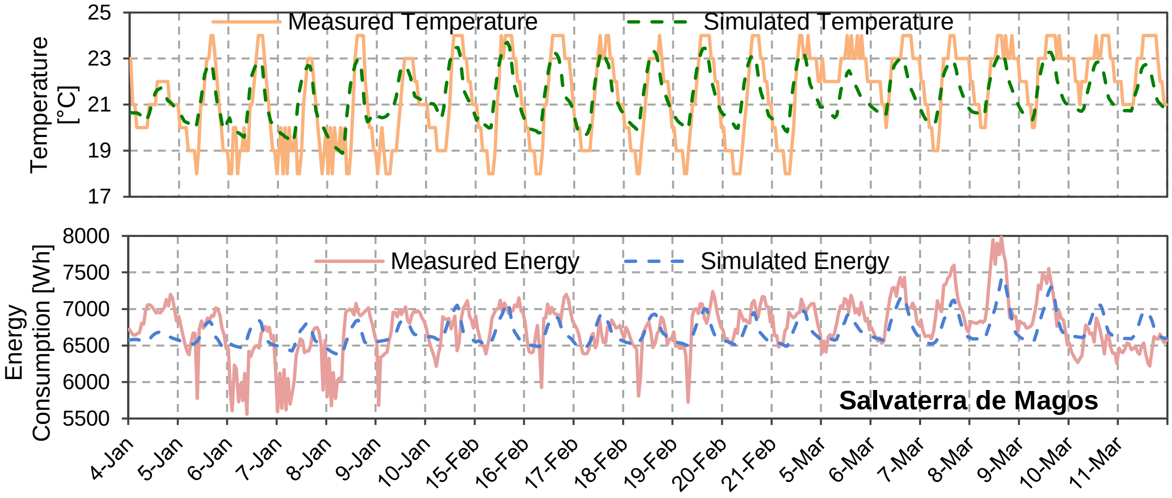

Figure 4-3: Calibrated model solution for Salvaterra de Magos: comparison of measurement and simulation of container temperature and energy consumption

In the optimization problem, two objective functions are set for minimization: the sum of CVRMSE and the sum of NMBE. Compared to the parametric analysis, less than 10% of the computational time is needed as less simulations are executed. The optimization runs can identify the solutions with the best trade-off of error indices: 10.23% (sum of CVRMSE) and 1.43% (sum of NMBE) for Salvaterra de Magos and for Cinfaes 7.22% and 0.72%. Figure 4-3 illustrates the calibrated solution for Salvaterra de Magos, showing container temperature and energy consumption over the three weeks simulation period. It is visible that the simulated outputs are generally matching the measurements.

4.3 Sensitivity Analysis

Sensitivity analysis can identify the level of influence of each design variable on the calibrated output factors operative temperature and facility energy consumption. The calibration results of Cinfães and Salvaterra de Magos are analyzed. The sensitivity analysis is performed using jEPlus, EnergyPlus and SimLab. Two different methods are applied: Morris and Sobol method. Both methods can identify the general sensitivity trend, although there are some minor differences. In terms of operative temperature, both methods detect *temperature set point* followed *by insulation thickness* as the most influential input parameter for both locations. *ICT equipment power* has the greatest impact on energy consumption calibration. *Infiltration rate* has no influence in temperature and energy consumption calibration.

5 Multi-Objective Optimization

5.1 Individual Solutions

Initially, seven individual solutions are developed with the objective to optimize the containers energy performance. An overview of the obtained results in EnergyPlus for the individual solutions for a run period of three weeks is plotted in Figure 5-1. The most promising solution in terms of HVAC savings is the economizer function for both Salvaterra de Magos and Cinfães. Looking at the total energy savings, the best solution for Cinfães is the implementation of photovoltaic panels. Pre-cooling may not beneficial and is not further considered in the MOO models.

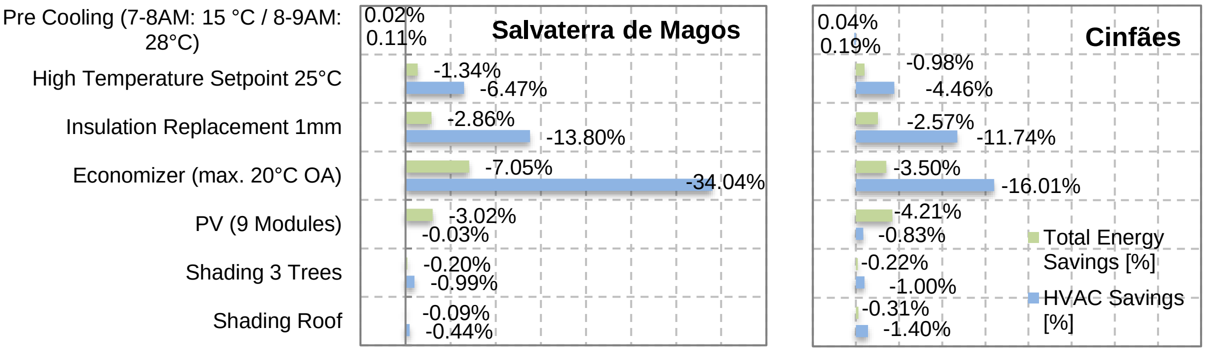

Figure 5-1: Results summary for all individual optimization solutions for Salvaterra de Magos and Cinfães: total facility energy savings [%] and HVAC energy savings [%] compared to calibrated solutions

5.2 Multi-Objective Optimization Models

Both calibrated thermal simulation models are optimized regarding their energy consumption. The MOO models join each individual solution into a combination of solutions to identify the Pareto optimal solutions with the best combinations. The goal is to minimize both investment costs and energy costs. It is introduced a tri-rate energy tariff of EDP (Energias de Portugal) that allows to display energy costs in the results [17]. Equal to the individual solutions, the run period is three weeks. The optimization is executed in jEPlus+EA, as showed in Figure 4-2. The parameter tree is pictured in Figure 5-2 and results in 495 solutions. Investment costs per unit are estimated based on simplified assumptions: PV panel (280 EUR), roof shading large/small (250/50 EUR), tree (200 EUR), insulation change (150 EUR).

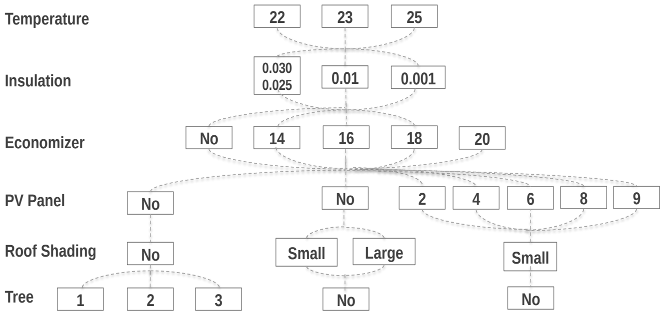

Figure 5-2: Parameter tree for multi-objective-models for both locations

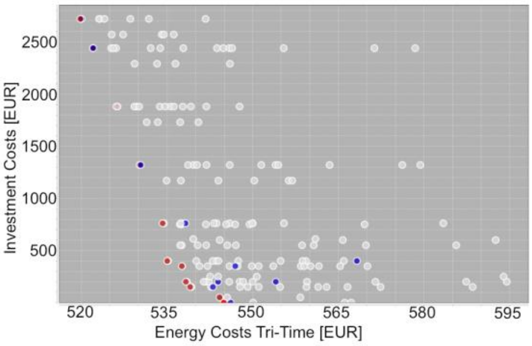

Figure 5-3: Scatter plot result of optimization for Salvaterra de Magos.

The scatter plot of the optimization run for Salvaterra de Magos is illustrated in Figure 5-3. It shows the Pareto front (red dots) consisting of 11 Pareto optimal solutions. Solutions with the lowest energy costs (but highest investment costs) are 520 EUR for Salvaterra de Magos and 530 EUR for Cinfães. For Salvaterra de Magos, cost savings are 95 EUR (14.81%) for the “cheapest” and 120 EUR (18.74%) cost savings for the “most expensive” solution compared to the calibrated solution with a simple tariff. Energy consumption reductions vary between 10.8% to 15.2%. For Cinfães, the “cheapest” solution can make up cost savings of 66 EUR (10.40%), compared to the calibrated solution. Whereas the “most expensive” solution reduces the total costs by 107 EUR (16.78%). Here energy consumption savings differ from 6.1% to 13.3%. The combination of economizer utilization, increment of temperature set point and insulation reduction are promising optimization measures for both locations. Optional PV panels can significantly reduce facility energy consumption, especially in summer. The shading alternatives may be beneficial, but are especially integrated in the optimization model to show a wider range of viable solutions.

6 Conclusion and Future Work

The implementation of Modular Data Centers (MDCs) for ICT purposes has been an ongoing trend over the last decade, especially caused by the increasing demand for cloud-based storage. Those facilities generate large cooling needs that must be constantly satisfied by HVAC systems. Thus, they have an enormous potential for intelligent energy reduction measures.

The present work proposed to create and calibrate four thermal models for containerized MDCs in remote locations within Portugal. Data about ICT equipment and air conditioning settings were not available. After designing a model for each facility, two MDCs with identical geometries were successfully calibrated with manual and automated calibration methods. Calibration of Salvaterra de Magos resulted in a sum of CVRMSE of 10.23% and sum of NMBE of 1.43%, while Cinfães reached indices of 7.22% and 0.72%. Based on their calibrated parameter information, the facilities' energy performances were improved with the advantage of multi-objective optimization (MOO) models. MOO models that combine six individual solutions as decision variables with two minimization objectives were created: investment costs and energy costs. Results in terms of energy consumption savings compared to calibrated solutions are between 10.82% and 15.18% for Salvaterra de Magos and between 6.06% and 13.29% for Cinfães. Thus, MDCs offer great opportunities to decrease energy costs without making enormous initial investments. Immediate adjustments, such as a change from simple to tri-rate tariff and the utilization of free-cooling function, may lead to rapid savings in energy consumption.

Future investigations may involve another more detailed consideration of calibration and optimization. Another look may be invested on the calibration of the small containers that were not successfully calibrated. Implementation of immediate measures in practice, such as free cooling or an increased temperature set point, may be attractive to verify the simulations.

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