Building energy efficiency improvement using multi-objective optimization for heating and cooling VRF thermostat setpoints

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Abstract. The variable refrigerant flow system is one of the best heating, ventilation, and air conditioning systems (HVAC) thanks to its ability to provide thermal comfort inside buildings. But, at the same time, these systems are considered one of the most energy-consuming systems in the building sector. Thus, it is crucial to well size the system according to the building's cooling and heating needs and the indoor temperature fluctuations. Although many researchers have studied the optimization of the building energy performance considering heating or cooling needs, using air handling units, radiant floor heating, and direct expansion valves, few studies have considered the use of multi-objective optimization using only the thermostat setpoints of VRF systems for both cooling and heating needs. Thus, the main aim of this study is to conduct a sensitivity analysis and a multi-objective optimization strategy for a residential building containing a variable refrigerant flow system, to evaluate the effect of the building performance on energy consumption and improve the building energy efficiency. The numerical model was based on the EnergyPlus, jEPlus, and jEPlus+EA simulation engines. The approach used in this paper has allowed us to reach significant quantitative energy saving by varying the cooling and heating setpoints and scheduling scenarios. It should be stressed that this approach could be applied to several HVAC systems to reduce energy-building consumption.

1 Introduction

The building sector is considered among the most sectors that consume energy [1]–[5]. The biggest part of the energy used in buildings is consumed by heating, ventilation, and air conditioning systems (HVAC) [6]–[8]. Although these systems are energy-consuming, they are essential in providing thermal comfort in buildings [9]–[11]. Therefore, it is crucial to well size these HVAC systems according to the building's cooling and heating needs and the indoor temperature fluctuations, while taking into consideration the weather climate conditions [12]. The variable refrigerant flow system (VRF) is a multizone direct expansion system composed of one single outdoor unit, containing the compressor and the condenser, that supplies several indoor units [13]. This system is considered one of the best HVAC systems thanks to its ability to provide cooling and heating simultaneously in different thermal zones of the same building. It is also well known for its ability to recover the heat rejected from spaces requiring cooling and reuse it to heat other spaces necessitating heating. Although many researchers have studied the building energy performance considering heating or cooling needs, using air handling units [14], radiant floor heating [15], [16], and direct expansion valve systems [17], [18], few studies have considered the use of VRF systems for both cooling and heating needs aiming to enhance the building energy efficiency. Thus, the optimization of the building energy performance relies mainly on the minimization of the cooling and heating energy consumption. Many studies [19]–[23] have focused on minimizing HVAC energy use by the application of multi-objective optimization strategies. In the majority of these studies, the parameters used for the optimization process are based on a previous sensitivity analysis. The sensitivity analysis is performed to help at detecting the parameters that mainly affect the energy expenditure in buildings to minimize the optimization time. The parameters used in the literature for these optimization-based studies are the U-value of opaque and glazing materials, the thickness of building construction and insulation materials, the G-value, the solar heat gain and the visible transmittance of windows, the infiltration, occupancy schedule, HVAC schedules, and thermostat setpoints. In general, the solutions obtained from such optimization-based strategies could be beneficial in the case of building renovations, or in the case of a new building in the conception and design phase. These options are not always practical in reality for already-built buildings.

So, in the aim of this study, we have focussed on minimizing the energy consumed by a VRF heat pump system in a residential building using only the heating and cooling thermostat setpoints and scenarios. The use of optimal heating and cooling setpoints depending on external weather conditions and internal thermal comfort could provide great savings on the overall

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energy consumption in buildings without the need for any further renovations or any financial expenditure. Therefore, a sensitivity analysis has been conducted on the ten most used building parameters to prove the great impact of cooling and heating setpoints on HVAC energy consumption. The Latin Hypercube sampling method was used for the sensitivity analysis. Then a multi-objective optimization has been accomplished using jEPlus and jEPlus+EA coupled with EnergyPlus simulation software. The non-dominated sorting genetic algorithm NSGA-II was used for the minimization of the objective functions, the VRF heating, and cooling energy use, using an rvx formatted file. Then, the Pareto front solutions were extracted and the optimal solution was selected afterward.

The remainder of this essay is organized as follows; Section 2, presents and details the methodology undertaken in the framework of this paper, along with the building validation, sensitivity analysis, and multi-objective optimization process. Section 3, presents the main findings and results obtained from the optimization procedure. Then, finally, Section 0 gives an overview of the overall study conducted, the main findings, and the possible recommendations and perspectives for future studies.

2 Methodology

This study focuses on the development of a multi-objective optimization approach in an existing real residential building. The aim is to improve the energy efficiency of the building by decreasing heating and cooling energy use while gathering an acceptable indoor thermal comfort level inside the studied building. **Fig.** ***1*** summarizes the main steps of the methodology conducted in this study. The initial step involved developing the building energy model using the actual input parameters for the construction and its energy systems. Subsequently, using ASHRAE statistical indices, the model was calibrated and validated, before starting a sensitivity analysis based on linear regression standardized coefficient. The sensitivity analysis was essential to know the parameters that impact the building energy use before performing the multi-objective optimization.

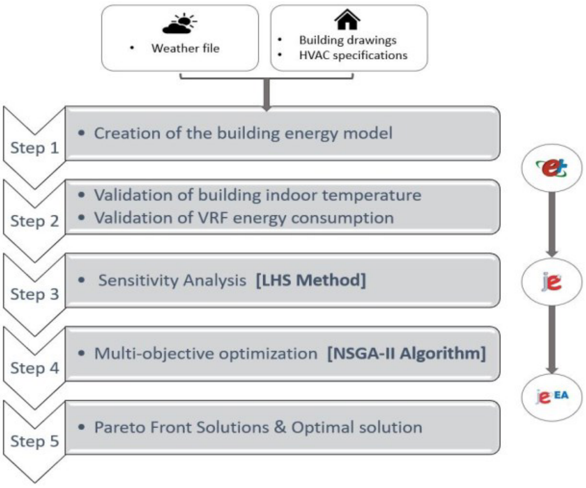

Fig. 1. Multi-Objective Optimization Methodology

2.1 Building Energy Model

This paper uses a two-story residential construction situated in Morocco's semi-arid climate of Benguerir city as a case study building. The building is built from a light wood structure with walls, roof, and floor insulation and double-glazing windows filled with air gaps. The building has a VRF heat pump system for heating and cooling comfort needs. The VRF thermostat used fixed setpoint temperatures for cooling and heating as shown in **Table 1**. The cooling and heating thermostats are working for 3 periods as detailed in **Table 1**. This building is built recently in 2019 in the Green and Smart Building Park platform for research purposes. So, the building is unoccupied for the studied period.

Table 1. Cooling and Heating Setpoints in the base model

	Period 1: January – March		
	08:00 - 13:00	14:00 - 19:00	20:00 - 07:00
Cooling SP	-	-	-
Heating SP	20	20	20
Period 2: April - September			
Cooling SP	22	22	22
Heating SP	-	-	-
Period 3: October - December			
Cooling SP	-	-	-
Heating SP	20	20	20

2.2 Building validation

Based on the building drawings, HVAC specifications, and weather file data, the building energy model has been created using EnergyPlus Software. Then, a building calibration has been undertaken to hourly indoor temperature, as shown in **Fig.** ***2***, and to hourly VRF energy use in cooling and heating periods as figured in **Fig.** ***3***. The numerical model validation was carried out based on ASHRAE Guideline 14 statistical indices. The validation of the energy consumption was based on the calculation and definition of 20 VRF performance curves based on manufacturer datasheets.

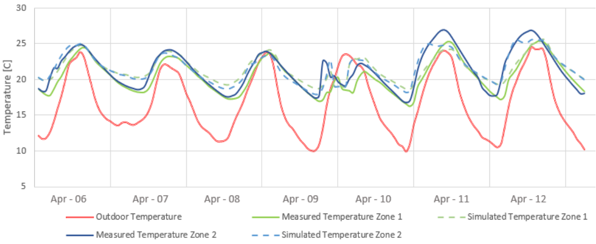

Fig. 2. Measured and simulated indoor temperatures VS Outdoor temperature

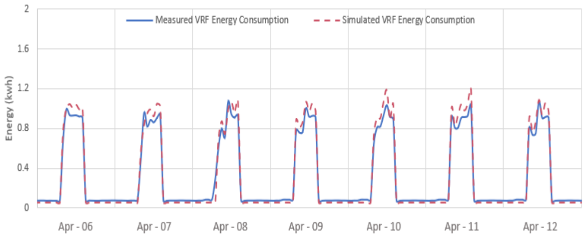

Fig. 3. Measured and Simulated VRF energy consumption

2.3 Sensitivity Analysis

A sensitivity analysis was conducted using jEPlus and jEPlus+EA coupled with EnergyPlus software. The sensitivity analysis was performed based on the Latin Hypercube Sampling (LHS) method using a 500-sample size and 50 population size. Then, the standardized rank regression coefficient (SRRC) was used as an index of sensitivity. This SRRC index's value specifies the input variable's importance on the output variable. Ten building parameters were involved in this study to evaluate the impact of each parameter on the variation of the cooling and heating energy use. **Table 2** summarizes all the building parameters included in this sensitivity analysis along with their ranges of variation. All these input variables have a continuous uniform probability.

Table 2. List of Inputs parameters included in the sensitivity analysis

Parameters	Range	Unit
Heating Setpoint	[17 - 22]	°C
Cooling Setpoint	[22 - 27]	°C
Infiltration	[0.3 - 4]	ACH
U-value of Glass	[0.5 - 1.5]	W/m^2 K
Orientation	[0 - 360]	°
Thickness of Insulation 1	[0.04 - 0.1]	m
Thickness of Insulation 2	[0.05 - 0.1]	m
Conductivity of Insulation 1	[0.02 - 0.1]	m^2 K/W
Conductivity of Insulation 2	[0.05 - 0.1]	m^2 K/W
Visible light transmission	[0.5 - 0.9]	-
Solar heat gain coefficient	[0.2 - 0.9]	-

2.4 Multi-Objective Optimization

Using the jEPlus tool the parameters used in the multi-objective optimization were defined along with their ranges of variation. **Table 3** describes the VRF thermostat setpoints, their ranges, and their schedules taken into consideration to optimize building energy performance. Two objectives were used in the optimization framework, including minimizing total annual cooling and heating energy consumption. Moreover, one single constraint has been undertaken while the multi-objective optimization, which is the average of the annual building temperature that should be in a range of thermal comfort; between 22ºC and 25ºC. This constraint was developed using a Python script integrated into jEPlus and jEPlus+EA. The Python script helps with reading the output files of EnergyPlus and then, calculating the annual temperature average of all the thermal zones existing in the building.

According to jEplus +EA recommendations, the NSGA-II optimization algorithm was used with the LHS sampling method. 200 generations have been used with 10 population sizes per generation. The tournament size was assigned to 2, the crossover rate to 100%, and the mutation rate to 20%. The choice of working with the non-dominated genetic algorithm NSGA-II was based on its high computation efficiency and its ability to find the best solutions possible.

The optimal solution definition among all Pareto front solutions remains one of the challenging points of multi-objective optimization-based approaches. Since the Pareto front presents a range of solutions it cannot minimize both solutions simultaneously. So, in our case, to choose the optimal solution, we will choose the solution that provides the minimum total energy consumption for both cooling and heating needs.

Table 3. Heating and cooling setpoints optimization parameters

Parameters	Definition	Range
P0	Heating SP in period 1 From 08:00 until 13:00	[17:1:22]
P1	Heating SP in period 1 From 14:00 until 19:00	[17:1:22]
P2	Heating SP in period 1 From 20:00 until 07:00	[17:1:22]
P3	Heating SP in period 3 From 08:00 until 13:00	[17:1:22]
P4	Heating SP in period 3 From 14:00 until 19:00	[17:1:22]
P5	Heating SP in period 3 From 20:00 until 07:00	[17:1:22]
P6	Cooling SP in period 2 From 08:00 until 13:00	[22:1:27]
P7	Cooling SP in period 2 From 14:00 until 19:00	[22:1:27]
P8	Cooling SP in period 2 From 20:00 until 07:00	[22:1:27]

3 Results & Discussion

This paper involves a multi-objective optimization approach for the improvement of building energy efficiency of a residential building situated in Morocco’s semi-arid climate. After the creation and validation of the numerical model. A sensitivity analysis was carried out on 10 variables of the building, to know the parameters that have a great impact on the cooling and heating needs. The sensitivity analysis was conducted using the SRRC index based on linear regression. Based on **Fig. *4*** and **Fig. *5***, the heating setpoint and cooling setpoints are the most influencing parameters on heating and cooling energy use. Then, we find the infiltration rate and the solar heat gain of glazing.

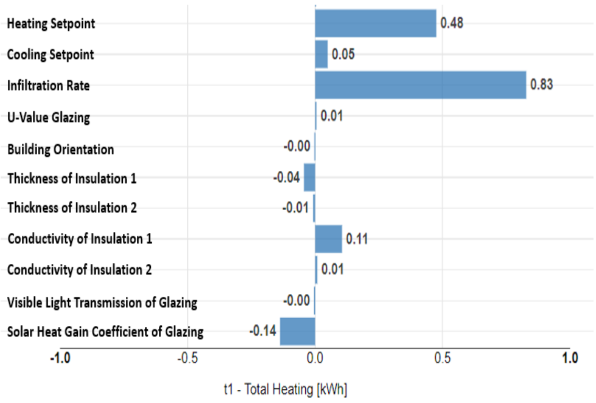

Fig. 4. Sensitivity analysis performed to total heating energy

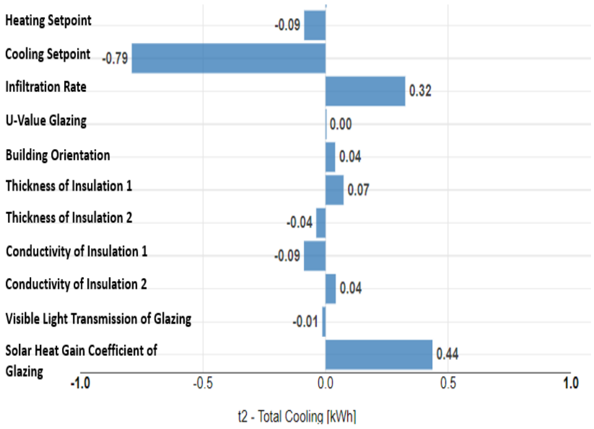

Fig. 5. Sensitivity analysis performed to total cooling energy

Therefore, for the multi-objective optimization, we have chosen to work with only heating and cooling setpoints as parameters based on their high influence on energy use as found with the sensitivity analysis performed before. Moreover, it is hard to control the airtightness of the building, since it is highly related to the occupancy schedule, HVAC schedules, and opening and closing of doors and windows. Furthermore, the solar heat gain coefficient is related to the glazing type used in windows, thus it is not practical to change windows in an existing building.

The multi-objective optimization with the NSGA-II algorithm was conducted using jEPlus and jEPlus+EA optimization tools. **Fig.** *6* shows the possible solutions, including the best solutions and the feasible solutions. After 140 generations, 10 best solutions were found, as shown in **Fig.** *7*. All these best solutions respect the range of indoor thermal comfort that we have created as a constraint for the optimization simulation.

Table 4 shows the ten optimal solutions found within Pareto front solutions along with the value of the heating and cooling objective functions and improvement achieved from the base model and optimized models.

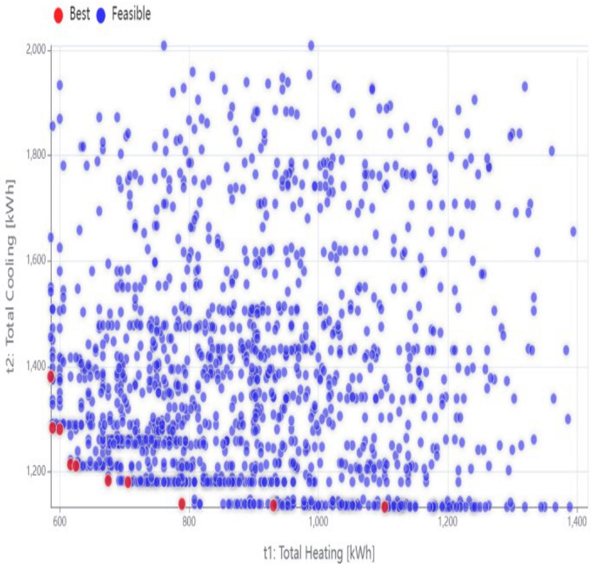

Fig. 6. Possible solutions after multi-objective optimization

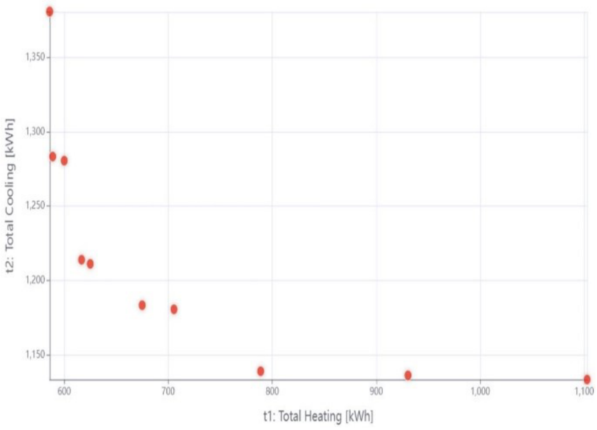

Fig. 7. Pareto front solutions

Table 4. Comparison of base model energy consumption and Pareto front solutions energy savings

Building Model	Objective functions	Value (kWh)	Improvement (%)
Base Model	Heating Cooling	1118.1 2007.4	-
Solution 1	Heating Cooling	586.1 1381	47.58 31.20
Solution 2	Heating Cooling	588.9 1283	47.33 36.08
Solution 3	Heating Cooling	600 1281	46.33 36.18
Solution 4	Heating Cooling	616.7 1214	44.84 39.52
Solution 5	Heating Cooling	625 1211	44.10 39.67
Solution 6	Heating Cooling	675 1183	39.62 41.06
Solution 7	Heating Cooling	705.6 1181	36.89 41.16
Solution 8	Heating Cooling	788.9 1139	29.44 43.25
Solution 9	Heating Cooling	930.6 1136	16.76 43.40
Solution 10	Heating Cooling	1103 1133	1.35 43.55

We have chosen solution 4 from Pareto front solutions as the optimal solution since it is the best solution that provides the minimal total energy consumption of both heating and cooling needs. The initial total energy consumption of both heating and cooling of the base model is 3125.5 kWh and optimal solution 4 provides an annual total VRF energy use of 1830.7 kWh. The design parameters of solution 4 are shown in **Table 5**.

Table 5. Design parameters of the optimal Pareto solution

	Period 1: January – March		
	08:00 - 13:00	14:00 - 19:00	20:00 - 07:00
Cooling SP	-	-	-
Heating SP	17	17	17
Period 2: April - September			
Cooling SP	27	27	27
Heating SP	-	-	-
Period 3: October - December			
Cooling SP	-	-	-
Heating SP	17	17	17

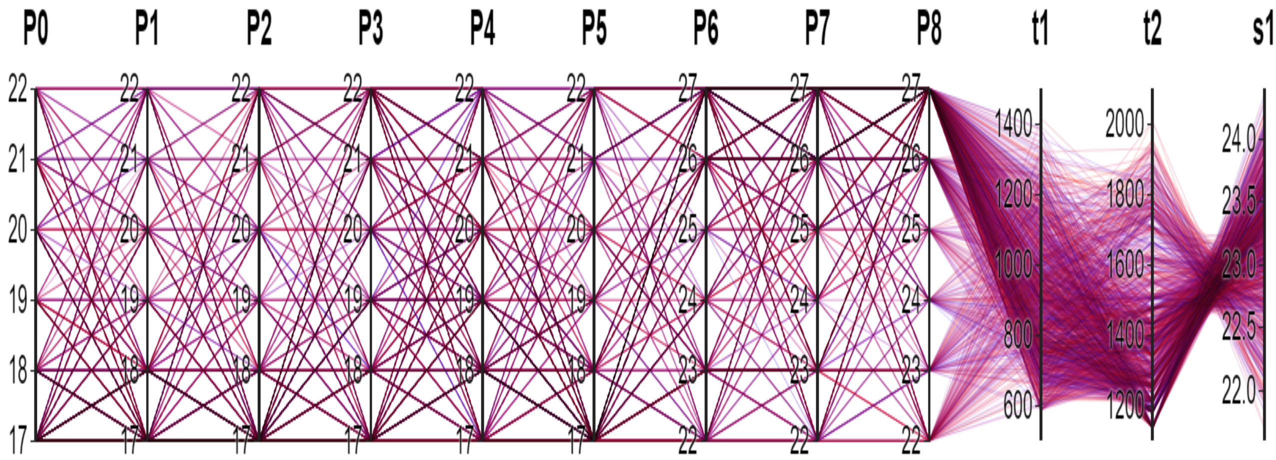

Fig. 8. Combination of possible solutions

The combination of all the possible solutions of the multi-objective optimization problem is presented in **Fig. 8**. The parameters of the optimization are listed from P0 until P8. The objective functions are t1 and t2 respectively corresponding to the minimization of the total heating energy consumption and the total cooling energy consumption. Whereas, s1 represents the average building indoor air temperature constraint. According to these findings there exist a variety of possible solutions.

4 Conclusion

This paper describes a framework of multi-objective optimization strategy for improving the building energy efficiency based only on the cooling and heating setpoint thermostat. The findings of the sensitivity analysis performed on the majority of building influencing parameters prove that cooling and heating setpoints are the most important variables in buildings that impact the cooling and heating energy consumption along with infiltration rate and the solar heat gain of glazing. In the aim of this paper, we have chosen to work with only thermostat setpoints, since the infiltration rate and the solar heat gain are hard to improve in reality in an existing building. Nevertheless, they could be taken into consideration in future studies aiming at building renovations or even in the building design phase. Moreover, in case of the improvement of the building efficiency in an existing real building, the choice of optimal heating and cooling setpoint could provide high savings of energy with no further financial costs or time waste. Thus, the finding of this study could be of high interest to future research studies in building and HVAC systems designs.

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