



Adapting French buildings to future climate: passive design optimisation

Anaïs Machard, Christian Inard, Jean-Marie Alessandrini, Charles Pelé,
Jacques Ribéron

► To cite this version:

Anaïs Machard, Christian Inard, Jean-Marie Alessandrini, Charles Pelé, Jacques Ribéron. Adapting French buildings to future climate: passive design optimisation. Building Simulation 2021, International building performance simulation association (IBPSA), Sep 2021, Bruges, Belgium. 10.26868/25222708.2021.30718 . hal-04067726

HAL Id: hal-04067726

<https://cstb.hal.science/hal-04067726>

Submitted on 13 Apr 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Adapting French buildings to future climate: Passive design optimisation

Anaïs Machard^{1,2}, Christian Inard¹, Jean-Marie Alessandrini², Charles Pelé², Jacques Ribéron³

¹Laboratoire des Sciences de l'Ingénieur pour l'Environnement (LASIE, UMR CNRMS 7356), La Rochelle Université, 23 avenue Albert Einstein, 17000 La Rochelle, France

²Département Energie et Environnement, Centre Scientifique et Technique du Bâtiment (CSTB), 84 avenue Jean Jaurès, Champs-sur-Marne, 77447 Marne-la-Vallée cedex 2, France

³Département Santé et Confort, Centre Scientifique et Technique du Bâtiment (CSTB), 84 avenue Jean Jaurès, Champs-sur-Marne, 77447 Marne-la-Vallée cedex 2, France

Abstract

With climate change projected warming temperatures, ensuring that buildings designed and built today will be adapted to future extreme heat is essential. For this purpose, the use of an optimisation algorithm is appropriate to identify best designs in both present and future climate. Future weather files with heatwaves allow to assess the overheating risk in different building designs. For the proposed building case-study, results are presented with two different ventilative cooling solutions, with a reference configuration with only hygienic ventilation, with mechanical free-cooling and with natural ventilation. Results indicate strong design tendencies regarding the building fabric (thermal mass, glazing percentage and cool paints), different for the two case-study cities.

Key Innovations

- A methodology is proposed to optimise the building envelope in order to both mitigate and adapt to climate change
- Future weather files assembled from climate projections including heatwaves are used to analyse the summer thermal discomfort
- Visual representation of all non-dominated Pareto for both optimisation objectives

Practical Implications

Air-conditioning is not common in France in the residential sector and with climate change its implementation might increase especially in the South. This work is limited to one type of building and one set of future climate projections, but the optimised building fabric to reduce summer discomfort with ventilative cooling solutions showcases a high level of thermal discomfort. These preliminary results indicate that additional passive measures might need to be implemented on buildings to avoid the use of air-conditioning in the South of France.

Introduction

In recent years, overheating in new energy-efficient French buildings has been more and more frequent during the summer period. In fact, due to climate change, the summer mean temperature in France has already increased by + 1.5 °C since the pre-industrial period and will continue to increase at least until the mid-century

even with mitigation measures. Besides mean temperatures, heatwaves are also becoming much more frequent (Bador 2017). Numerous research reports demonstrate the relationship between extreme high temperatures and human mortality, and the French population witnessed this during the 2003 heatwave which resulted in 15,000 excessive deaths in France (Robine et al., 2008). In case of extreme heat, the built fabric is supposed to act as a protective factor, in its capacity to absorb and modulate heat. While efforts have been concentrated on mitigating climate change in recent years, adapting buildings to extreme heat is today an additional challenge. As air-conditioning is an easy option to cope with extreme heat, its use in future years might largely increase if buildings keep overheating. According to (International Energy Agency, 2018), cooling is already the fastest growing use of energy in buildings worldwide, and projections for air-containing penetration are daunting. However, as this solution does currently not mitigate climate change as it is very energy consuming, in this paper we investigate alternative passive cooling solutions. *Can we propose building designs suited for both the winter and summer periods that contribute to adapt to and mitigate climate change?* Our study is focused on the optimization of a building case-study for the future typical climate of the mid-century, with two objectives: minimizing heating needs and minimizing summer discomfort, assuming that no cooling system is installed on the building. Multiple passive strategies and two ventilative cooling strategies are compared in Carpentras and in La Rochelle. In order to provide optimised designs, we use an optimisation algorithm based on the variation of different design parameters related to the building fabric and the operation of the ventilation strategies. Building optimisation has been ongoing for the past two decades, however optimising buildings to future climate is an on-going area of research and much recent work is currently under development on this topic. Authors explore a variety of objectives: reducing energy loads or consumption, minimizing lighting consumption, maximizing daylighting, reducing summer thermal discomfort, reducing building construction or energy system costs, reducing the carbon emissions, or most related to climate change, reducing future climate uncertainty (Moazami 2019)(Forde 2020)(Lapisa 2018)(Kim and Clayton 2020)(Nguyen 2021)(Bamdad 2021).

Methods

The methodology used in this paper is introduced in Figure 1. From a building case-study and using different weather files (present and future), different design variables related to the building envelope and architecture, and different ventilative cooling solutions are explored. Building thermal simulations analyses are conducted with the software EnergyPlus, while optimized solutions are selected using the NSGA-II algorithm (Deb 2002) implemented in the Python library *Deap* (De Rainville et al., 2012)

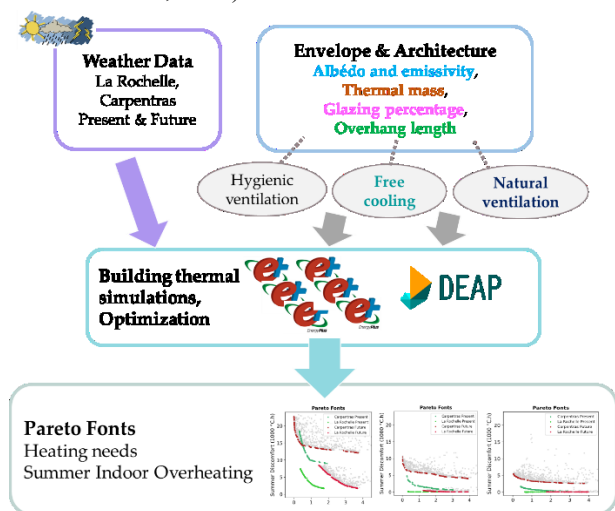


Figure 1: Methodology for the paper

Present & Future Climate Data

In this paper we analyse the building designs in two cities: La Rochelle, which is located on the French West coast, is characterized by an oceanic climate while Carpentras, located in the South-East of France is characterized by a Mediterranean climate. Carpentras is the city with the highest temperature maxima recorded in France, but summer nights are relatively fresh in present climate because of the close by presence of the Mont Ventoux (1910 m high). In La Rochelle, summer maxima and daily temperature variations are lower due to the proximity to the Atlantic Ocean. Raw multi-years climate data were downloaded from the CORDEX platform (Kotlarski 2014) for the model IPSL-RCA4 for the present (1990-2019) and future periods (2040-2069, scenario RCP 8.5). The raw climate data were then bias-adjusted using multi-years historical observations (2000-2019) for six weather variables (dry-bulb temperature, relative humidity, atmospheric pressure, wind speed, global solar radiation and cloud cover). The four first weather variables were bias-adjusted with the MBC method (Cannon, 2018) which preserves the correlation between the weather variables. The latter two were bias-adjusted with the QDM method (Cannon 2015). Finally, typical years were assembled from the bias-adjusted present and future climate data, following the norm EN 15927-4 (ISO, 2006). The methodology was described in (Machard 2020). Figure 2 presents the outdoor dry-bulb temperatures during the present and future typical years

in La Rochelle and Carpentras. In La Rochelle, in the future typical year extreme cold winter temperatures will be less frequent, and warm temperatures during summer will be more frequent. The increase in warm temperatures (when the red curve is above the green curve) occur mostly between 20 °C and 25 °C, indicating that night summer temperatures might be increasing. The increase in maximum temperatures is less pronounced, as they are around 35 °C in both present and future climate. The present climate is reassembled from years 1990-2019 and already contains a + 1.5 °C increase in mean temperature in France in comparison to the early 20th century. In Carpentras, the increase in warm temperatures is more pronounced between 25 °C and 40 °C, indicating an increase in both night and day summer temperatures. The maximum temperature increases from 38 °C to 42 °C between the present and future typical year. The typical year in Carpentras contains two heatwaves with higher severity than in 2003, according to the French definition of both *vague de chaleur* (Ouzeau 2016) et *canicule* (Laaïdi 2013). This means that in the future typical climate in Carpentras, heat stress might occur which emphasizes the need to adapt the built fabric. Note that these observations are specific for this climate model (IPSL-RCA4) projections only and that the selection of the typical year is made with equivalent weight given to the dry-bulb temperature, the relative humidity and the global solar radiation.

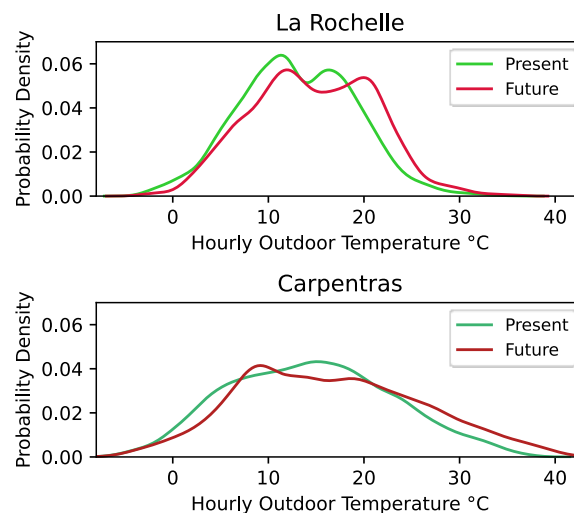


Figure 2 – Present & Future Temperature during typical years in La Rochelle and Carpentras

Building case-study description and modelling

The building case-study is a residential collective building, we investigate only the top-floor apartment, represented on Figure 3. The West façade is in contact with the outdoors while the East wall is considered in contact with an adjacent apartment, it is adiabatic. Similarly, the apartment roof is in contact with the outdoor but the floor is adiabatic. The building is oriented North-South with fully glazed facades. The apartment is conditioned in between two non-conditioned buffer zones: the glazed cavity, and the veranda, which acts as a sunspace during winter and can be used as additional

space during the summer. In the initial design from the architect, there is an additional Trombe wall on the south façade, from which the warm air is transported to the glazed cavity, this is not modelled here. The air temperature in the glazed cavity during the winter is always superior to the exterior temperature, so it acts as a buffer space.

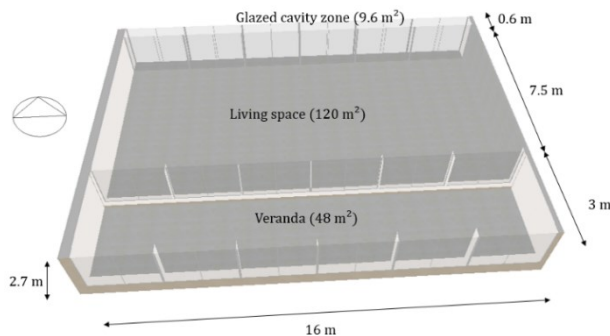


Figure 3 – Apartment case-study thermal zoning

All windows are double glazing (U_{window} from 1.2 to 1.4) except the exterior windows of the veranda that are single glazing ($U_{window} = 5.5$). The exterior wall is made of 18 cm concrete with exterior insulation 15 cm polystyrene for a $U_{wall} = 0.23 \text{ W/(m}^2\text{.K)}$. The roof is made of 18 cm concrete with exterior insulation 14 cm of polyurethane for a $U_{roof} = 0.16 \text{ W/(m}^2\text{.K)}$. The floor is 18 cm concrete with 3 cm polystyrene and is considered adiabatic, as the East-facing wall. The apartment is modelled with the interface DesignBuilder and the software EnergyPlus version 8.8. The apartment has a surface area of 120 m^2 and the veranda of 50 m^2 and has three distinct thermal zones represented on Figure 3. For the glazed cavity, the *TrombeWall* algorithm is used for internal convection while the default *TARP* is used for the two other zones. For the heat balance the default *CFT* algorithm is used. The apartment is inhabited by 5 people including one that remains home all day. The average metabolic heat of occupants is about 81 W and is modulated according to their presence and when they are sleeping. The occupants vesture is about 1 clo during winter and 0.5 clo during summer. The hygienic mechanical ventilation has a minimum airflow rate of $105 \text{ m}^3/\text{h}$ and functions at maximum capacity ($210 \text{ m}^3/\text{h}$) 3 hours a day. The internal gains during the historical period are the one defined by the French Thermal Regulation RT-2012 (5.7 W/m^2 and lights 1.4 W/m^2). For the future period, internal gains are reduced according to a report from the operator network about projections of new equipment efficiency by 2035 (RTE, 2017). The internal gains for specific equipment in the future are about 3 W/m^2 and for lights about 0.5 W/m^2 . This variation in internal gains in the future increases the heating needs and decreases the summer discomfort, independent to the changing climate. The heating needs are modelled with the EnergyPlus *IdealLoadsAirSystem* component with heat-recovery efficiency of 0.7 and heating is allowed during the extended winter period from the 15th of October until the 15th of May with a set-point air temperature of 20°C . In

order to reduce the heating needs, shutters are using on the exterior windows of the glazed cavity during the winter. Due to high solar radiation in the winter, the veranda tends to overheat and we assume that occupants open the windows when $T_{air_veranda} > 26^\circ\text{C}$. In the extended summer periods solar shades are used in the veranda and the exterior windows of the glazed cavity and of the veranda can be opened. These actions are summarized on Table 1.

Table 1 – Actions in the buffer spaces to reduce heating needs or summer discomfort

	Action	Control
Extended Winter Period 15 th October – 15 th May	Shutters on north façade glazed cavity during the night*	Scheduled from 10 pm to 7 am
	Ventilation of the veranda during winter	When $T_{air_veranda} > 26^\circ\text{C}$
Extended Summer Period 15 th May – 15 th October	Internal shades on the exterior windows of the veranda	When $SR_{ext_windows_veranda} > 300 \text{ W/m}^2$
	Ventilation of the glazed cavity and of the veranda	When $T_{air_zone} > 18^\circ\text{C}$

*The period of use of the winter shutters is reduced from the 1st November until the 30th of April.

Design parameters

The objective of the study is to determine design principles for a set of parameters of the building case-study. The goal of the study is to find compromise designs that are suited for both winter and summer periods, i.e. reduce heating needs and summer discomfort related to overheating. The choice of the design parameters was made following a sensitivity analysis not presented here. The parameters and their range of variation is introduced on Table 2. The initial design of the building has high thermal mass, with concrete of density 2300 kg/m^3 . The concrete in the initial design is replaced with other materials such as wood, earth, brick, etc. To simulate this, a relationship is established between the changing material density, thermal capacity, thermal conductivity and isolation thickness to maintain a similar U-value in all designs. The minimal thermal delay for the lowest thermal mass value is about half an hour and the maximal thermal delay is about twelve hours.

Table 2 – Range of variation of design parameters

Design Parameter	Range of variation	Unit	1	2	3
Thermal mass	650 - 2300	kg/m^3	x	x	x
Albedo & Emissivity	0.1 - 0.9	-	x	x	x
Glazing %	35 - 95	%	x	x	x
Overhang length	0 - 1	m	x	x	x
ΔT Free-cooling	0.5 - 6	$^\circ\text{C}$		x	
Percentage of windows opening	0 - 100	%			x

The second parameter is the optical properties of exterior coatings (roof and exterior wall facing West) that impact the external heat balance. As the ideal material must have a high albedo in the short wave-length and a high emissivity in the long wave-length, these two parameters are changed simultaneously. Even though this might not seem realistic, it is chosen to explore a large domain of variation, such as coatings with metallic pigments. As the apartment is fully glazed, we tempt to reduce the glazing percentage with a minimum value of 35 % which corresponds to 1/6 of the surface area according to the RT-2012. The fourth parameter is the length of the overhang on the South façade, to prevent solar gains in addition to the interior blinds already in place. For this study we optimise three different building configurations. For configuration 1, the four parameters are varied with only hygienic ventilation, this configuration serves as reference for the other two. For configuration 2, the four parameters are varied, and in addition the airflow rate of the mechanical ventilation is increased, it is the free-cooling system. For configuration 3, the four parameters are varied, and the space is ventilated through natural ventilation with windows opening in addition to the hygienic ventilation. In Configuration 2, the free-cooling is modelled using the simplified ventilation model with the EnergyPlus RunTime Language (ERL) to control the varying airflow. The maximum airflow is fixed at $0.26 \text{ m}^3/\text{s}$ (3 ACH). If $T_{\text{air_living}} > 20 \text{ }^\circ\text{C} > T_{\text{air_ext}}$ the free-cooling starts operating. The free-cooling runs at maximum airflow at $20 \text{ }^\circ\text{C} + \Delta T$, while the airflow is modulated linearly at each time-step between $20 \text{ }^\circ\text{C}$ and $20 \text{ }^\circ\text{C} + \Delta T$. We aim to optimise the ΔT , it varies between 0.5 and $6 \text{ }^\circ\text{C}$. If $T_{\text{air_living}} > 26 \text{ }^\circ\text{C}$, the free-cooling operates at maximum airflow. In Configuration 3, windows opening is modelled with the *Airflow Network* that has a nodal approach, calculating air flows considering stack pressure and wind-driven air exchanges (Gu, 2007). We decomposed each façade in six large windows, three out of which can be opened. Windows are modelled as detailed openings, through which airflow can be bi-directional. The discharge coefficient for each opening is 0.65 while the wind pressure coefficients are derived by EnergyPlus from correlations for low-rise buildings (Swami and Chandra, 1988). The control for windows opening is the same as for the free-cooling: $T_{\text{air_living}} > 20 \text{ }^\circ\text{C} > T_{\text{air_ext}}$. The model assumes that airflows are unaffected by the presence of shading devices, and that windows are always closed for the calculation of conductive heat transfers and solar gains. It is possible to determine to which percentage each window is opened, it is this number that is varied here. The three openable windows coefficients vary simultaneously.

Optimisation

For this analysis the well-known multi-objective optimisation genetic algorithm NSGA-II is used (Deb, 2002) with the Python package *Deap* (De Rainville et al., 2012). This algorithm is widely used for building design (Nguyen et al., 2014). The goal of the optimisation is to minimize the two objectives:

- Energy needs ($\text{kWh}/(\text{m}^2 \cdot \text{year})$)
- Summer discomfort: DH ($^\circ\text{C} \cdot \text{h}$) when $T_{\text{op_living}} > 25 \text{ }^\circ\text{C}$

The algorithm parameters are subject to debate, as some authors choose a high number of generations with a small number of individuals, or the opposite and there is no general rule. However, a minimal number of runs is necessary to obtain convergence. For instance, (Hamdy 2016) demonstrated that around 1400-1800 evaluations were enough to reach stabilised non-dominated solutions and that a higher number of runs did not improve the convergence. For our study, we conducted the optimization in separate runs from 24, 48 to 96 individuals and from 80, 40 to 20 generations respectively (1920 simulations in all cases) and found that in all cases convergence was reached, as all solutions on the Pareto front were non-dominated. The optimization was faster for 96 individuals and 20 generations, without compromising the Pareto front in comparison with the other evaluations, so we used this setting. We also found that a higher number of individuals or generations did not improve the Pareto Fronts. We selected a crossover coefficient of 0.9 and a mutation coefficient of 0.1 . With these parameters, the simulation time to run the configurations 1 and 2 is about 1.5 hours parallelized on 16 processors while the simulation time to run configuration 3 is about 5 hours due to the Airflow Network modelling that is more time-consuming.

Results

Optimisation results are presented on Figure 4, Figure 5 and Figure 6 for configuration 1, 2 and 3 respectively (see Table 2). The term “albedo” refers to a simultaneous change in albedo and emissivity. On each Figure, the middle graph is the Pareto front for four separate optimisations with the four different typical weather files. The Pareto Fronts during the present periods are in green and the Pareto Fronts during the future period are in red. The top and bottom graphs on each Figure represent the normed input parameters for the solutions of the Pareto Fronts. The top graph is for the climate Carpentras future and the bottom graph is for the climate La Rochelle future. By vertical visualisation, one can understand the input design parameters for each of the Pareto Front optimised solutions. When analysing the Pareto Fronts, we can notice a similar trend between configurations 1, 2 and 3: In the future climate of Carpentras, the optimised solution with minimum heating needs (left part of the Figures) have lower heating needs in the future than in the present. For all configurations, the optimised solution with minimum heating needs reaches $0 \text{ kWh}/(\text{m}^2 \cdot \text{year})$. In La Rochelle, the opposite can be noticed: the optimised future heating needs actually increase. This can be explained by the fact that internal gains were reduced by half and therefore increase the heating needs. This means that the increase in heating needs due to the internal gains is predominant in comparison to the decrease in heating needs due to climate change.

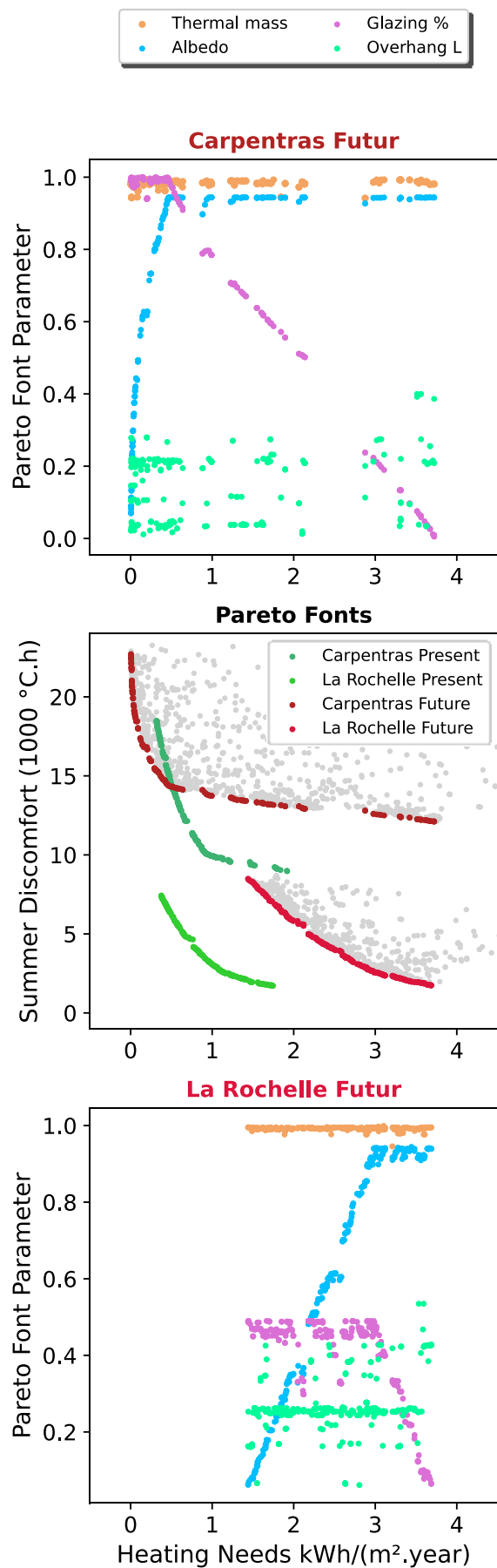


Figure 4 – Results for Configuration 1

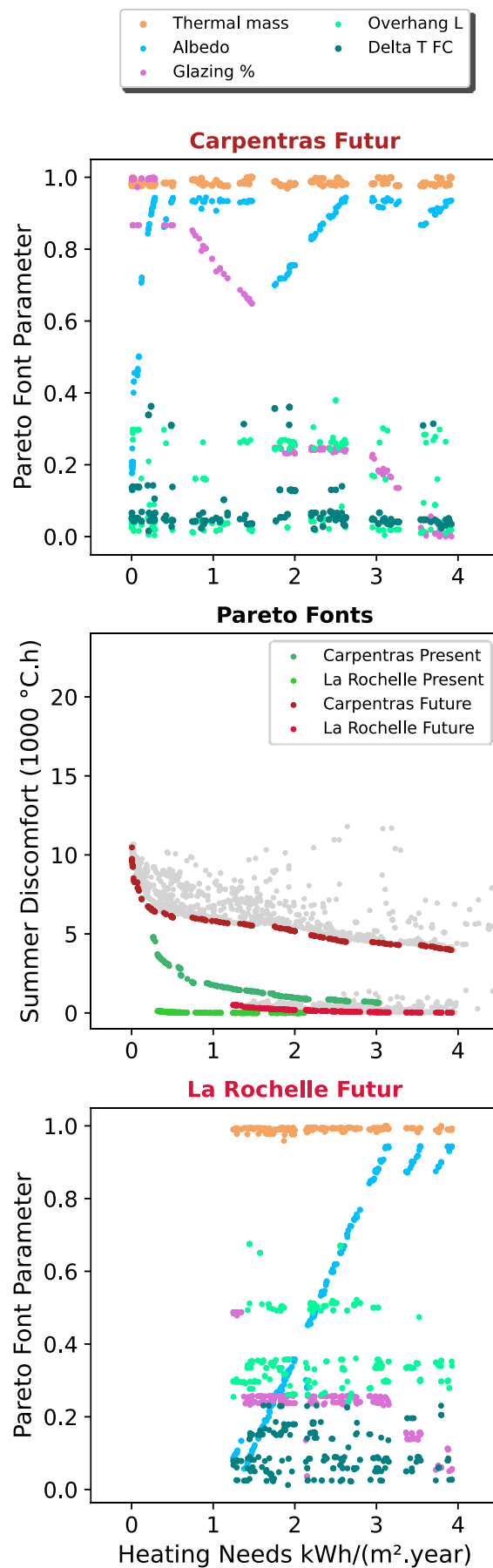


Figure 5 – Results for Configuration 2

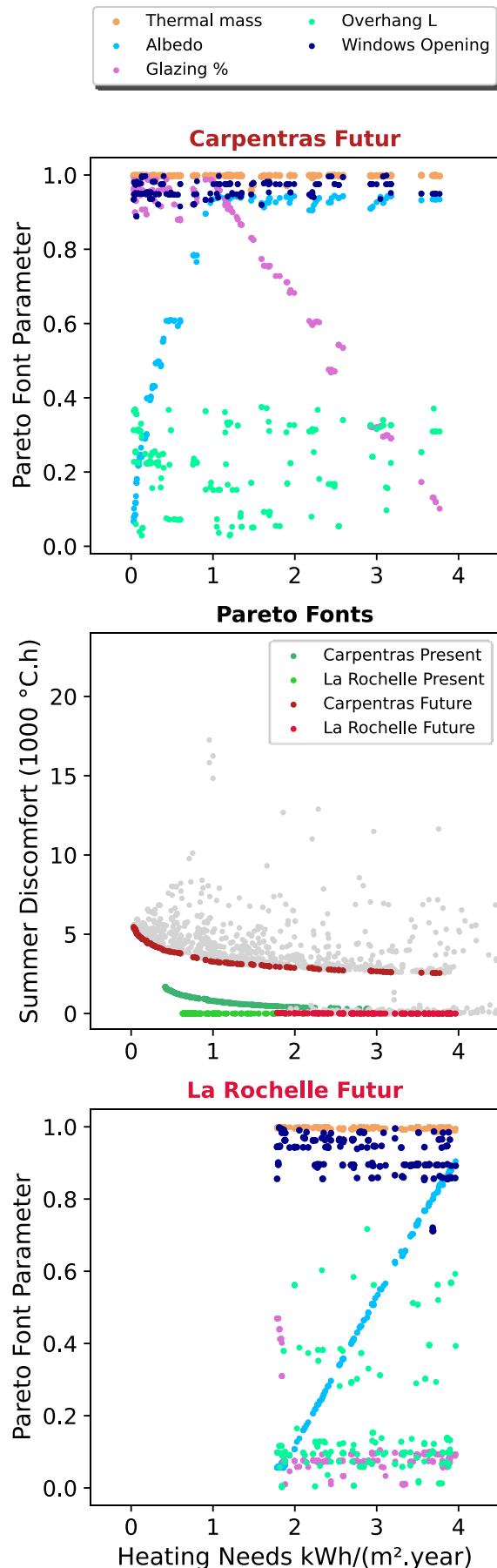


Figure 6 – Results for Configuration 3

In terms of summer discomfort, the discomfort values for the optimised solutions with minimal summer discomfort for each configuration and each climate file are shown on Table 3. In Carpentras the optimised solution with minimal summer discomfort (right part of the graph) showcases very high discomfort both in the future and in the present with only the hygienic ventilation compared to the discomfort for the free-cooling and natural ventilation solutions. However, in the future, the summer discomfort remains high for all the solutions in Carpentras. The higher reduction in configuration 3 can be explained by the fact that airflow rates are higher via natural ventilation by windows opening in comparison to mechanical ventilation with the free-cooling system. In La Rochelle, the optimised solutions for heating needs are under 2 kWh/(m²/year). About summer discomfort, the absolute values are much lower than in Carpentras due to the oceanic climate. For the optimisation with only hygienic ventilation, the optimised solutions to reduce summer discomfort both have values around 1700 °C.h in both present and future climate.

Table 3 - Discomfort value (°C.h) when Top > 25 °C for the optimised solutions to reduce summer thermal discomfort on the Pareto Fonts

	No ventilation	Free cooling	Natural ventilation
La Rochelle-H	1719	0	0
La Rochelle-F	1746	18	0
Carpentras-H	8967	640	288
Carpentras-F	12112	3977	2557

The fact that there is no bigger increase in future climate can be explained because of the internal gains that are reduced in the future, thus the summer discomfort as well. For configurations 2 and 3, the optimised solutions on the Pareto Fonts for summer discomfort reach 0 °C.h or almost 0 °C.h. For a better understanding of these results, we analyse the variation in input parameters for all the solutions on the Pareto Fonts (top and bottom Figures of Figure 4, Figure 5 and Figure 6). For all optimised solutions for Configurations 1,2 and 3 and for both cities, a high thermal inertia is always the optimum. This means that the high thermal inertia benefits both objectives to reduce heating needs while minimizing summer discomfort. No solution with a lower thermal mass is present on any Pareto Font. Regarding the optimisation of albedo value and glazing percentage, they are similar for the three configurations in Carpentras and La Rochelle but differ from one city to the other. In Carpentras, the only possible solution to drastically reduce the number of summer discomfort is a high albedo value. From configuration 1 to 3, as the summer discomfort is reduced, the high albedo value is present in 90 % to 75 % of the Pareto Font solutions. The contrast with the glazing percentage is strongly visible: For solutions with a high albedo, the glazing percentage is linearly reduced as the heating needs increase. The gain in reduction in summer discomfort is much lower when lowering the glazing

percentage is comparison to increasing the albedo. However, an increase in glazing percentage is needed to reduce the heating needs, to balance the high albedo exterior coatings that increase the heating needs during the winter period. The South overhang length is optimised between 0 and 0.4 m, which might indicate that the internal shades on the Southern windows are enough to limit the summer discomfort and that the overhang length is optimised short for the winter period. In La Rochelle, the designs are also similar for the three configurations but the optimised values of albedo and glazing percentage are different. Similarly, as in Carpentras, a high albedo combined to a low glazing percentage is the best combination to minimize summer discomfort, and solutions with a high albedo represent only around 30 %, 25 % and 1 % from configuration 1 to 3 respectively. For this climate it is the albedo parameter that varies linearly as summer discomfort increases and as heating needs are reduced. An intermediate glazing percentage (60 %) is an acceptable solution in configuration 1 for most of the solutions except the ones with the lowest summer discomfort for which the glazing percentage linearly decreases. In configuration 2, as the summer discomfort is much lower due to the use of the free-cooling, it seems that minimizing the heating needs is a priority for the glazing percentage, as it is minimized at lower values in configuration 2 (most simulations with glazing percentage of around 50 %) and even lower in configuration 3 (most simulations with glazing percentage of around 40 %) in comparison with configuration 1. In configurations 2 and 3 only the optimised solutions that prioritize the reduction in heating needs are optimised with a glazing percentage of 60 %. In configuration 2, the ΔT controlling the free-cooling system is optimised as a low value both in Carpentras and in La Rochelle. A low value of ΔT means that the maximum possible airflow is reached faster than with a higher ΔT , and therefore that the air temperature in the living space is further reduced. In Carpentras, the ΔT is optimised between 0.5 °C and 2 °C and in La Rochelle between 0.5 °C and 1 °C, but the difference in between these values is minimal as the number of hours when $20.5\text{ °C} < T_{air,living} < 22\text{ °C}$ (under 20.5 °C there is no ventilation and above 22 °C, solutions for $\Delta T = 0.5\text{ °C}$ and $\Delta T = 2\text{ °C}$ run both at the maximum airflow) and $T_{op,living} > 25\text{ °C}$ (discomfort criterion) is low. For configuration 3, the percentage of opened windows in Carpentras is always close to 100 %, meaning that the natural ventilation potential is fully used. In La Rochelle, for some solutions the percentage is lowered to 85 % indicating that there is no need to open 100 % of the windows to reduce overheating. During the present period in La Rochelle, for some solutions opening 20 % of the windows is enough (not shown on Figure 6).

Discussion and Conclusion

This paper presents the analysis of an optimised case-study building in two French cities in present and future climate. The results propose some optimised design

guidelines for a given building case-study, set of design variables and future climate projections. In both cities, a high thermal mass is optimised for all configurations, allowing to both reduce heating needs and summer overheating. In the city of La Rochelle, optimum solutions were found between low heating needs and reduced summer thermal discomfort for the configurations with mechanical and natural ventilation. While the ventilative cooling solutions do not need to be used at their full potential during present climate, in the future the optimised parameters (percentage of windows opening and ΔT for the free-cooling) are using almost all cooling potential. In La Rochelle a low albedo and emissivity values was necessary to reduce the heating needs while in Carpentras the summer period is predominant and a high albedo and emissivity value are needed to drastically decrease the summer thermal discomfort. In both cities, the optimisation of the albedo value and of the glazing percentage are complementary. In the Mediterranean city Carpentras, a strong summer thermal discomfort is observed for the future weather file, even for the configurations with ventilation, indicating that additional cooling measures might be needed. This analysis opens perspectives for studying alternative building designs with additional passive cooling solutions alternative to air-conditioning such as earth-to-air heat exchangers, adiabatic cooling or radiative cooling. The high summer thermal discomfort in future climate can partially be explained by the fact that the typical weather file contains two heatwaves of higher magnitude than 2003. To analyse further the robustness of these results, other climate scenarios from different climate models must be investigated. Furthermore, a comfort study to assess the level of summer discomfort and heat stress will be complementary to these results since the discomfort hours were counted from a fixed set-point of $T_{op} = 25\text{ °C}$.

Acknowledgements

The authors thank the EURO-CORDEX contributors for providing future climate data, developers of the open-source software EnergyPlus and of the Python DEAP library.

References

- Bador, M., Terray, L., Boé, J., Somot, S., Alias, A., Gibelin, A.L., Dubuisson, B., 2017. Future summer mega-heatwave and record-breaking temperatures in a warmer France climate. *Environ. Res. Lett.* 12. <https://doi.org/10.1088/1748-9326/aa751c>
- Bamdad, K., Cholette, M.E., Omrani, S., Bell, J., 2021. Future energy-optimised buildings — Addressing the impact of climate change on buildings. *Energy Build.* 231, 110610. <https://doi.org/10.1016/j.enbuild.2020.110610>
- Cannon, A.J., 2018. Multivariate quantile mapping bias correction: an N-dimensional probability density function transform for climate model simulations of multiple variables. *Clim. Dyn.* 50, 31–49. <https://doi.org/10.1007/s00382-017-3580-6>

- Cannon, A.J., Sobie, S.R., Murdock, T.Q., 2015. Bias correction of GCM precipitation by quantile mapping: How well do methods preserve changes in quantiles and extremes? *J. Clim.* 28, 6938–6959. <https://doi.org/10.1175/JCLI-D-14-00754.1>
- De Rainville, F.M., Fortin, F.A., Gardner, M.A., Parizeau, M., Gagné, C., 2012. DEAP: A Python framework for Evolutionary Algorithms. *GECCO'12 - Proc. 14th Int. Conf. Genet. Evol. Comput. Companion* 85–92. <https://doi.org/10.1145/2330784.2330799>
- Deb, K., Pratap, A., Agarwal, S., Meyarivan, T., 2002. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Trans. Evol. Comput.* 6, 182–197. <https://doi.org/10.1109/4235.996017>
- Forde, J., Hopfe, C.J., McLeod, R.S., Evins, R., 2020. Temporal optimization for affordable and resilient Passivhaus dwellings in the social housing sector. *Appl. Energy* 261, 114383. <https://doi.org/10.1016/j.apenergy.2019.114383>
- Gu, L., 2007. Airflow network modeling in energyplus, in: Florida Solar Energy Ce (Ed.), 10th International Building Performance Simulation Association Conference and Exhibition. Beijing, China, pp. 964–971.
- Hamdy, M., Nguyen, A.T., Hensen, J.L.M., 2016. A performance comparison of multi-objective optimization algorithms for solving nearly-zero-energy-building design problems. *Energy Build.* 121, 57–71. <https://doi.org/10.1016/j.enbuild.2016.03.035>
- International Energy Agency, 2018. The Future of Cooling Opportunities for energy- efficient air conditioning.
- ISO, 2006. 15927-4: Performance hygrothermique des bâtiments. Calcul et présentation des données climatiques. Partie 4: Données horaires pour l'évaluation du besoin énergétique annuel de chauffage et de refroidissement.
- Kim, H., Clayton, M.J., 2020. A multi-objective optimization approach for climate-adaptive building envelope design using parametric behavior maps. *Build. Environ.* 185, 107292. <https://doi.org/10.1016/j.buildenv.2020.107292>
- Kotlarski, S., Keuler, K., Christensen, O.B., Colette, A., Déqué, M., Gobiet, A., Goergen, K., Jacob, D., Lüthi, D., Van Meijgaard, E., Nikulin, G., Schär, C., Teichmann, C., Vautard, R., Warrach-Sagi, K., Wulfmeyer, V., 2014. Regional climate modeling on European scales: A joint standard evaluation of the EURO-CORDEX RCM ensemble. *Geosci. Model Dev.* 7, 1297–1333. <https://doi.org/10.5194/gmd-7-1297-2014>
- Laaïdi, K., Ung, A., Wagner, V., Beaudéau, P., Pascal, M., 2013. The French Heat and Health Watch Warning System : principles , fundamentals and assessment.
- Lapisa, R., Bozonnet, E., Salagnac, P., Abadie, M.O., 2018. Optimized design of low-rise commercial buildings under various climates – Energy performance and passive cooling strategies. *Build. Environ.* 132, 83–95. <https://doi.org/10.1016/j.buildenv.2018.01.029>
- Machard, A., Inard, C., Alessandrini, J.M., Pelé, C., Ribéron, J., 2020. A Methodology for Assembling FutureWeather Files including Heatwaves for Building Thermal Simulations from the European Coordinated Regional Downscaling Experiment (EURO-CORDEX) Climate Data. *Energies* 13, 1–36. <https://doi.org/10.3390/en13133424>
- Moazami, A., Carlucci, S., Nik, V.M., Geving, S., 2019. Towards climate robust buildings: An innovative method for designing buildings with robust energy performance under climate change. *Energy Build.* 202, 109378. <https://doi.org/10.1016/j.enbuild.2019.109378>
- Nguyen, A.T., Reiter, S., Rigo, P., 2014. A review on simulation-based optimization methods applied to building performance analysis. *Appl. Energy* 113, 1043–1058. <https://doi.org/10.1016/j.apenergy.2013.08.061>
- Nguyen, A.T., Rockwood, D., Doan, M.K., Dung Le, T.K., 2021. Performance assessment of contemporary energy-optimized office buildings under the impact of climate change. *J. Build. Eng.* 35, 102089. <https://doi.org/10.1016/j.jobbe.2020.102089>
- Ouzeau, G., Soubeyroux, J.M., Schneider, M., Vautard, R., Planton, S., 2016. Heat waves analysis over France in present and future climate: Application of a new method on the EURO-CORDEX ensemble. *Clim. Serv.* 4, 1–12. <https://doi.org/10.1016/j.cliser.2016.09.002>
- Robine, J.M., Cheung, S.L.K., Le Roy, S., Van Oyen, H., Griffiths, C., Michel, J.P., Herrmann, F.R., 2008. Death toll exceeded 70,000 in Europe during the summer of 2003. *Comptes Rendus - Biol.* 331, 171–178. <https://doi.org/10.1016/j.crv.2007.12.001>
- RTE, 2017. Bilan prévisionnel de l'équilibre offre-demande d'électricité en France.
- Swami, M.V., Chandra, S., 1988. Correlations for pressure distribution on buildings and calculation of natural-ventilation airflow, in: ASHRAE Transactions. pp. 243–266.