

PAPER • OPEN ACCESS

Electrochromic window integration in adaptive building envelopes in different climates: a genetic optimization of switchable glazing parameters to reduce energy consumptions in office buildings

To cite this article: F Carlucci *et al* 2021 *J. Phys.: Conf. Ser.* **2069** 012131

You may also like

- [Weight determination of glazing properties for Trombe wall application in Johannesburg: An entropy method implementation](#)

C.K. Oluah, E. T. Akinlabi and H. O. Njoku

- [Performance of Electrochromic Glazing: State of the Art Review](#)

Kheira Anissa Tabet Aoul, Daniel Efurosibina Attoye and Lama Al Ghafirif

- [Thermal Transmittance around Edge of Vacuum Glazing](#)

Ivan Chmurny

View the [article online](#) for updates and enhancements.



The Electrochemical Society
Advancing solid state & electrochemical science & technology

241st ECS Meeting

May 29 – June 2, 2022 Vancouver • BC • Canada

Extended abstract submission deadline: **Dec 17, 2021**

Connect. Engage. Champion. Empower. Accelerate.
Move science forward



Submit your abstract



Electrochromic window integration in adaptive building envelopes in different climates: a genetic optimization of switchable glazing parameters to reduce energy consumptions in office buildings

F Carlucci¹, A Cannavale^{2,3} and F Fiorito¹

¹ Department of Civil, Environmental, Land, Building Engineering and Chemistry, Polytechnic University of Bari, 70125 Bari, Italy.

² Department of Sciences in Civil Engineering and Architecture, Polytechnic University of Bari, 70125 Bari, Italy.

³ National Research Council, Institute of Nanotechnology (CNR-NANOTEC), Via Monteroni 73100, Lecce, Italy.

francesco.carlucci@poliba.it

Abstract. During last decades, many efforts have been made to address challenges regarding building energy consumption. A particularly interesting and effective field of development in the building domain is represented by responsive technologies applied to transparent envelopes. Among these technologies, the electrochromic (EC) glazing is one of the most developed solutions thanks to its capability to dynamically modulate daylight and thermal radiation, simply applying a controlled external voltage. The aim of this study is to provide a methodology to analyse smart responsive technologies and optimize the properties of an ideal switchable glazing to find the best configuration for a medium office in different climatic zones. The genetic optimization considers a 5-elements genome, constituted of the following genes: i) solar heat gain coefficient in bleached (SHG_C_B) and ii) coloured state (SHG_C_C), iii) visible light transmittance in bleached (VLT_B) and iv) coloured state (VLT_C) and v) thermal transmittance (U). Moreover, different European cities were selected as representative of different climatic zones and results obtained give a set of ideal EC glazing configurations in the case of EC window controlled by daylighting sensors.

1. Introduction

The huge global energy consumption and the resulting high amount of CO_2 released in the atmosphere are leading to a climate crisis more quickly than expected. In facing this global threat, the building field plays a key role as responsible of nearly 32% of the global energy consumption [1] and of nearly 40% of consumption in highly developed countries [2]. The European Union is aligned with these figures as in 2016 the energy consumption related to the building field accounted for 458 Mtoe corresponding to nearly the 41% of total energy consumption [3]. These figures are increasing the awareness among policymakers of the need of intervention in the building domain and researchers are focusing their attention on these topics trying to develop new technologies and methodologies to support this change.

Among new technologies, particular attention has been recently paid on adaptive technologies. These systems, allow to reversibly adjust their properties in response to external stimuli in order to adapt their



Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](#). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

behaviour to climate fluctuations and meet users' requirements [4]. Different promising fields of development in adaptive technologies such as Phase Change Materials [5], adaptive solar shading [6], multifunctional facades [7] and switchable glazing [8] were identified. Switchable glazing is one of the technologies that is getting major attention thanks to the key role played by transparent envelopes in the energy flow control – both in summer and winter conditions – and thanks to their high retrofitting suitability. Depending on their functioning, these systems can be classified in active or passive switchable glazing [9]. Active systems react to an externally controlled electrical stimulus changing their properties; this category includes, for example, electrochromic (EC) glazing [10], gasochromic glazing [11], Suspended Particle Devices (SPD) [12], and Liquid Crystal devices (LC) [13]. On the contrary, passive systems react autonomously to environmental stimuli – such as temperature or solar radiation – and include for example photochromic (PC) glazing [14], thermochromic (TC) glazing [15], PhotoElectrochromic devices (PECDs) [16], and PhotoVoltaChromic (PVC) glazing [17].

In particular, EC windows – the main focus of this study – can react to external electrical stimulus modifying their optical properties switching between bleached and coloured state thanks to a reversible oxidation or reduction reaction ensured by a multi-layer coating applied to the glass panes. The outer layers of the coating are composed by two external transparent electrical conductors, the following two layers are composed by EC film deposited on each conductor, and finally the middle layer is constituted by a liquid, gel or solid electrolyte [18,19] as shown in figure 1.

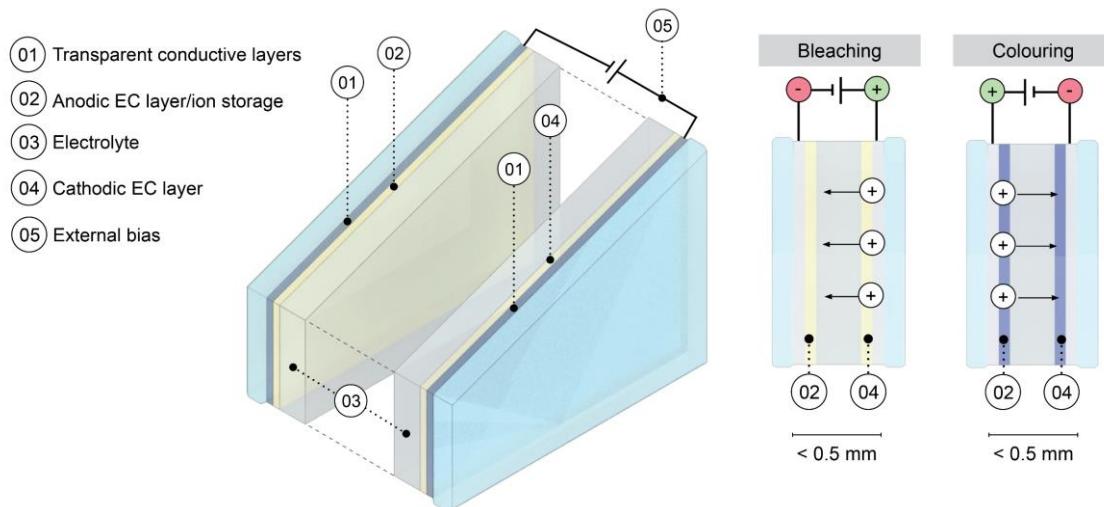


Figure 1. Typical structure and functioning – schematic and not to scale – of an EC device.

The cations – usually H^+ or Li^+ – contained in the electrolyte can be moved from the cathodic EC coating to the anodic EC coating (or alternatively an ion-storage coating) simply applying a low voltage to the transparent electrical conductor. Hence, to balance this charge displacement, electrons are extracted or added to the coating through the electrical conductors causing the transmittance properties change.

Depending on the films applied on the device, different behaviours can be observed in these systems. For example, tungsten oxide films are usually used in the so called Conventional ElectroChromic (CEC) glazing which has been widely studied and many commercial products are already available. CEC glazing acts on both Near Infrared Radiation (NIR) and on Visible Light (VL) showing, on the one hand, a good behaviour in glare and cooling loads control but, on the other hand, this system increases the lighting consumption and changes the façade aesthetic. To improve this behaviour, many studies were conducted and recently NIR-switching ElectroChromic (NEC) and Dual-Band ElectroChromic (DBEC) glazing grabbed researchers' attention. One of the main advantages of NECs is that they can modulate the NIR range, without acting on the Visible Light Transmittance (VLT) [20]. The DBECs can offer one more configuration, switching their behaviour between three different states: i) transparent in both NIR and VL spectrum, ii) dark in the NIR spectrum and transparent in the VL spectrum, and iii) dark in both NIR and VL spectrum [10].

Considering this new flexibility of EC devices, many alternatives can be chosen for this technology and the main aim of this study is to understand, referring to different climates, which could be the ideal thermal and optical properties of an EC window. To that end, a broad analysis was conducted finding, for 6 representative European cities, the best EC parameters to reduce energy consumption in an office building. According to the above explained functioning criterium, the EC windows behaviour was described through five different parameters: i) solar heat gain coefficient in bleached ($SHGC_b$) and ii) coloured state ($SHGC_c$), iii) visible light transmittance in bleached (VLT_b) and iv) coloured state (VLT_c) and v) thermal transmittance (U) as better explained in following paragraphs.

To face the high number of possible combinations of the EC parameters, a Python algorithm was developed to run an elitist genetic optimization. The Genetic Algorithms (GAs) – firstly proposed by J. Holland [21] – are heuristic optimisation techniques inspired by Darwinian evolutionary principles that falls in the wider category of evolutionary algorithms. GAs are widely the most diffuse evolutionary optimization tools; nevertheless, different other algorithms can be found such as genetic programming, evolutionary programming, differential evolution, and cultural algorithm. In the GAs, taking inspiration by natural selection, each possible configuration can be seen as an individual with its own genome, constituted by a certain number of genes. Therefore, the optimization parameters are considered as genes and each genome is a point in the solution space and has a particular fitness which describes its suitability with respect to a certain problem. The GA starts with a randomly generated initial population and – depending on the fitness of each genome – selects, mutates, and recombines genes to produce the first population's offspring. This process is then repeated and, after each optimization loop, the population is iteratively replaced with its offspring increasing the average fitness [22]. Depending on the number of objectives of the optimization, these algorithms can be classified as Single-Objective Evolutionary Algorithms (SOEAs) or Multi-Objective Evolutionary Algorithms (MOEAs). According to specific state-of-the-art surveys regarding the energetic optimization in the building field [23], nearly 50% of the optimization studies conducted were based on single-objective tools and – regarding the optimization focus – nearly 40% are based on HVAC optimization, 46% are based on building envelope, and 14% on solar generation. However, these algorithms are often adopted for many different topics from structural analyses to architectural form-finding studies. Further details of the GA used in this study are described in following paragraphs.

This approach allows to evaluate a high number of parameters combinations, reducing the number of simulations. Therefore – considering that no constraints were used, except of those needed for physical consistency – this study can offer, for the first time, a deep evaluation of EC functioning to find the best ideal EC device for each climatic zone.

2. Methodology

2.1. Energy analysis: software, models, and locations

To understand the EC glazing behaviour in an office building, energy analyses were conducted using EnergyPlus v.9.4 thanks to its capability to guarantee a good multidomain integration and a reliable dynamic simulation of adaptive façades. Moreover, the U.S. Department of Energy developed 16 validated EnergyPlus reference models that can be used as starting point for energy efficiency oriented researches [24]. Among these models, the medium office – whose characteristics are reported in table below – was chosen as starting point to investigate the EC windows benefits.

Table 1. Medium office reference buildings main characteristics.

Building type	Number of floors [-]	Gross floor area [m^2]	Floor-to-floor height [m]	Floor-to-ceiling height [m]	Window-to-Wall Ratio [%]	Number of thermal zones [-]
Medium office	3	4982	3.96	2.74	33%	6 per floor (5 zones + 1 plenum)

To properly adapt this model to European climates, all thermal properties were adjusted as follow to meet different climate requirements starting from the main European energy-containment laws. Therefore, a reference thermal transmittance was considered for each construction type – roofs, walls, slabs, windows – depending on the law requirements and climatic zones. A summary of the thermal properties considered for the analyses are reported in table 2. With regards to glazed surfaces, the static windows adopted for northern façade are characterized by thermal and optical parameters in accordance with table 2 while the eastern, southern, and western windows parameters were automatically changed during the optimization loops as described in following sections. Hence, 6 representative European cities – with highly variable Heating Degree Days (HDD) and different climatic zones – were selected and, for each one, an EnergyPlus model was created updating thermal and optical properties, weather files, and ground temperatures.

Table 2. Thermal and solar parameters considered in each analysed location.

City	Köppen-Geiger classification	HDD _{18°C}	Opaque envelopes U [W/m ² K]			Windows			East South West	
			Ext. wall	Slab	Roof	North				
						U [W/m ² K]	SHGC [-]	VLT [-]		
Larnaca	Bsh	759	0.43	0.44	0.35	2.2	0.35	0.60		
Brindisi	Csa	1151	0.34	0.38	0.33	2.2	0.35	0.60		
Madrid	Csa	1965	0.29	0.29	0.26	1.8	0.35	0.60	To	
Paris	Cfb	2644	0.26	0.26	0.22	1.4	0.35	0.60	optimize	
Copenhagen	Dfb	3563	0.24	0.20	0.24	1.1	0.35	0.60		
Reykjavik	Dfc	4917	0.17	0.10	0.09	0.8	0.35	0.60		

Considering that the analyses were run in different locations, different HVAC types and systems sizing could affect the consumption results. Therefore, the real HVAC systems – related to the U.S. systems – were substituted with ideal loads systems which occupy the same hierarchical place in EnergyPlus and are not connected to a central system but each ideal loads air system supplies heating or cooling in order to satisfy the zone setpoint [25]. Then, ideal loads systems were properly calibrated to guarantee the same behaviour of a real validated HVAC systems.

The implementation of EC windows changes both thermal and lighting behaviour of the model. To correctly study how these systems affect this behaviour, a linearly dimmable artificial lighting system was implemented, controlled by an illuminance sensor – placed in the middle of each thermal zone – with a 500 lux target illuminance to fulfil the technical standards requirements for offices [26]. This daylighting setpoint was also considered as EC activation threshold; this setting allows to reach the target illuminance with natural daylighting when possible, increasing the users' comfort and reducing light consumptions. Finally, the EnergyPlus simulation settings were changed to correctly account the dynamic behaviour of the EC windows, considering 6 timesteps per hour and updating the shadows calculation every timestep.

2.2. Genetic optimization: algorithm and settings

Starting from the above-described models, a Python algorithm – whose structure is shown in figure 2 – was developed to control the simulation engine and run a genetic optimization considering as goal the minimization of the total energy consumption in order to account heating, cooling, and lighting consumptions. The 5-genes genome considered to minimize the objective function is composed by the main parameters of the EC windows: SHGC_B, SHGC_C, VLT_B, VLT_C, and U.

Each parameter can be assigned to a model according to following boundaries: $SHGC_B$ and VLT_B values can be assigned in the range from 0.05 to 0.95 while $SHGC_C$ and VLT_C values are higher than bleached-state corresponding parameters and can vary in the range from 0.10 to 0.99. The choice of using theoretical boundaries rather than literature or commercial values is driven by the aim of understanding the ideal EC glazing for each climate and its behaviour. The use of these wide range can, for example, allow a convergence of bleached and coloured properties that could suggest the unsuitability of EC for that specific climate.

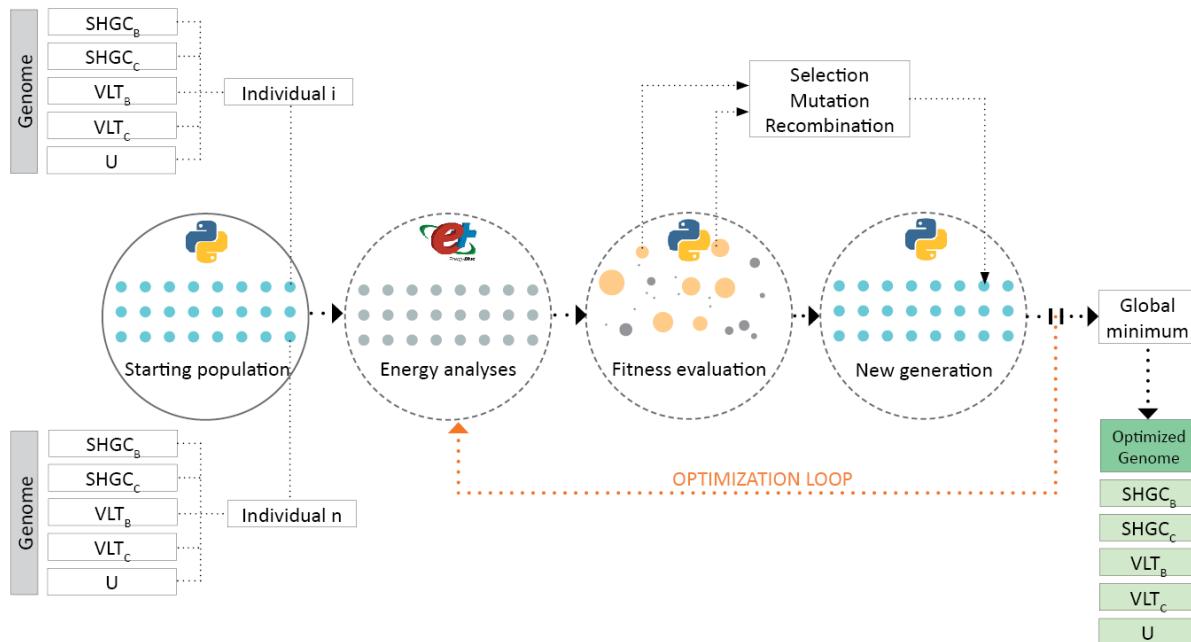


Figure 2. Schematic structure of the optimization and simulation algorithm.

Moreover, to avoid physical inconsistencies and to consider the intrinsic relationship between $SHGC$ and VLT , proper constraints were implemented. Therefore, a maximum distance of 0.35 is allowed between $SHGC_B$ and VLT_B (equation 1.a), and between $SHGC_C$ and VLT_C (equation 1.b); furthermore, another constraint was introduced to guarantee that parameters in bleached state are always greater than the corresponding in coloured state (equations 1.c and 1.d).

$$\begin{cases} |SHGC_B - VLT_B| < 0.35 & (a) \\ |SHGC_C - VLT_C| < 0.35 & (b) \\ SHGC_B > SHGC_C & (c) \\ VLT_B > VLT_C & (d) \end{cases} \quad (1)$$

In order to explore all the fitness landscape and find the global minimum, different preliminary analyses were run on few selected models to choose the right optimization parameters. The adopted settings, reported in table 3, can be considered as the balance between computational demand and fitness landscape requirements.

Table 3. Optimization algorithm settings.

Population size	Number of generations	Mutation probability	Elite ratio	Crossover ratio	Parents portion	Termination criterium
80	12	0.1	0.01	0.5	0.3	4 generations without improvements

3. Results and discussion

Considering the described methodology, each model was run more than 800 times inside the GA to find the ideal EC glazing parameters to reduce energy consumptions. Figure 3 shows the variations of the total energy consumption in each model during the genetic optimization on a sample model. The global minimum obtained for each model is characterized by a specific optimized genome and all the optimized results obtained are summed up in figure 4.

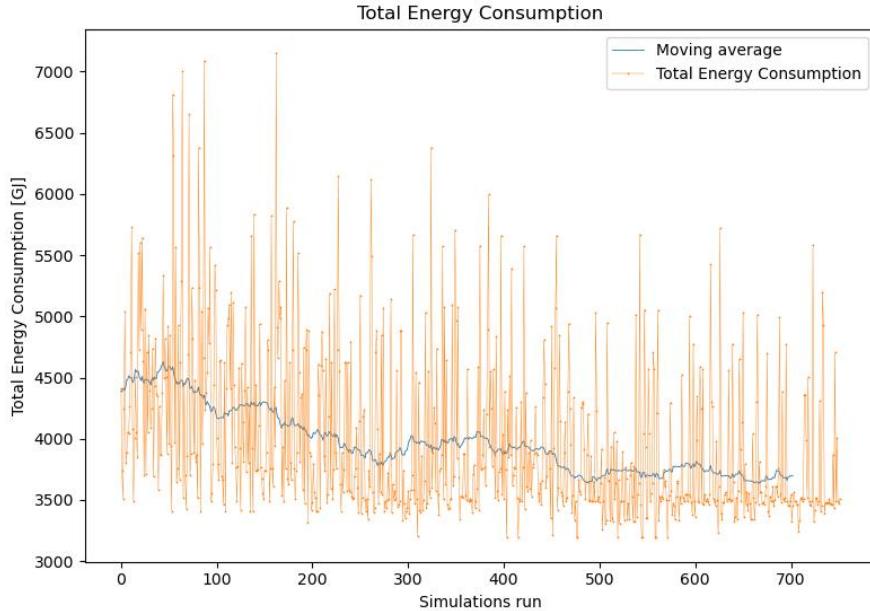


Figure 3. Total energy variation during the genetic optimization in a sample model.

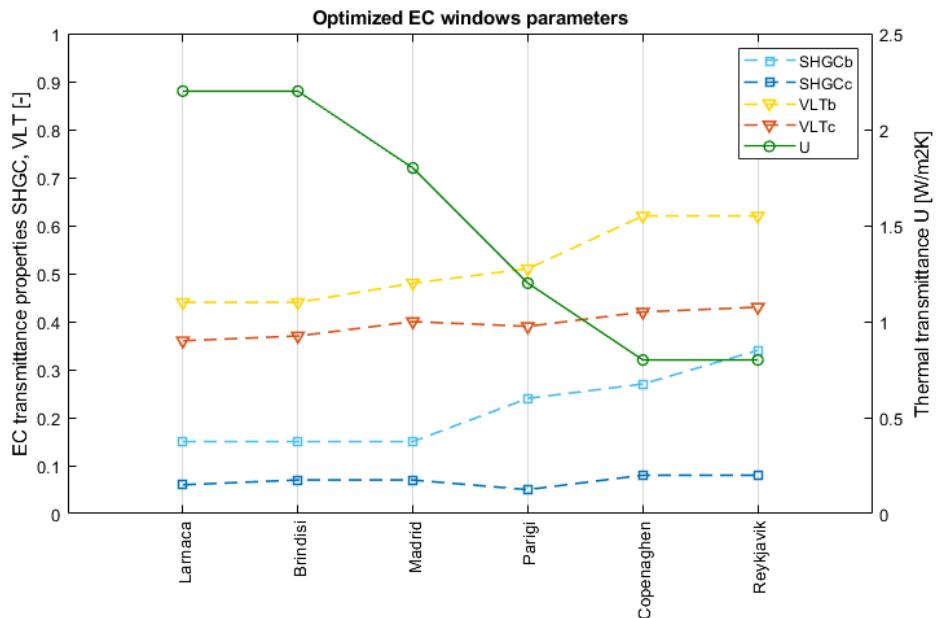


Figure 4. Optimization results.

To properly read the results obtained, it should be considered the strong relationship between the different parameters considered. Particularly, in this case, VLT_C and VLT_B influences both lighting consumptions and EC activation and, subsequently, the solar gains; moreover, VLT_C and VLT_B are related respectively with SHGC_C and SHGC_B through the physical consistency constraint previously described. Finally, in this specific case, U does not directly affect the EC activation but – thanks to its capability to foster or reduce the heat exchange – depends on the EC state as well as, clearly, on the climatic zone.

Firstly, the clearest trend that can be easily deducted from the graph regards the thermal transmittance U that decreases, in the cities considered, from hot to cold climates. In hottest and coldest climates, the U values coincide – $2.2 \text{ W/m}^2\text{K}$ for Larnaca and Brindisi; $0.8 \text{ W/m}^2\text{K}$ for Reykjavik and Copenhagen – due to the minimum and maximum boundaries imposed. Nevertheless, further analyses were conducted to confirm that higher U values in Larnaca and lower U values in Reykjavik would have further reduced the energy consumptions of the models. The difference found between U values can be easily explained considering both the climatic zone and the building type. On the one hand, the high internal gains of the medium office and the major impact of cooling on the total energy consumption have led to a maximization of the thermal transmittance in hotter climates to ease the heat exchange. On the other hand, colder climates are characterized by a minimization of U to satisfy the higher heating demand and reduce the heat losses. Intermediate climates can be seen as the right balance between thermal insulation – with main benefits during heating periods – and the envelope capability to avoid overheating, useful during cooling periods.

Other important trends that can be identified in the results shown, regard the variations of EC transmittance parameters. Optimized genomes show, in every model, very low SHGC_C values, which are close to the lower limit allowed. No significant variations can be found between different cities with values ranging from 0.05 to 0.08 confirming that, with this activation criterium, minimizing the SHGC_C can be considered advisable. On the contrary, a clear difference can be found in bleached state parameters. While in hot and intermediate climates – Larnaca, Brindisi, Madrid – no particular distinctions can be highlighted, SHGC_B values increase in colder climates proportionally to the HDD. However, SHGC_B values are relatively lower compared to commercial EC SHGC in bleached state confirming that relatively low values are suggested even in cold climates.

Similar trends can be identified for the VLT curves; in particular, the values obtained from the GA show that VLT, in both coloured and bleached state, are similar to the sum of the corresponding SHGC optimized values and the maximum distance allowed by constraints. Therefore – considering the above mentioned SHGC values – a maximization of the VLT can be suggested in both EC states.

4. Conclusions

The study conducted can be considered firstly a useful methodological approach to understand the behaviour of EC windows – or, in general, complex adaptive systems – where each parameter of the system (gene) and each combinations of parameters (genome) can affect differently energy consumptions components and users' comfort. In this case, the strong relationship between each parameter makes difficult predicting the best configuration among all the possible alternatives. Another aim of this paper is to give the ideal EC glazing configuration to understand which could be the best solution among the different available products for each climatic zone or which could be the main goals of manufacturers to develop a particularly efficient EC glazing.

From the results described above it can be concluded that despite each location has a specific ideal EC glazing configuration, two main groups of ideal trends can be identified for this specific building type and activation criterium. According to results, in hot-intermediate climates an ideal EC glazing should modulate its transmittance parameters in a very small range; this behaviour could be therefore very similar to a properly designed static glazing. Despite this technology offers undoubtedly an improvement with respect to static glazing – which is one of the possible genomes considered in the GA –, further studies could analyse these differences to evaluate the affordability of this optimized technology in these climates compared with a static window. Instead, different conclusions can be drawn for intermediate-cold climates where the modulation range is significantly higher.

Finally, another development of this study could be the evaluation of different activation criteria. In this case, the users' daylighting comfort was considered as the main goal of the design activities; further studies could consider both consumptions and daylighting in a complex activation algorithms as main goal to understand how optimized genomes changes.

References

- [1] IPCC 2014 *Climate Change 2014: Final report - Chapter 9. Mitigation of Climate Change Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel*

- on Climate Change*
- [2] U.S. Department Of Energy 2015 *Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities*
 - [3] Rousselot Marie and Pollier K 2018 *Energy efficiency trend in buildings*
 - [4] Aelenei D, Aelenei L and Vieira C P 2016 Adaptive Façade: Concept, Applications, Research Questions *Energy Procedia* **91** 269–75
 - [5] Navarro L, de Gracia A, Colclough S, Browne M, McCormack S J, Griffiths P and Cabeza L F 2016 Thermal energy storage in building integrated thermal systems: A review. Part 1. active storage systems *Renew. Energy* **88** 526–47
 - [6] Fiorito F, Sauchelli M, Arroyo D, Pesenti M, Imperadori M, Masera G and Ranzi G 2016 Shape morphing solar shadings: A review *Renew. Sustain. Energy Rev.* **55** 863–84
 - [7] Favoino F, Goia F, Perino M and Serra V 2016 Experimental analysis of the energy performance of an ACTive, REsponsive and Solar (ACTRESS) façade module *Sol. Energy*
 - [8] Cannavale A, Martellotta F, Cossari P, Gigli G and Ayr U 2018 Energy savings due to building integration of innovative solid-state electrochromic devices *Appl. Energy*
 - [9] Casini M 2018 Active dynamic windows for buildings: A review *Renew. Energy* **119** 923–34
 - [10] DeForest N, Shehabi A, Selkowitz S and Milliron D J 2017 A comparative energy analysis of three electrochromic glazing technologies in commercial and residential buildings *Appl. Energy* **192** 95–109
 - [11] Feng W, Zou L, Gao G, Wu G, Shen J and Li W 2016 Gasochromic smart window: Optical and thermal properties, energy simulation and feasibility analysis *Sol. Energy Mater. Sol. Cells*
 - [12] Ghosh A, Norton B and Duffy A 2015 Measured overall heat transfer coefficient of a suspended particle device switchable glazing *Appl. Energy*
 - [13] Hosseinzadeh Khaligh H, Liew K, Han Y, Abukhdeir N M and Goldthorpe I A 2015 Silver nanowire transparent electrodes for liquid crystal-based smart windows *Sol. Energy Mater. Sol. Cells*
 - [14] Nie H, Self J L, Kuenstler A S, Hayward R C and Read de Alaniz J 2019 Multiaddressable Photochromic Architectures: From Molecules to Materials *Adv. Opt. Mater.*
 - [15] Saeli M, Piccirillo C, Parkin I P, Binions R and Ridley I 2010 Energy modelling studies of thermochromic glazing *Energy Build.*
 - [16] Cannavale A, Martellotta F, Fiorito F and Ayr U 2020 The challenge for building integration of highly transparent photovoltaics and photoelectrochromic devices *Energies* **13**
 - [17] Fiorito F, Cannavale A and Santamouris M 2020 Development, testing and evaluation of energy savings potentials of photovoltaicchromic windows in office buildings. A perspective study for Australian climates *Sol. Energy* **205** 358–71
 - [18] Granqvist C G, Bayrak Pehlivan İ and Niklasson G A 2018 Electrochromics on a roll: Web-coating and lamination for smart windows *Surf. Coatings Technol.*
 - [19] Cannavale A 2020 Chromogenic Technologies for Energy Saving *Clean Technol.* **2** 462–75
 - [20] DeForest N, Shehabi A, Garcia G, Greenblatt J, Masanet E, Lee E S, Selkowitz S and Milliron D J 2013 Regional performance targets for transparent near-infrared switching electrochromic window glazings *Build. Environ.* **61** 160–8
 - [21] Holland J H 1975 *Adaptation in natural and artificial systems : an introductory analysis with applications to biology, control, and artificial intelligence*
 - [22] McCall J 2005 Genetic algorithms for modelling and optimisation *J. Comput. Appl. Math.*
 - [23] Li T, Shao G, Zuo W and Huang S 2017 Genetic algorithm for building optimization - State-of-the-art survey *ACM International Conference Proceeding Series* vol Part F128357 (Association for Computing Machinery) pp 205–10
 - [24] Field K, Deru M and Studer D 85AD Using Doe Commercial Reference Buildings for Simulation Studies *SimBuild 2010*
 - [25] US Department of Energy 2010 EnergyPlus Engineering Reference: The Reference to EnergyPlus Calculations *US Dep. Energy*
 - [26] [CEN] C E D N 2002 EN 12464-1 Light and lighting - Lighting of work places - Part 1 : Indoor work *Eur. Stand.*