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Simulation of Responsive Envelopes in Current and Future Climate Scenarios: A New Interactive Computational Platform for Energy Analyses

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Abstract: Despite the strong interest concerning the responsive façades, today there are still few built examples and few tools to assess their benefits due to the complex description of the phenomenon. Energy simulations should consider the interactions between a time-varying environment and an environment-dependent envelope, increasing the intricacy of the problem; moreover, these strong environment–envelope interlinkages increase the importance of the location and climate scenarios considered. The aim of this study is to provide a tool to easily model these phenomena in different geographical and climate contexts. For this purpose, an innovative interactive computational platform (ICP) was developed based on EnergyPlus as a simulation engine, Python as a simulation manager, and Grasshopper as a user interface. Thanks to a single user-friendly environment, the users can simply select the climate scenario, the location, the responsive technology, and its main properties to set and run the dynamic energy simulation. After an overview of the current state of the art, this study provides a description of the structure and workflow adopted for developing this platform and details regarding its functioning and input management. Finally, the platform was tested to run an evolutionary optimization of an electrochromic window control strategy in different climate scenarios.

Keywords: climate change; responsive envelopes; architectural engineering; sustainable design; digital innovation

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1. Introduction

1.1. Responsive Envelopes and Energy Context

One of the main aims of the global community in the XXI century is clearly the reduction in greenhouse gas (GHG) emissions to mitigate the effects of the ongoing climate crisis. The United Nations Sustainable Development Goals [1], the Paris Agreement Commitment [2], and the Glasgow Climate Pact [3] are few of the commitments undertaken by the international community to reach net-zero GHG emissions in the following decades. Nowadays, it is slightly difficult to provide an overview of the energy consumption trends of the last years due to specific events such as the pandemic and the energy crisis; however, the building sector is not keeping up with the 2050 targets for carbon neutrality, and further efforts are required [4]. In particular, the envelope design field is one of the furthest from the set goals, as shown in the latest International Energy Agency (IEA) tracking report [5].

In this field, one of the primary objectives has been, for many years, the maximization of the envelope thermal insulation. According to this design strategy, the indoor-outdoor disconnection was increased to improve the energy conservation in buildings [6]. Although this strategy minimizes the heat losses, it is based on a static approach that does not consider the dynamism of the surrounding environment. Nevertheless, in the last years, recognizing that environmental variables can continuously change throughout the hours, days, seasons, and years has led to a novel dynamic conception of the building envelope. The adoption of dynamic systems allows to change the envelope properties according to

the boundary conditions; thanks to this feature, these devices can react not only to the short- and mid-term environmental variations (hourly, daily, seasonally) but also to the possible long-term (decades) variations related to the climate change [7,8]. It follows that these modern technologies allow to take advantages and maximize the positive impact of both outdoor and indoor environments while minimizing their negative impacts on the energy balance of a building. Nevertheless, the great potential of these technologies can be expressed only by designing with reference to the weather characteristics of each specific region and building use to maximize the benefits of these devices. Hence, to ease the spread of these technologies, it is necessary to develop a strong scientific and methodological foundation for the design of climate adapted envelopes in order to exploit the full potential of these systems and to search for new innovative solutions. Before describing the methodology adopted to develop the computational platform presented in this paper, an overview of the current tools and strategies to model responsive envelopes is required. Therefore, a brief description of the available computational tools and modeling approaches is provided in the next subsection to show the main strategies for modeling the most diffuse responsive devices, highlighting their limitations and advantages.

1.2. Responsive Envelopes and Modeling Tools

Despite the new awareness regarding the continuous environmental variations, currently the spread and the potentials of dynamic façades seem still limited, mainly because of a lack of proper modeling tools [9]. Indeed, compared with static envelopes, responsive systems require a more complex description of the physical phenomenon due to the envelope-changing properties. Adding a new interaction between the time-varying-environment and environment-dependent envelopes significantly increases the modeling and simulation complexity [10]. Moreover, it follows that energy results, settings, climate, and building model are strongly intertwined, increasing the complexity of the topic. Considering this strong dependency, currently there are very few comparable studies on the same responsive technologies [11], slowing the spread of these promising systems; therefore, recent studies are trying to define new methodological approaches to detect, a priori, preferable responsive technologies in the early design stages [12]. Delving into the modeling techniques, nowadays only a few simple responsive devices—such as the venetian blinds—can be easily modelled in the main energy simulation software [13]. On the contrary, complex envelope systems require specialized programming skills and specific computational workarounds, which are slower and less accessible. Previous studies [14,15] described a broad number of available responsive technologies characterized by several different functions; nevertheless, not every responsive system can be modelled in an energy simulation software. Given its widespread and proven robustness [16], EnergyPlus was selected—after investigating the main available energy simulation software [13]—as a reference tool in this review and in the proposed ICP; furthermore, it embeds different default modules for modeling responsive systems, which makes this software the most adopted in this research field.

Different EnergyPlus simulation strategies may be classified—according to the modeling techniques—in the default modules and in the EMS-based modules. The former is the simplest way for modeling responsive technologies but is limited to the EnergyPlus built-in functions, while the latter is based on the energy management system (EMS) programming module and is, thus, more customizable but more complex. Phase change materials (PCMs) [17], thermochromic [18], electrochromic (EC) [19], and a few shading systems—as better explained later—are the main technologies embedded as EnergyPlus built-in modules. Instead, a higher degree of customization can be reached through additional customized algorithms adding the appropriate strings of code in the EMS module. The EnergyPlus simulation variables and parameters, such as, for example, the indoor temperature, may be transformed—through dedicated EMS sensors—into inputs for the customized EMS code. Therefore, starting from these acquired inputs, the users can modify schedules, properties, etc., utilizing the EMS actuators, which can update the EnergyPlus

simulation inputs according to a certain number of operations stated in the EMS code. The EMS-based strategy is clearly more complex but allows to model other devices such as, for example, opaque thermochromic envelopes [20] or photochromic windows [21].

Going one step further by delving into each built-in module, the specific "Material Property: Phase Change" field allows to describe the enthalpy curve of a PCM simply by inputting its enthalpy values and their relative temperatures; hence, modeling the material in this module (rather than in the standard material module) allows to create responsive constructions with PCMs. In this case, the output accuracy can be increased by adopting the "Conduction Finite Difference" heat balance algorithm coupled with values of the simulation timesteps larger than 20 (they can range up to 60) [21].

Considering thermochromic glazing, EnergyPlus allows to model them simply through the dedicated "Window Material: Glazing Group: Thermochromic" module, which allows to couple different glazing properties to specific glazing temperatures. Hence, in each simulation timestep, according to the glazing temperature, the software takes into account the related glazing characteristics [21].

A different approach should be adopted for other chromogenic systems, such as the EC devices. In this case, the bleached and colored states of the EC windows should be modelled as separate static constructions in EnergyPlus, and the transition from bleached to colored is managed through the "Window Shading Control" module. In this module, the user can select "switchable glazing" as a shading control system and can provide the colored state construction as a shaded configuration in the dedicated field "Construction with shading name". Different control strategies can be used with this modeling technique, and, as the EC device is basically treated as a shading system, further details on this topic are reported in the next paragraph regarding the solar shading systems to avoid redundancies.

The solar shading modeling can be conducted using the EnergyPlus built-in functionalities only for certain systems. Firstly, EnergyPlus categorizes these devices as either supplementary window layer (i.e., window material) or as an external impediment to the sunrays defined as attached/detached shading surfaces. The former category can be selected to model blinds, screens, drapes, or pull-down shades, while the latter is usually considered for trees, surrounding buildings, overhangs, fins, etc. [22]. Similarly to the EC devices, the reference module for the dynamic solar shading systems is the "Window Shading Control" module. Nevertheless, the dynamism can be associated only with window additional layers; therefore, it follows that no dynamic external surfaces can be modelled through the default EnergyPlus modules. Moreover, the built-in modules allow to switch between retracted or activated states of the shading systems, while no intermediate states can be easily modelled as described in previous studies [13].

To overcome these limitations, we proposed [13] an innovative algorithm to properly model complex dynamic shading. This workaround is based on the use of the shading coefficients, which represent the ratio of shaded area for each timestep and each modelled surface. These coefficients can be calculated considering the shading system fixed in a specific configuration during the whole simulation. It follows that, for each state of the dynamic shading, the algorithm calculates the shading coefficients and—subsequently—these coefficients are mixed in a new shading coefficient file according to the environmental variables to represent the dynamic behavior of the shading. Hence, this mixed file is uploaded in the model as an external shading file and is considered during the simulation run, rather than calculating the shadows. The primary advancement of this research relies on its capability to accurately account for the transient nature of the thermal and energy events. Indeed, in the traditional modeling techniques, the algorithm simulates each state of the dynamic shading system as a static configuration and then selects and combines the output of these simulations depending on the control strategy selected. Many physical variables, such as, for example, illuminance and glare, change instantaneously and therefore perfectly fit in these traditional techniques; nevertheless, thermal and energy variables require a unique simulation to accurately describe their transient nature. The approach proposed in the above-mentioned study [13] allows to combine inputs (i.e., the

shading coefficients) rather than outputs (consumption, temperatures, etc.), obtaining the energy results as the output of a single run instead of a combination of multiple simulations. Hence, this technique allows thermal variables to follow the continuous shape variations of the shading system in a reliable, gradual way.

Finally, regarding the existing computational platform, the only study [23] that aimed to provide a tool for adaptive systems energy modeling was based on a statistical white-box model. The white-box models can be classified as physical—or numerical—and statistical [24]; the former is based on the use of mathematical equations to describe the physical phenomenon, and the latter is based on linear regression and decision tree models to describe the same phenomenon. While recent existing studies [23] are based on the statistical model, the platform presented in this paper allows the user to directly perform the energy calculations—increasing the reliability and customizability—without any specific programming knowledge required.

1.3. Climate Change and Future Analyses

Another important topic in this study regards the effects of climate change and the analysis of the possible long-term benefits of responsive technologies in this changing environment. In this regard, it is worth highlighting that the weather files adopted in the building energy analysis field are, usually, made up of a series of the most typical climate parameters derived from recorded data. These weather files are defined as typical meteorological year (TMY) [25] and do not represent an actual year of recorded data but are a representation of the typical year for a certain location. Considering that the TMY was first introduced in 1978 and significant changes have occurred in the past years, currently, two updated versions—TMY2 [26] and TMY3 [27]—are available. Nowadays, since the effects of climate change are turning historical weather records into unreliable data, the only use of TMY could be considered less accurate. Researchers are now progressively becoming aware of this issue and are considering the climate change effect on building energy consumption, as demonstrated by the rising number of studies concerning simulation analyses in future scenarios.

Given the strict connection between emissions and climate, working with future energy analyses inevitably requires the definition of different emission scenarios that can affect the future climate. In the last years, the Intergovernmental Panel on Climate Change (IPCC) provided different emission scenarios since its first IS92 report in 1992 [28] through the subsequent Third Assessment Report (TAR) [29] (2001), fourth Assessment Report (AR4) [30] (2007), fifth Assessment Report (AR5) [31] (2014), up to the latest sixth Assessment Report (AR6) [32] released in 2022. The IPCC Assessment Reports propose different scenarios depending on the possible socio-economic developments considered as emissions driving forces [33]. In particular, considering the latest versions, the AR4 refers to four qualitative storylines (A1, A2, B1, B2) for the emissions driving forces (demographic, social, economic, technological, and environmental forces), divided into different scenarios (fossil fuel intensive, non-fossil fuel, and balanced) and in different harmonization levels [34]. The following report (AR5) considers different emission scenarios translated into several representative concentration pathways (RCPs), ranging from the most optimistic scenario (RCP2.6) to the worst scenario (RCP8.5). Finally, the AR6 introduced the shared socio-economic pathways (SSPs), which consider five different socio-economic narratives (from the most sustainable SSP1, to the most fossil-based SSP5) coupled with the expected radiative forcing in 2100. To obtain future weather forecasts, many techniques can be adopted starting from the numerical models validated against past climate observations—called global climate models (GCMs) [35]—forced with the above-mentioned emissions scenarios. As the GCMs are referred to on a large scale (monthly data and grids larger than 100 km^2), the generation of future weather files for building energy simulations requires the spatial and temporal downscaling of the GCMs, which can be done using three different approaches. Firstly, the downscaling can be based on statistical techniques [36] if the weather files are adapted according to empirical relationships deduced from historical local and global climate data.

The main advantage of this technique is the low computational demand required to run the downscaling, to the detriment of a slightly lower precision. The accuracy of the results could be improved by adopting the dynamical downscaling technique, which uses higher-resolution (from 2.5 to 50 km^2) climate models—the regional climate models (RCMs)—to represent the local environment. This technique is based on physical assumptions rather than on statistical assumptions and applies local data and specific equations to process the atmospheric fields of the GCMs to generate local weather data [36]. An intermediate solution between statistical and dynamical is offered by hybrid methods, which try to reduce the computational time of the dynamical approaches using also statistical assumptions. Despite the higher reliability of the dynamical methods, the extremely high computational demand, the limited number of RCMs, and the large resolution scale are slowing their spread. Therefore, statistical techniques are, currently, still the most adopted in the building energy field. Moreover, the large availability of software—both commercial and open source—for statistical downscaling, such as, for example, CCWorldWeatherGenerator v.1.8, WeatherShift, Meteonorm v.8, and Future Weather Generator v.2, is increasing the spread of these downscaling techniques. Furthermore, it is worth noting that, in the building field, the differences between statistically and dynamically downscaled weather files lead to limited differences in terms of environmental parameters and—consequently—to negligible differences in the final energy consumptions [37]. Coupling future weather prediction and building energy analyses is already a well-developed research topic [38,39]; the effects of global warming have already been assessed with reference to thermal mass [40], green walls and roofs [41], natural ventilation, etc. Nevertheless, currently, only a few studies investigate the contribution of responsive systems in changing climates, despite the responsiveness of these devices, which can be extremely helpful to face climate change. Starting from this evidence, the following sections highlight the main literature gaps and provide a possible solution to bridge these gaps through the definition of an easy-to-use computational tool, which is useful to test the effectiveness of responsive envelope in both current and future climates.

1.4. Literature Gaps and Research Questions

The current state of the art provided in the previous sections highlights the lack of proper and easy tools to analyze and compare the energy behavior of responsive envelopes in different climatic scenarios. For this reason, the scientific community is focusing its attention mainly on the technological analyses rather than on the performance analysis of complex dynamic systems. Nevertheless, all these factors hinder the development of responsive façades, which might represent a lost chance to improve the envelope industry with innovations that can adapt themselves rather than just providing an indoor-outdoor disconnection. In view of these limitations, this work aims to give all the necessary tools to assess the energy behavior of responsive devices in a trustworthy, comparable, and future-projected environment. Starting from these premises, the main research questions that this study aims to address can be summed up in the following main points:

- How can we study the energy behavior of responsive technologies in different locations and climates running trustworthy comparisons?
- How can we simplify the simulation workarounds for complex dynamic systems working in a single easy-to-use simulation environment?
- Can we consider the effects of climate change in the responsive façade design workflow?
- Can we provide the users with a fast and user-friendly single tool that can address the above-mentioned research questions?

The analyses of these research questions led to the development of an interactive computational platform (ICP) to assess, easily and reliably, the energy behavior of responsive facades in different climate and geographical contexts. Since the responsive devices are inevitably climate dependent, the developed ICP provides all the required tools to study these systems in 25 different European locations and in different current and future climate scenarios. Another key feature of the ICP is the comparability of the results; indeed,

thanks to the use of the same reference building, different technologies, locations, and climate scenarios can be easily compared on the same reference model to highlight their strengths and drawbacks. According to the above-mentioned reasons, the adoption of specific modules regarding future climates was considered fundamental mainly for two reasons. On the one hand, currently, energy analysis can be regarded as up to date only if they take into account also the climate change effects; on the other hand, the dynamism of responsive façades can play a pivotal role in increasing the climate resilience of buildings thanks to their adaptation to climate change long-term variations.

In order to provide all the tools required to answer these research questions, the following section provides information regarding the adopted models, software, locations, and weather files adopted in the ICP. Afterwards, a dedicated section presents the structure of the platform and describes in detail the user's interface and the modeling techniques adopted. Finally, a simple case study is considered to test the platform and optimize the behavior of an electrochromic window in different climate scenarios.

2. Materials and Methods

In order to define a reliable and easy-to-use ICP, preliminary methodological investigations were conducted on the three main topics involved in this research, which correspond to the three main stages of the platform definition. Firstly, a thorough investigation regarding the energy modeling software and the reference models was conducted to identify the most suitable energy tools to be implemented in the platform. Subsequently, the reference model was updated and calibrated in order to be suitable in all the different locations available on the platform, providing reliable heating, cooling, and lighting consumption. As already mentioned, the strong relationship between responsive behavior and environmental parameters requires testing the responsive technologies in different climates; to that end, 25 European locations were adopted as representative of several climate zones, and the reference model envelope properties were changed according to each location. Internal loads and operational schedules were also updated to account for the latest technologies and building typologies. Finally, the last phase of this methodological approach regards the future projections of the typical weather files in order to account for climate change in the ICP. Each of the above-described topics is addressed in a dedicated subsection: software and reference models are described more in detail in Section 3.1, locations and envelope properties in Section 3.2, and future weather files in Section 3.3. The description of the platform itself—which is the main core of this study—is described in the following chapter, as it is considered mainly the result of this research activity rather than its methodological approach.

2.1. Software and Reference Model

After investigating the main available energy simulation software—EnergyPlus v.9.6, IES-VE v.2023, TRNSYS v.18, IDA ICE v.4.8, and ESP-r v.13.1 [13]—EnergyPlus v.9.6 [42] was selected as the simulation engine of the ICP thanks to its multi-domain analyses (thermal, visual, mass-flow, and building services [43]) and high customizability. Moreover, EnergyPlus includes few built-in simple responsive technologies—as already described in the previous sections—increasing its versatility and integrability. A further key advantage of adopting EnergyPlus is the availability of a set of validated reference building energy models extremely suitable in the energy efficiency research field [44] based on the Commercial Buildings Energy Consumption Survey (CBECS), ASHRAE Standards 90.1 [45], and other scientific sources [46]. In this first version, the medium office model was considered a reference model to test the methodology and workflow; the main characteristics of this model are reported in Figure 1.

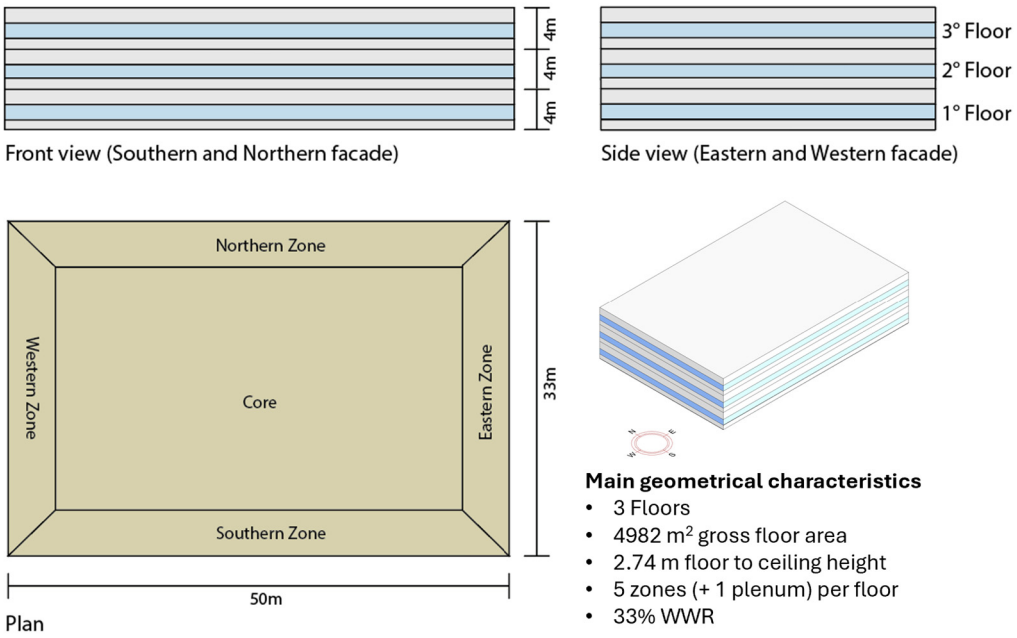

Figure 1. Medium office reference model geometry.

The main goal of the ICP is to provide the users with a simple tool to compare responsive technologies in different locations and climate scenarios. Therefore, specific settings were adopted to obtain reliable, comparable models. Specifically, to avoid the dependency on the HVAC sizing, a properly calibrated ideal loads air system was adopted instead of the default auto-sizing HVAC system. The main advantage of the ideal load systems is that they directly supply heating or cooling energy to satisfy the adopted setpoints without considering the generation and distribution energy; therefore, they do not depend on the sizing of the system [21]. It follows that the ideal load systems directly provide the thermal demand rather than the energy consumption. Hence, to account for the actual energy consumption, the ICP considers a common efficiency value equal to 3—for both the energy efficiency ratio (EER) and the coefficient of performance (COP)—which can be considered a reliable average value for packaged direct expansion air systems. The EER and COP represent, respectively, the ratio of cooling and heating provided by a system, with reference to the total amount of electrical input required to generate it. Therefore, the final energy consumptions are obtained by dividing the ideal loads heating and cooling demands by these COP and EER, respectively.

With reference to the internal loads, all the operating schedules from the original DOE model—updated to September 2012—were validated and revised, when required, in the ICP. While the daily profiles were confirmed, the lighting efficiency, electrical equipment power density, and occupancy rates were updated to avoid overestimation of the internal loads due to outdated reference values. Starting from existing research [47], the effects of the increasing attention on the energy efficiency in office buildings have been quantified, defining new updated trends. In particular, the main findings indicate that both the power absorption of electrical equipment and the lighting power density have been strongly reduced, driven by the spread of LEDs and efficient workstations. The variation in the number of occupants per unit area is another essential input variable of the energy models; indeed, the recent widespread tendency toward open-plan offices over traditional private offices is changing the actual density of occupants in our offices, accommodating more people and reducing the number of empty workstations. In light of these findings, the lighting and equipment power densities have been reduced from 10.76 W/m^2 to 6.5 W/m^2 and 5.52 W/m^2, respectively, and the occupancy rate was changed from 18.58 m^2/person to 13.9 m^2/person, as better described in a dedicated study, currently under publication. To define the most significant variables considered, this study proposes a sensitivity analysis

conducted in the 25 selected locations, and the reference values are deducted from the review of recent office buildings realized in the last five years. Clearly, it is fundamental emphasizing that each energy model has unique inputs that rely on specific non-predictable constraints (such as number of tenants, number of occupants, building geometry, internal distribution, etc.) and that the aim of these changes is simply to adopt more updated and reliable reference figures rather than providing exact values always applicable.

2.2. Locations and Envelope Properties

As already mentioned, 25 locations were selected to properly test the potential of responsive envelopes in different climates and to offer a wide range of weather scenarios. To this end, the locations were accurately selected in order to cover the widest range of variation in the main weather parameters, as summed up in Table 1.

Table 1. Description of the main weather parameters for the locations selected.

City	Köppen–Geiger Class	T_{min} [°C]	T_{max} [°C]	μ_T [°C]	σ_T [-]	HSR_{max} [Wh/m^2]	μ_{HSR} [Wh/m^2]	σ_{HSR} [Wh/m^2]
Larnaca	BSh	1.0	36.5	19.4	6.8	998	401.7	299.7
Seville	Csa	−2.0	43.0	18.4	7.9	992	380.4	294.9
Athens	Csa	2.0	37.2	17.9	7.3	997	358.2	287.0
Brindisi	Csa	−1.0	35.8	17.1	6.5	972	338.0	279.9
Santander	Cfb	1.6	31.2	14.8	4.6	955	265.3	239.0
Rome	Csa	−4.6	40.4	14.3	8.6	997	347.1	282.6
Porto	Csb	0.0	32.0	14.3	4.9	976	340.1	286.6
Madrid	Csa	−4.0	31.8	15.8	6.9	958	312.9	259.5
Plovdiv	Cfa	−9.1	34.9	10.3	6.7	878	197.8	192.0
Milan	Cfa	−6.8	32.1	10.4	7.7	946	256.8	242.0
Paris	Cfb	−5.9	31.3	10.2	6.0	893	220.1	216.1
London	Cfb	−11.0	32.6	11.8	8.9	952	279.5	253.9
Timisoara	Dfa	−6.0	30.0	11.1	6.9	902	231.6	216.1
Brussels	Cfb	−11.0	36.3	12.7	9.5	942	279.5	225.2
Geneva	Dfb	−12.0	33.8	11.1	9.4	937	294.3	253.6
Ankara	BSk	−22.0	33.8	9.6	9.7	1007	317.7	263.6
Ljubljana	Dfc	−9.6	26.8	8.3	6.6	827	210.5	204.1
Copenhagen	Dfb	−21.0	33.4	9.2	8.9	906	232.4	223.6
Prague	Dfb	−16.5	33.3	8.0	8.4	918	243.4	232.8
Munich	Dfb	−15.0	32.0	8.1	8.5	890	209.8	204.4
Bergen	Cfb	−8.0	27.7	7.1	5.6	774	162.1	174.9
Moscow	Dfb	−21.7	28.7	5.2	8.8	772	204.5	199.7
Helsinki	Dfb	−29.2	22.7	−1.1	10.1	669	163.8	160.7
Reykjavik	Dfc	−25.2	30.6	5.5	10.8	826	212.2	200.4
Kiruna	Dfc	−10.1	18.4	4.5	5.1	721	170.1	170.3

The values reported in the table highlight how the ICP can assess the behaviour of responsive technologies in extremely cold weather—e.g., −29.2 °C recorded in Helsinki as minimum temperature—or, vice versa, in hot weather—with a maximum temperature of 43 °C recorded in Seville. A further confirmation is provided by the mean temperatures (μ_T) that range from −1.1 °C in Helsinki to +19.4 °C in Larnaca, including several intermediate values that cover a wide range of European climates. Similarly, also the maximum (HSR_{max}) and mean (μ_{HSR}) horizontal solar radiation affected the choice in order to cover different latitudes and clouding conditions, as demonstrated by the large differences recorded—for example—between Larnaca (μ_{HSR} = 401.7 Wh/m^2) and Bergen (μ_{HSR} = 162.1 Wh/m^2). Finally, another key point in the selection of the locations was the variability of the outdoor air temperature and horizontal solar radiation, represented by their standard deviations (σ_T and σ_{HSR}, respectively). For example, Ankara is characterized by an extremely variable weather (σ_T = 9.7 °C, σ_{SHR} = 263.3 Wh/m^2), while in Santander the fluctuations are lower

in magnitude (σ_T = 4.6 °C, σ_{SHR} = 239 Wh/m^2), while all other locations cover quite well the intermediate cases.

Considering this wide variation in the environmental parameters, the envelope thermal properties must be changed accordingly. These values were deducted starting from a reference [48] that provides the envelope properties depending on the Heating Degree Days (HDD). For all those locations whose weather does not fall within this classification, specific local regulations [49–52] were considered as further references to define standard values. Hence, the 25 selected locations were grouped into 6 clusters—according to their HDDs—and specific properties were assigned to each group as highlighted in Table 2, which reports the envelope thermal characteristics adopted in the ICP as the main reference.

Table 2. Main thermal properties of the building envelope components, adapted from [53].

Locations	Component	U-Value [W/m^{2}K]	SHGC [-]	VLT [-]
Larnaca, Seville	External wall	0.43	n.a. *	n.a.
	Slab	0.44		
	Roof	0.35		
	Window	2.2	0.35	0.6
Athens, Brindisi, Santander	External wall	0.34	n.a.	n.a.
	Slab	0.38		
	Roof	0.33		
	Window	2.2	0.35	0.6
Rome, Porto, Madrid	External wall	0.29	n.a.	n.a.
	Slab	0.29		
	Roof	0.26		
	Window	1.8	0.35	0.6
Plovdiv, Milan, Paris, London, Timisoara, Brussels, Geneva	External wall	0.26	n.a.	n.a.
	Slab	0.26		
	Roof	0.22		
	Window	1.4	0.35	0.6
Ankara, Ljubljana, Copenhagen, Prague, Munich	External wall	0.24	n.a.	n.a.
	Slab	0.20		
	Roof	0.21		
	Window	1.1	0.35	0.6
Bergen, Moscow, Helsinki, Reykjavik, Kiruna	External wall	0.17	n.a.	n.a.
	Slab	0.10		
	Roof	0.09		
	Window	0.8	0.35	0.6

* SHGC and VLT are not applicable (n.a.) for opaque envelope components.

This classification results in thermal transmittance values (U-value) that range from 0.17 W/m^{2}K to 0.43 W/m^{2}K (μ = 0.288 W/m^{2}K, σ = 0.09 W/m^{2}K) for the opaque external walls, from 0.10 to 0.44 W/m^{2}K (μ = 0.278 W/m^{2}K, σ = 0.12 W/m^{2}K) for the slabs, from 0.09 to 0.35 W/m^{2}K (μ = 0.243 W/m^{2}K, σ = 0.09 W/m^{2}K) for the roofs, and from 0.8 to 2.2 W/m^{2}K (μ = 1.58 W/m^{2}K, σ = 0.58 W/m^{2}K) for transparent envelopes. This approach allows to manage a large number of locations, adopting the same reference criterion to assign the envelope properties; however, starting from these suggested default settings, these values can be easily changed in the ICP for a more targeted analysis.

2.3. Future Weather Files

According to the above-described state of the art, the statistical models can be considered sufficiently reliable for building energy analyses on an annual basis. In particular, in the first release of the ICP, the energy simulations in future scenarios are based on weather files statistically downscaled using the tool CCWorldWeatherGenerator. This weather file generator is based on the HadCM3 climate model (adopted in the third and fourth IPCC

reports) and is combined with the A2 emission scenario; thanks to a series of algorithms based on the morphing method, this tool allows to easily update typical climate files into future climate projections. These projections can be referred to the periods 2011–2040 (usually named 2020s), 2041–2070 (2050s), and 2017–2100 (2080s). Despite this tool being not the most up to date, it allows to use open source, simple, and rapid software—hence easily replicable—that is still widely used. It follows that the users can expand the range of the preinstalled locations adding specific new locations by simply using a widespread open-source tool. Currently, a new version of the platform is under development in order to consider the scenarios adopted in the latest Assessment Report (AR6) through the tool Future Weather Generator. Nevertheless, as already mentioned, the differences between more accurate (dynamical downscaling) or more up-to-date tools are extremely limited in terms of annual energy consumption [37,54]; it follows that also the current version of the ICP can provide reliable energy results. Moreover, recently, machine learning methods based on neural networks have shown potential in accelerating weather forecasting [55] and have been increasingly adopted to generate accurate predicted values in both short- and long-term periods. In the light of these continuous evolutions, the platform was designed to allow to locally change the future weather file with a custom one generated with a specific third-party tool, thanks to the flexibility of its structure.

3. Functioning of the Interactive Computational Platform

One of the main results presented in this study is the platform itself, as its primary goal is to be adopted, on the one hand, as a methodological reference to develop new energy simulation tools and, on the other hand, as a simple tool to investigate the behavior of responsive envelopes. Indeed, the structure of the ICP can be reproduced for any purpose—ranging from thermal comfort to daylighting, etc.—when EnergyPlus is required as a simulation engine and a simple 3D modeling and graphical interface is needed to set and run custom simulations. Moreover, the ease in setting and simulating complex responsive envelopes makes this ICP a fundamental tool for beginners who are not comfortable with programming languages or advanced simulation tools. As confirmation, during the testing phase, this platform was adopted as the main simulation tool by several thesis students with no programming knowledge; despite this, simply after a 15–20 min tutorial, the students were able to smoothly model, set, and simulate their responsive envelope case studies. The following subsections aim to describe, respectively, the structure of the ICP—useful as a reference for new computational tools and as an introductory guide for beginners—the modeling technique, and the results of a simulation campaign conducted to test the platform.

3.1. ICP: Structure, Components, and Interface

The structure, components, and interface adopted for the computational platform derive from the primary goals of this study: the development of a user-friendly tool that allows to easily simulate responsive envelope technologies, running trustworthy comparisons between different locations and climate scenarios in a single easy-to-use simulation environment. Moreover, starting from this concept, all the choices defined during the development of the platform aim to maximize the spread of this tool—and consequently of the responsive technologies—in several areas, such as the professional sector, where responsive systems are still rarely considered as viable alternatives despite their potential. To meet these objectives, the ICP is structured in three main modules organized as follows:

- a core module used to model, simulate, and process the results to provide reliable and clear output reporting sheets;
- a user interface module adopted to collect the users' input and display the simulation outputs without using any kind of complex programming or simulation components (embedded in the main module);
- a virtual connection between the above-mentioned core and interface modules.

As already mentioned, the core module adopts EnergyPlus v.9.6 as simulation engine while a dedicated algorithm developed in Python v.3.8.11 reads the inputs and manages the modeling phase, the simulations, and the output processing phase. The adoption of a three-module structure is driven by the need to distinguish the possible users of the ICP. For example, practitioners or beginners can simply work only in the interface module using predefined models, weather files, and settings to investigate the potential of responsive technologies until they develop a broader knowledge in the simulation and programming fields. Hence, the choice to include only EnergyPlus and Python in the inner module allows to limit the access of less experienced users to more complex components to ensure platform reliability. Indeed, the core codes and models cannot be accessed through the platform itself but must be done directly in the programming software or in EnergyPlus. Hence, the adoption of this structure allows to avoid wrong modeling by beginners who are starting to approach these topics; nevertheless, it allows experienced users to access—in dedicated environments—the inner module of the platform to customize the simulation or to develop new components for expanding the ICP potentials.

To this end, the user interface and 3D modeling tools were based on two software, Rhinoceros v.7 and Grasshopper v.1.0 (GH), which are widely used in both the scientific and industrial fields; this interface prevents direct access to models and codes but simply allows to set and manage them according to the user's needs. In particular, the user can easily select, in the GH canvas, the desired location, exposure, climate scenarios, and the main features of the responsive technology (e.g., activation criteria, activation thresholds, thermo-optical properties, etc.) to run an energy simulation. Moreover, the same module deals with the output reporting, which is automatically shown in the GH canvas—as both graphical and numerical outputs—once all the simulations are completed. It follows that an unexperienced user can simply select the desired inputs and read the final outputs directly in the GH canvas without any specific direct energy modeling activity.

The use of two strongly distinguished modules was allowed thanks to the third module, which is basically a virtual connection between the core and the interface module. The connection module fundamentally receives the inputs selected by the user in the GH canvas and sends them to the core module to run the simulation; once all the calculations are completed, the connection module sends the simulation outputs to the user interface to show the final results (Figure 2).

These information exchanges are managed with Hops, which is a GH plugin that allows to send the inputs collected in a GH component to the Python codes by means of a virtual local server. The use of this plugin is needed mainly for two reasons. The first one is a practical issue to keep the main core clearly distinguished by the user interface to avoid access to the main core, as already mentioned. The second reason is mainly a technical issue related to the Python version (v.2.7) adopted in Grasshopper for Rhinoceros v.7; indeed, the simulations conducted require the use of recent Python libraries (which require Python v.3.8), which are not supported in the GH version adopted. The recent launch of Rhinoceros v.8 (distributed in 2024) can partially solve this second issue because it is based on Python v.3.9; currently, an update of the ICP is under evaluation to get the most out of this update, as better described in the final section.

From a practical point of view, the whole platform is embedded in a folder that contains all the scripts, reference models, and weather files. Once all the required software packages are installed, the user simply has to open the interface module in GH to follow the instructions to select the desired inputs and run the simulation. The whole process can be easily managed directly from this GH algorithm without accessing other software; everything is controlled through pop-up menus and sliders, as shown in Figure 3.

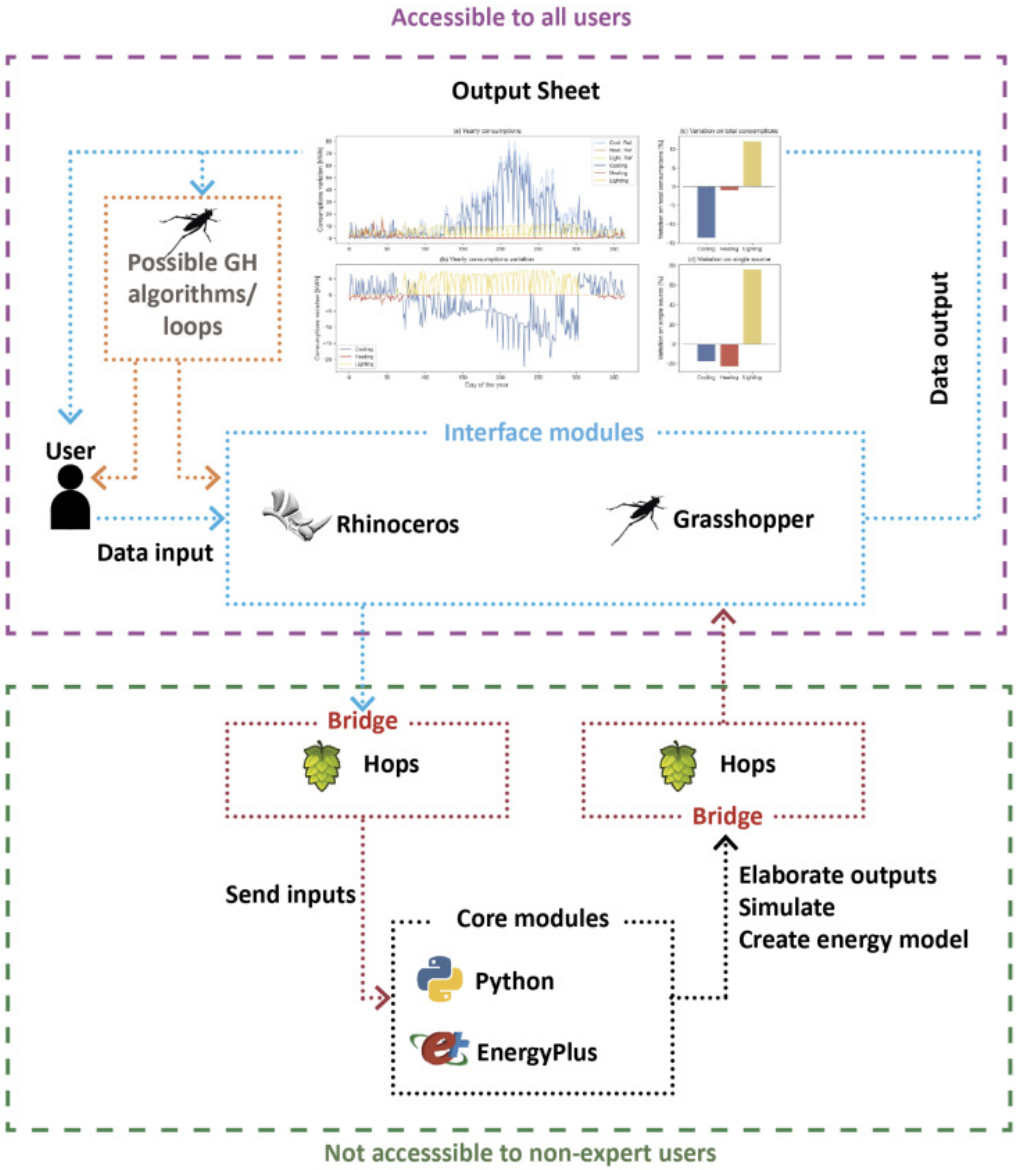

Figure 2. Structure, components, and workflow adopted for the ICP.

Specifically, the user can follow the algorithm structure, from left to right, finding all the instructions needed to manage the process grouped in four macro categories (Figure 3):

1. General inputs: in this area, the user provides the ICP folder path, the location, the climate scenario (TMY, 2050, or 2080), the responsive technology (in the current version: EC windows, PCM walls, and dynamic shading), and the exposure required. The first output of the platform is immediately displayed in this phase, thanks to the location evaluator tool, to help the user in selecting the most appropriate climate. This component shows the chosen location on a map providing longitude, latitude, and two heatmaps that describe the annual trends of dry bulb air temperatures and horizontal solar radiation.
2. Data processing: these components simply process the given inputs and provide the following instructions—in the form of pop-up messages—for sending the information to the core module.
3. Specific inputs: according to the selected technology, the user fills in one of the colored boxes (where specific device data are required) and launches the simulation. For example, for electrochromic windows, thermo-optical properties of glass, activation

criteria, activation thresholds, and operating schedules are required before running the simulation. Further details are provided in the following dedicated subsections.

4. Output: these components automatically import the results calculated in the core modules and show them as float values and charts. In addition to the above-mentioned location evaluator tool, from an energy perspective, the results are shown both as absolute consumptions in kWh (distinguished in lighting, heating, and cooling) and as absolute and percentage differences compared to a traditional static model, as better explained below.

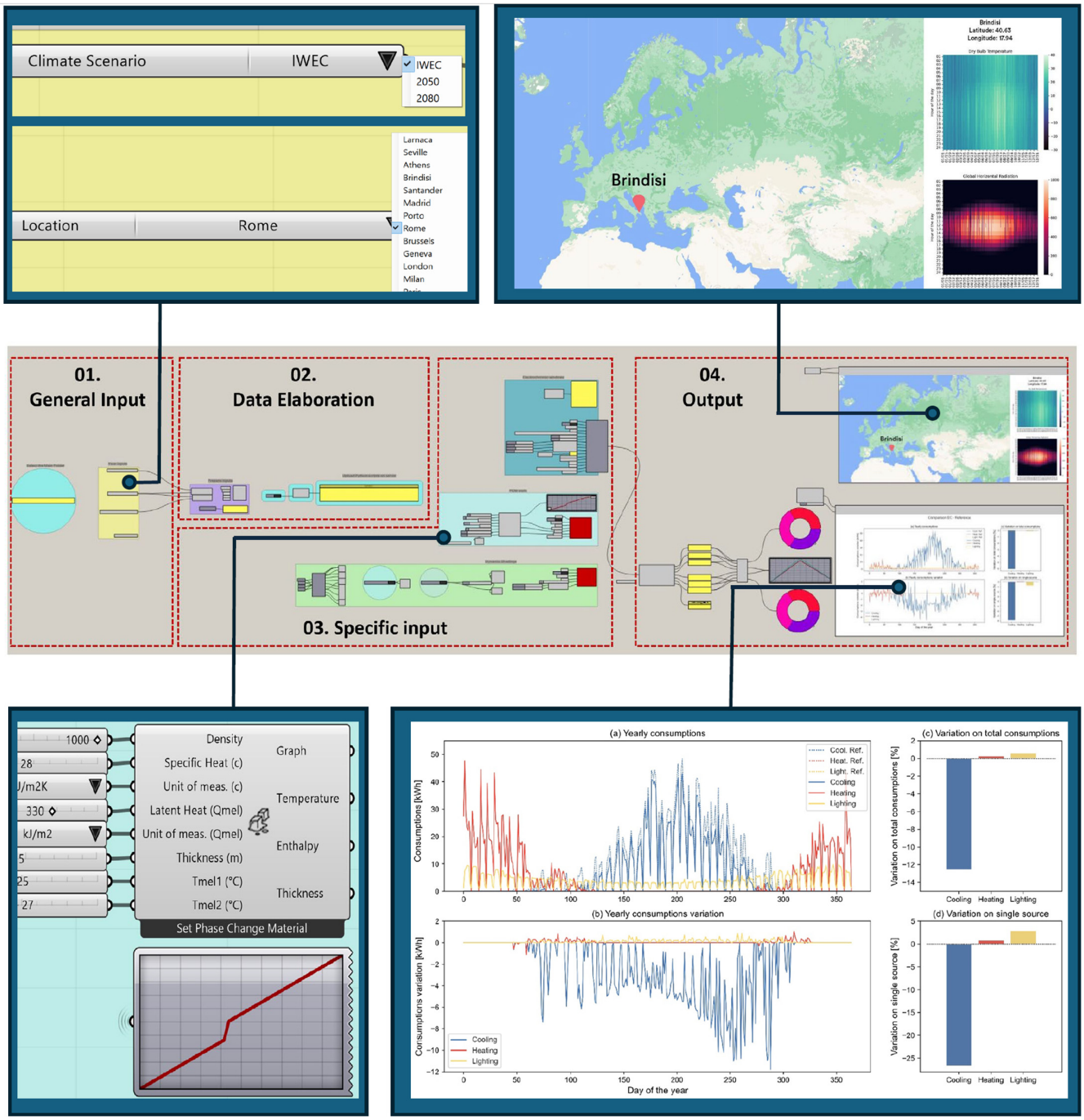

Figure 3. Overview of the user interface module developed in the GH canvas (middle) and zoom of specific components (callout boxes).

Looking in detail at the final output of the platform, the raw EnergyPlus consumption variables are automatically processed in the core module, providing a user-friendly output sheet to evaluate the responsive technology adopted. To this end, the ICP always simulates both the inputted responsive model and an equivalent static model in order to quantify the energy benefits and drawbacks of the selected responsive technology compared with a traditional building envelope. Hence, every simulation is automatically run twice in the core module, and the final results regard the consumption of the responsive model, the consumption of the traditional static model, and their comparison summed up in the final output sheet (Figure 3, lower-right callout box). The output sheet is basically composed of 4 graphs; two of them (line plots) report the hourly/daily/yearly (depending on the selected input) consumption trends, while the other two (bar plots) represent the yearly percentage differences between responsive and static models. Considering the line plots, the first graph reports the absolute consumption of both responsive and static models overlapped; instead, the second one directly plots their differences, considering negative values when the responsive envelope is more energy efficient and positive values when the traditional envelope is more effective. Moving to the yearly bar plots, the energy consumptions obtained from the simulations are processed to highlight the main differences between the responsive and static models, figuring out how the responsive technology behaves. Since all the consumption data provided by the ICP are always reported by end use (lighting, heating, and cooling), total consumption (lighting + heating + cooling), and divided into responsive and static models, the main simulation outputs are rearranged according to the following equations (Equations (1) and (2)) to provide the two bar plots.

$$\text{Total energy variation by use} = \frac{(\text{Energy use})_{\text{Responsive}} - (\text{Energy use})_{\text{Static}}}{(\text{Total energy})_{\text{Static}}} \quad (1)$$

$$\text{Single use variation} = \frac{(\text{Energy use})_{\text{Responsive}} - (\text{Energy use})_{\text{Static}}}{(\text{Energy use})_{\text{Static}}} \quad (2)$$

The first equation—represented in the first bar plot—describes the variation in the total consumption associated with each energy use and can be extremely useful to understand how the responsiveness of the selected technology impacts the overall energy behavior. Nevertheless, great variations in a single energy use could be missed in this graph if the impact of that energy use on the total consumption is very limited (e.g., cooling in extremely cold weather). Therefore, the second bar plot—derived from Equation (2)—completes the description of the energy behavior of the responsive device by showing the variation in each energy use regardless of their impact on the total consumption; this approach can lead to suggesting a specific technology for other climates rather than underestimating its potential. The final information provided in the output section is, clearly, the total yearly energy variation between the two models, which sums up the overall benefits/drawbacks of the selected technology compared with a traditional envelope (Equation (3)).

$$\text{Total energy variation} = \frac{(\text{Total energy})_{\text{Responsive}} - (\text{Total energy})_{\text{Static}}}{(\text{Total energy})_{\text{Static}}} \quad (3)$$

The above-mentioned consumption data are provided in graphical form, as briefly described, to ease the interpretation of the results; however, they are clearly available also as numerical output directly in the GH canvas for further analyses. Having a numerical output in GH allows to embed the ICP in a wider algorithm, which can run, for example, genetic optimization to find the most suitable optical properties of an EC glazing in a specific location and climate scenario, or find the most suitable activation thresholds, etc. However, it is worth highlighting that regardless of the input selected and the output shown directly in the GH canvas, the EnergyPlus standard output report is directly saved in the ICP main folder and can be always accessed and used for any additional purpose.

3.2. ICP: Responsive Technologies Specific Inputs

The aim of this subsection is to describe the functioning of the specific modules developed in the platform; in particular, the first version of the platform allows to model the EC windows, the PCM walls, and complex 3D dynamic shading systems. Further technologies are constantly under development because the ICP structure allows to gradually implement new codes and responsive technologies without compromising its main structure and operations. Basically, the specific input components are custom precompiled GH components where the user can provide all the required inputs simply using sliders and dropdown lists. Each technology is characterized by a specific component or set of components—which are described more precisely in the following subsections—activated only when that specific technology is selected in the general input module.

3.2.1. EC Windows

Looking more closely at the EC technology, the ICP allows to select the main input variables required to properly describe several EC devices. Indeed, the user can provide the solar heat gain coefficient (SHGC) and the visible light transmittance (VLT) referred to both clear and colored states. The thermal transmittance (U) depends on the selected location, and it is set by default according to Table 2; nevertheless, custom EC double/triple glazing units can be considered simply connecting a custom thermal transmittance value in the specific input module. General inputs such as path, climate scenarios, exposure, etc. are automatically loaded in the EC component, while other inputs such as model number, activation criteria, activation thresholds, operation schedules, calculation accuracy, and output reporting frequency can be selected directly by the user, as better described in Table 3 and Figure 4, which show also how to upload the EC component—only for the first simulation—starting from a simple Hops component (the same approach is valid also for other technologies).

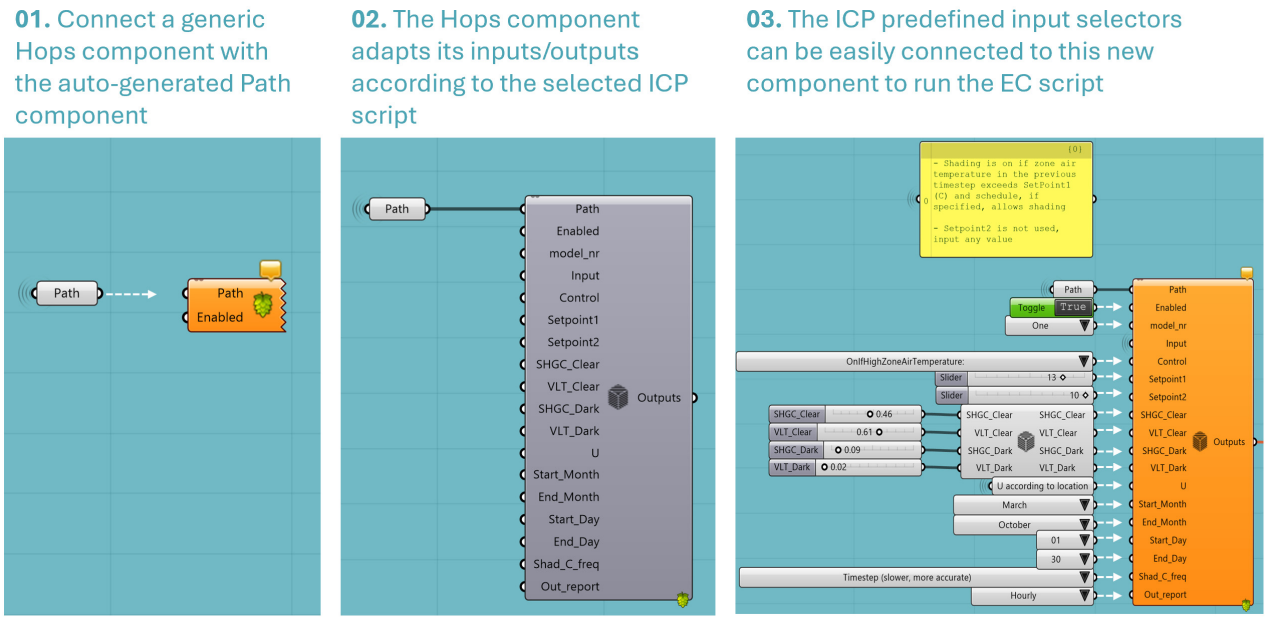

Figure 4. Overview of the EC input component in the GH canvas.

Once all the required information has been provided, the user can run the simulation simply clicking on the Boolean toggle of the EC component; then, these settings are sent to the core module, and, after the simulation time, results will appear directly in the output components of the GH canvas. From a simulation point of view, the Python script simply reports the selected inputs to the EnergyPlus model and creates a switchable glazing shading device using the EnergyPlus embedded modules.

Table 3. Input of the EC component.

Input	Available Options
Model number	• Custom value (allows to number and identify different devices in order to save several results without overwriting them in the output folder)
Activation strategies	• always on • always off • on if schedule allows • on if high solar on window • on if high horizontal solar • on if high outdoor air temperature • on if high zone air temperature • on if high zone cooling • on if high glare • meet daylight illuminance setpoint • on night if low outdoor temperature and off day • on night if low indoor temperature and off day • on night if heating and off day • on night if low outdoor temperature and on day if cooling • on night if heating and on day if cooling • off night and on day if cooling and high solar on window • on night and on day if cooling and high solar on window • on if high outdoor air temperature and high solar on window • on if high outdoor air temperature and high horizontal solar
Setpoint 1	Custom value (once the activation strategy is selected, further details appear in a note box to describe which parameter refers to this setpoint)
Setpoint 2	Custom value (once the activation strategy is selected, further details appear in a note box to describe which parameter refers to this setpoint)
SHGC clear	Custom value $\in$ [0;1] (values should be higher than SHGC dark, automatic check are conducted, and error messages are shown if values are not consistent)
VLT clear	Custom value $\in$ [0;1] (values should be higher than VLT dark, automatic check are conducted, and error messages are shown if values are not consistent)
SHGC dark	Custom value $\in$ [0;1] (values should be lower than SHGC clear, automatic check are conducted, and error messages are shown if values are not consistent)
VLT dark	Custom value $\in$ [0;1] (values should be lower than VLT dark, automatic check are conducted, and error messages are shown if values are not consistent)
U	Default values according to the location selected or custom values
Schedule	Custom values (values must be entered as starting day, starting month, end day, and end month)
Accuracy	• periodic shading calculation (faster, less accurate) • timestep shading calculation (slower, more accurate)
Output reporting frequency	• Hourly • Daily • Monthly

3.2.2. PCM Walls

Considering the PCM walls, the ICP allows to add a PCM board as an inner layer of the envelope because it can stabilize the radiant temperature; however, future versions of the platform will also include different positions of the PCM boards in the multilayered walls. To avoid variations related to the addition of a new layer, the same layer without any phase change properties is also implemented in the static reference model adopted to run the energy comparison described in the previous chapter. Looking more in detail at the ICP canvas, the material properties are pre-processed in a first component and then sent to the simulation component. The first component allows to set the PCM material by providing its density, specific heat, latent heat, thickness, and melting temperatures, while the second one simply allows to select output report frequency and the model number as detailed in Table 4 and Figure 5. Considering that many companies provide different units of measurement for different products, the input components allow for choosing the preferred unit, and the conversions are directly embedded in the Python code to speed up the setting process.

Table 4. Input of the PCM components.

Input	Available Options
Density	• Custom value expressed in [kg/m^3]
Specific Heat (c)	• Custom value expressed in [kJ/m^{2}K] or [kJ/kgK] (depending on the value selected in the following point)
Unit of measurement (c)	• [kJ/m^{2}K] • [kJ/kgK]
Latent heat (Qmel)	• Custom value expressed in [kJ/m^2] or [kJ/kg] (depending on the value selected in the following point)
Unit of measurement (Qmel)	• [kJ/m^2] • [kJ/kg]
Thickness	• Custom value expressed in [m]
Melting temperature	• Custom value expressed in [°C]
Model number	• Custom value (allows to number and identify different devices in order to save several results without overwriting them in the output folder)
Output reporting frequency	• Hourly • Daily • Monthly

Once all the PCM properties are provided, a graph reporting the enthalpy curve of the product designed is shown directly below the setting component (Figure 5). This chart briefly represents the typical enthalpy jump of the PCMs that allows to improve the thermal inertia of the PCM boards. From a simulation point of view, the Python code sends the selected inputs to the EnergyPlus model and changes the heat balance algorithm from the default conduction transfer function (CTF) to the conduction finite difference (ConFD) algorithm, increasing the timesteps from 6 to 20 [56] to improve the simulation reliability. These settings are considered the best trade-off between simulation time and accuracy; indeed, increasing further the number of timesteps would increase

significantly the simulation time, reducing the error by nearly 1% [57], which can be considered acceptable for yearly energy simulation results.

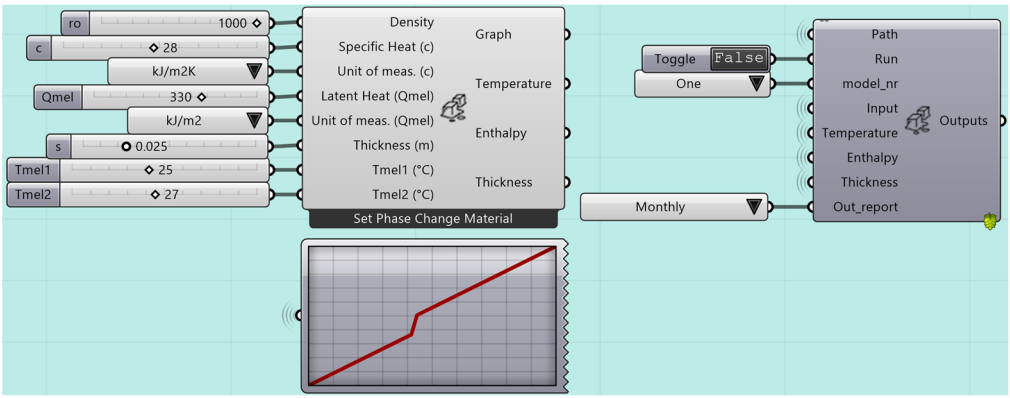

Figure 5. Overview of the PCM input component in the GH canvas.

3.2.3. Dynamic Shading

Finally, the third module included in the first version of the ICP regards the dynamic shading modeling. Despite the fact that the proposed approach can be adopted for any dynamic shading system, it is highly recommended mainly for complex devices, as simple venetian blinds or screens can be easily modelled directly in EnergyPlus. The algorithm behind the dynamic shading module allows to model a three-state shading device and was validated in a previous study [13], whose main features were already mentioned in the state-of-the-art section. With reference to the control technique adopted, the main aim is to maximize the benefits during both the heating and cooling seasons. To this end, the algorithm changes the shading geometry from less shading (ST.0) to more shading states (ST.1, ST.2) based on the combination of the incident façade irradiance (Gf) and outside temperature (To). To optimize the transitions between different states, users can provide two outdoor temperature thresholds (To_{max1} and To_{max2}) and a solar radiation threshold (Gf_{max}). These three thresholds are used to perfectly fit the control strategy to the energy signature of the model according to the designers' needs, as schematically represented in Figure 6, where the relationship between the thresholds, states, and consumptions is clearly reported.

Despite the fact that this activation criterion should be considered more flexible and efficient than others, more traditional control strategies (e.g., based only on one single temperature or radiation cut-off) can be easily adopted in this workflow by simply selecting properly the three above-mentioned thresholds. For example, to consider only temperature-driven devices, the Gf_{max} should be reduced to 0 W/m^2; similarly, to adopt a two-state shading device, two states should be modelled identical from a geometric point of view. Moving to the interface for modeling the dynamic shading, in this case the specific input box is composed of three main components. The first one creates the 3D geometry of the energy model and three layers ("Shading state 01", "Shading state 02", and "Shading state 03") in the Rhinoceros viewport by simply clicking on a dedicated button as shown in Figure 7. Then the user can directly model the shading system in Rhinoceros, being careful to model the geometry of each configuration in the right layer. This approach allows to take advantage of all the useful Rhinoceros modeling tools and plugins—including Grasshopper—enabling the modeling of complex shading devices. Once the modeling phase is completed, the graphical information can be sent to the ICP by simply clicking on the button "Create coordinate files". Once the coordinate files have been created, the user can simply fill in the last GH component, providing the threshold values, and enable the simulation through the Boolean toggle, similarly to what was already explained for the other technologies.

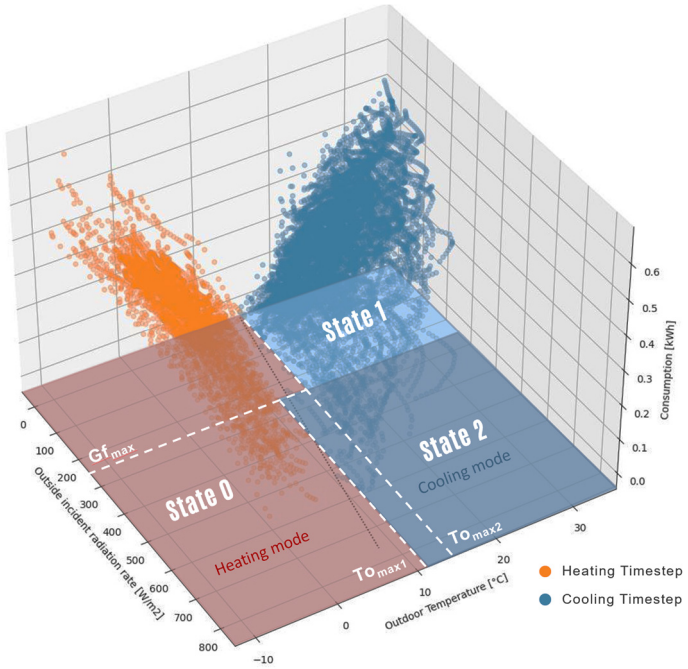

Figure 6. Example of the relationship between building energy signature, activation thresholds, and shading states.

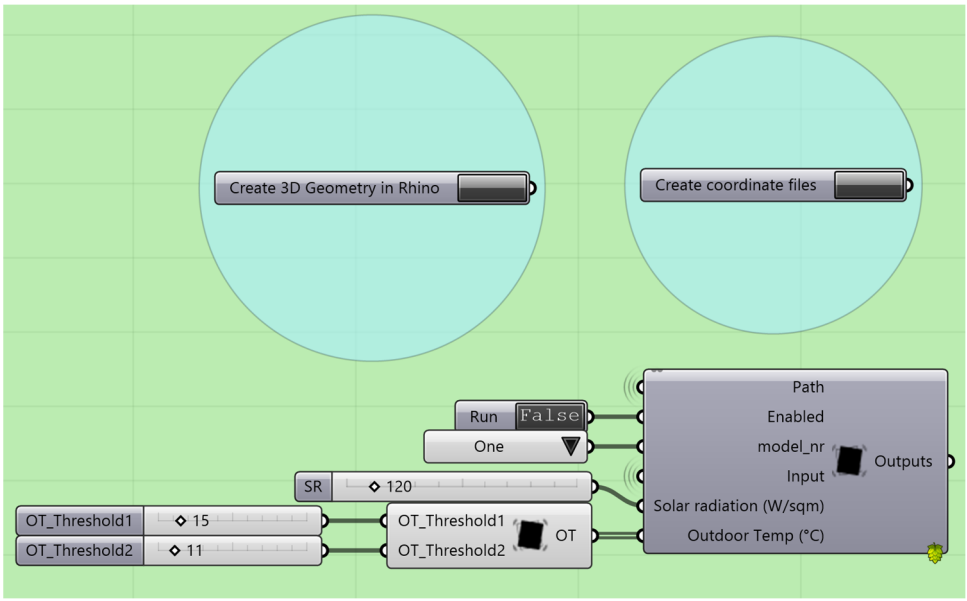

Figure 7. Overview of the dynamic shading input component in the GH canvas.

3.3. ICP: Simulation Results

In order to test the potential of the ICP, this tool was adopted successfully by several users, ranging from thesis students to expert users. This study reports the results of a few of these analyses conducted to find the best EC control strategy in different climate scenarios. In particular, a commercial EC glazing ($SHGC_{clear}$ = 0.46, $SHGC_{dark}$ = 0.09, VLT_{clear} = 0.61, VLT_{dark} = 0.02) was considered a reference to test its potential on a southern exposure in a warm climate (Brindisi, Köppen–Geiger class: Csa) in both typical and future weather scenarios to understand if the control strategy should be updated during its service life due to climate change. The aim of this simulation campaign is mainly to show the potential of the developed tool and its compatibility with other GH tools, rather than to conduct detailed and specific analyses regarding the device and its control. It follows that detailed

forecasting and analyses of the output parameters are currently out of the scope of this first paper, which aims to introduce and explain the ICP's functioning rather than provide specific conclusions regarding the EC's design and performance. On the contrary, the following studies will be focused only on the technology design and optimization using the ICP simply as a tool rather than as the main topic of the study. To this end, the EC module was embedded in a larger GH algorithm to run an evolutionary optimization with Galapagos in order to find the best activation thresholds for the considered location in both the typical weather scenario and the 2080 future projection. In particular, the EC device is activated according to specific incident solar radiation and outdoor temperature thresholds; when both values are exceeded, the device turns from a clear to a dark state. The goal of the optimization is to find the best couple of threshold values—i.e., to minimize the total energy—in both the climate scenarios analyzed. Galapagos is a common default GH component designed to run evolutionary algorithms without requiring specific programming knowledge; therefore, it has been selected for this workflow because it is aligned with the ICP idea as it can be easily run by students or less expert users. The Galapagos component requires a genome and a fitness to run the optimization; the genome represents the variables of the problem, while the minimization or maximization of the fitness is the optimization goal. In this specific optimization, the fitness is represented by the total energy variation recorded comparing the responsive and the static model, while the genome is represented by the two activation thresholds (incident solar radiation and outdoor temperature). As already stated, in this first phase, the goal is testing the algorithms rather than running a detailed study on EC devices; for this reason, the optimization does not consider particularly demanding settings but—according to the scientific literature [58]—it is based on a population size of 30 individuals and a termination criterion based on a maximum number of three generations without improvements. Considering the possible values of the genome, the temperature threshold can range between 0 °C and 30 °C while the solar radiation varies between 0 W/m^2 and 1000 W/m^2 (in steps of 100 W/m^2).

The results of the first optimization (typical weather file) highlight the importance of selecting proper activation thresholds, as the differences in the total energy consumption between the EC model can range between nearly −6% and +15%. Indeed, during the optimization, the GH algorithm tested several combinations of the two activation thresholds according to evolutionary rules, and many of the analyzed combinations led to energy consumption higher than those recorded in the reference static building. Hence, selecting the wrong thresholds can overturn the energy behavior of the building, increasing significantly the consumption of the EC model compared to a traditional static building (+15% recorded in the worst solution simulated). Instead, adopting 12 °C and 200 W/m^2 (optimal solution) as thresholds can reduce the energy consumption of about 6.3%. Clearly, the results obtained depends on several factors (ranging from control strategy, considered glass, reference model adopted, WWR, location, schedule, etc.); nevertheless, the savings obtained can be considered in line with other studies as cooling variation ranges between 19% and 26% when solar gains control is considered [59]. Moreover, as already stated, the main aim of these simulations is to test the overall functioning of the platform and not the functioning of each calculation module (EC, PCM, dynamic shading), which has already been validated by EnergyPlus or in dedicated studies [13].

The advantages of the EC windows are limited mainly due to their extremely low VLT when colored and to a non-optimized functioning schedule. Clearly, this value can be further improved by optimizing the functioning period of the device or adopting more performing EC films; nevertheless, at this stage, the main goal was testing the workflow and not the maximization of the energy performances, which is out of the scope of this paper. Instead, the second optimization was conducted to investigate if and how the effects of climate change influence consumption and optimal threshold values in 2080. The increase in outdoor temperature slightly affects the optimal genome (11 °C and 200 W/m^2), which is very similar to the result of the previous optimization (12 °C and 200 W/m^2); nonetheless,

the overall benefits of the implementation of EC windows rise up to nearly 8.5% with the same boundary conditions.

The ICP output graphs (Figure 8) can help to further explain the energy behavior of the model thanks to the differentiation of the single energy use. In particular, it is clear that—considering the warm climate analyzed—nearly all the energy benefits are driven by the reduction in the cooling consumptions thanks to the improved control of the thermal solar radiation. On the other hand, darkening the EC windows reduces the amount of natural daylight, leading to a larger use of artificial lighting with a subsequent increase in energy consumption. Moreover, since the SHGC in the clear state is higher than the reference value adopted for the static model (0.35), it follows that—when the window is in its clear configuration during the heating period—adopting EC windows can also improve the heating consumption. Nevertheless, in this specific case, the weight of the heating variation is extremely low (current scenario) or negligible (future scenario); for example, in the current scenario, the heating consumptions are reduced by nearly 10% (single use variation, Equation (2)), but these benefits contribute barely (1%) to the total energy benefits (Equation (3)). Similarly, comparing the four graphs, it is possible to explain the larger benefits recorded in the future scenario. In particular, the use of EC devices in the current scenario impacts significantly on the variation in the cooling consumption, but its weight (especially compared to the one of the lighting consumption) is lower than those recorded in the future scenario (due to different outdoor temperatures). It follows that, in the future scenario, the cooling benefits are amplified by a larger share of the total consumption while lighting drawbacks are limited by a lower impact on the overall balance; these different impacts result in an overall further reduction in the total consumption of nearly 2% in the 2080 scenario.

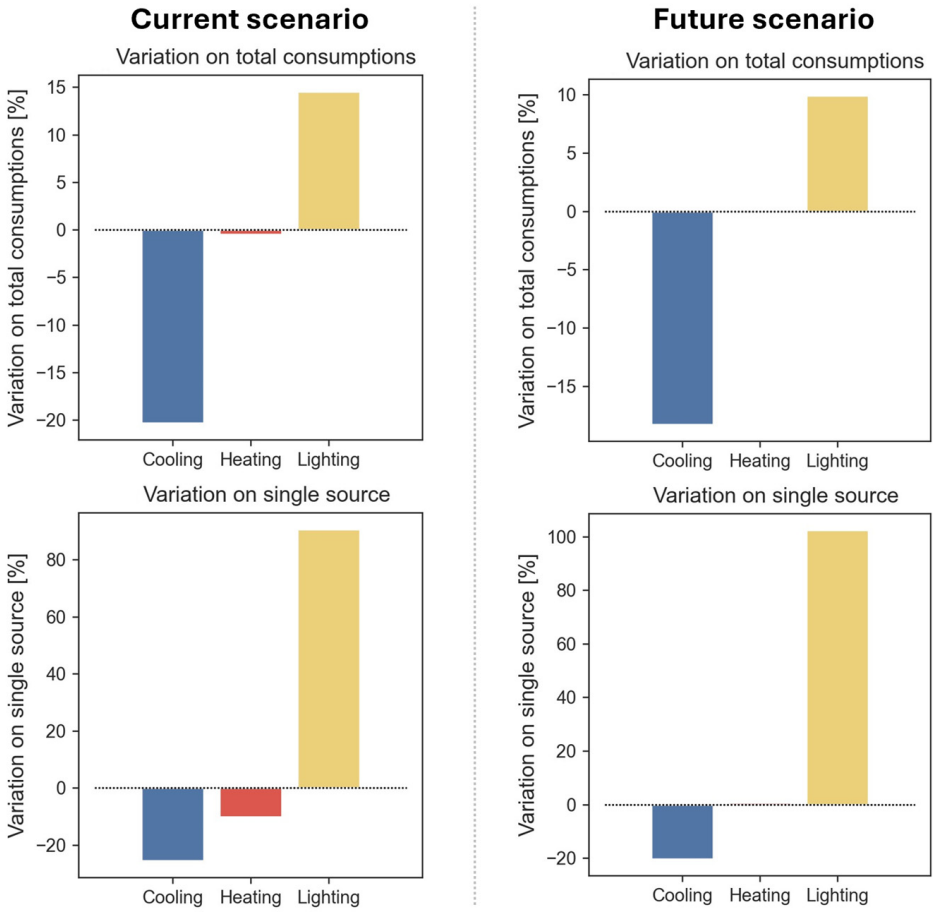

Figure 8. Optimal results obtained for the two optimizations conducted.

4. Discussion

This introductory study—whose main aim is to present the platform—represents the starting point of research that pursues the spread of responsive technologies in the building field. The description provided in the previous sections highlights the main features of the platform, introducing also a brief optimization example where a few of the potentials of the ICP were expressed. The main items arising from these first applications of the ICP can help to define the main strengths and weaknesses of the designed tool—which are briefly reported in these paragraphs—and to define a generalized methodology for conducting comprehensive experimental studies using this platform.

Firstly, the use of the platform as the main simulation tool for thesis students was a fundamental step to confirm the ease of use of the ICP. This feature ensures a wide number of possible users, ranging from students to practitioners and researchers, increasing the potential positive impact of this tool. Currently, the platform has been operated remotely by students located in different cities using the university facilities, with successful results. However, the ICP can be installed on a computer simply by importing a single folder containing all the codes, weather files, and models; instead, the main limitation and challenge is installing all the software, plugins, and libraries—required to run the platform—for non-expert users. Indeed, the Python codes contained in the core modules require a series of Python libraries (Pandas v.1.5.2, Numpy v. 1.24.1, Eppy v.0.5.63, etc. or following versions), which could not be preinstalled on the users' computers and which require few programming skills to be installed. For this reason, currently, this version of the platform is mainly used remotely, and additional efforts are underway to provide a single installer to allow easy installation of the ICP and all its dependencies on personal computers, as better described in the Section 5. At this stage, potential users can access the ICP remotely—installed on a dedicated computer at our institution—by simply contacting the authors to schedule and book remote access to the platform. Hence, after a brief 20 min video tutorial, the users can autonomously start to use the platform, considering the default ICP algorithm or customizing, where needed, the GH algorithm to conduct further specific analyses.

From an operational perspective, the use of the platform can be summed up in three main tasks: selection of the general inputs (location, climate scenarios, technology), transmission of the general input, and selection of specific inputs referred to the chosen technology. The whole process can be managed fast and smoothly, simply using drop-down lists or number sliders, with the only exception being the dynamic shading, which clearly requires the 3D modeling of the shading systems in Rhinoceros before running the analyses. For example, setting an EC energy model requires approximately only 1 min, while the simulation requires less than 30 s to be completed and compared with the traditional static envelope. Thanks to this simplicity and promptness, the simulations can be easily implemented as part of larger algorithms, as demonstrated by the optimizations conducted in the case study.

However, despite the simplicity of the platform, using Python, EnergyPlus, and Grasshopper as main tools for developing the ICP ensures, however, a high degree of flexibility and customization for expert users. Indeed, the reference EnergyPlus model can be easily modified simply by working directly on the idf to change any setting (schedules, WWR, thermal properties, etc.); the output sheet can be customized by changing the Python processing script; new locations and weather files can be easily added to the ICP weather folder, etc. Instead, using completely new custom models requires additional efforts because the Python scripts are based on the reference model structure (number of floors, number of thermal zones, name of the thermal zones, etc.). To overcome this limitation, the new energy model should be modified in order to be similar to the reference one (e.g., same thermal zone name and same exposures) when applicable; otherwise, the Python scripts should be updated in order to read properly the new model.

To sum up, the development and testing phase of the platform allowed us to highlight the main strengths and constraints of the designed platform—reported in Table 5—

considered fundamental to develop new versions more advanced and effective to further improve the spread of these technologies. Further details for improving these limitations are provided in the next section where the future directions of this research are reported.

Table 5. Main advantages and limitations of the ICP.

Advantages	Limitations
• Fast and easy to use, do not require any programming knowledge • Flexible and customizable • Includes several locations and future weather scenarios • Comparable results • Provide ready-to-use output sheets for comparing responsive and static envelopes • Can be easily implemented in larger GH algorithms (e.g., optimizations) • Easily upgradeable by expert users	• Not easy to be installed as it requires different libraries and plugins • Simulating new models requires specific modeling criteria or an update of the Python scripts

5. Conclusions

The spread of scientific investigations in the responsive envelope field in terms of material development is currently not supported by a similar growth in terms of simulation tools and, consequently, in real architectural applications. The main aim of this paper is to provide a new methodological framework to easily conduct energy simulations of responsive envelope technologies to bridge this gap and speed up the spread of these promising technologies. Considering the research questions posed at the beginning of this paper, the investigation conducted highlighted the following key points:

- The energy behavior of responsive technologies in different locations and climates can be predicted by means of a computational platform that couples reliable software (EnergyPlus in this study) with additional validated scripts; moreover, using the same largely shared reference models allows to conduct trustworthy comparisons.
- While several responsive technologies can be easily modelled directly in EnergyPlus, complex simulation workarounds can be easily managed—also by non-expert users—by providing a preset core module, where validated scripts can be run without a direct interaction with the final user, who simply describes the main inputs in a dedicated user interface.
- The undeniable effects of climate change can no longer be neglected in the building energy analyses. In particular, responsive envelopes can play a pivotal role in improving the resilience of buildings towards the changing climate thanks to their adaptability. Therefore, it is fundamental to implement these considerations in our energy analyses, thanks to all those tools that can convert current weather files into long-term forecasts.
- Finally, the developed interactive computational platform allows us to embed all these considerations into a single, fast, and user-friendly tool, based on the joint use of EnergyPlus, Python, and Grasshopper, that aims to improve the spread of these technologies.

Moreover, the platform described in this study can be easily replicated by expert research users for custom applications adopting the same structure, which has been proven to be intuitive and easy to use during the testing phase. Expert users can also develop their own models, weather files, and codes, which can be added to the same platform—using the same structure and interface—to expand its potential. Furthermore, the ICP can be used also by practitioners or less experienced researchers as a black box simulation tool, as already tested by several analyses conducted by thesis students.

The simulations conducted for this study have demonstrated the manageability and flexibility of this tool, as it can be easily implemented as part of more complex algorithms, opening a wide range of possible applications in both research and industry fields. Having

the chance to simulate and develop further analyses—such as running a genetic optimization as demonstrated in the case study—using a common tool such as Grasshopper can significantly increase the spread of these devices, as their main drawback is their modeling complexity and unpredictability. Moreover, the analyses of the optimization outcomes underline the importance of the outputs provided by the ICP, which allow an easy interpretation and comparison of the results and of the behavior of the studied device. Furthermore, having the chance to simulate different locations or climate scenarios on the same platform, simply changing sliders or drop-down lists, allows to conduct detailed studies and comparisons for a thorough understanding of the considered technology.

Clearly, the great potential of the first version of this tool is still limited by a few constraints; these limitations define the future directions of this research and are going to be addressed in the next releases of the ICP. Firstly, the platform is based on different tools (EnergyPlus, Python, Grasshopper) and several libraries and plugins, which require different steps before having all the dependencies ready in order to allow a smooth run of the platform. Hence, currently, for non-expert users, the easiest way to use the platform is to remotely access the ICP by contacting the authors; nevertheless, a single installer, which automatically provides all the required tools, would ease the installation of the platform, improving its spread. In this regard, the latest Rhinoceros release (v.8), distributed in 2024, can improve the user experience considering its default Python v.3.9 components adopted for the scripting editor. Future versions of the ICP could be based on the latest software versions to simplify the installation tasks in order to easily develop a single ready-to-use installer. Moreover, the platform is constantly being tested and developed to increase the number of technologies embedded; therefore, future versions are expected to include further technologies such as photochromic and thermochromic windows. However, in the meantime, several efforts are underway to package and share—on dedicated data articles or on GitHub—the scripts adopted in the main core in order to use them to develop similar platforms.

To sum up, the aim of this paper is to promote the use of a new approach to run energy simulations of responsive envelopes to contribute to a conscious design of these technologies. The main hope is to speed up their spread thanks to an easy computational platform that can be potentially adopted by any user, from beginners to experts.

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References

1. United Nations. *General Assembly Transforming Our World: The 2030 Agenda for Sustainable Development*; United Nations: New York, NY, USA, 2015.
2. United Nations. *The Paris Agreement*; United Nations: New York, NY, USA, 2015.
3. United Nations. *COP26 The Glasgow Climate Pact*; United Nations: New York, NY, USA, 2021.
4. Global CCS. *Global Status Report 2021*; Global CCS: Docklands, Australia, 2021.
5. Tracking Buildings 2021—Analysis—IEA. Available online: https://www.iea.org/energy-system/buildings#tracking (accessed on 20 October 2024).

6. Loonen, R.C.G.M. Approaches for Computational Performance Optimization of Innovative Adaptive Façade Concepts. Ph.D. Thesis, Technische Universiteit Eindhoven, Eindhoven, The Netherlands, 2018.
7. Shen, J.; Copertaro, B.; Sangelantoni, L.; Zhang, X.; Suo, H.; Guan, X. An Early-Stage Analysis of Climate-Adaptive Designs for Multi-Family Buildings under Future Climate Scenario: Case Studies in Rome, Italy and Stockholm, Sweden. *J. Build. Eng.* **2020**, *27*, 100972. [CrossRef]
8. Carlucci, F.; Campagna, L.M.; Fiorito, F. *Responsive Envelopes and Climate Change*; Springer Nature Switzerland: Cham, Switzerland, 2024. [CrossRef]
9. Borkowski, E.; Rovas, D.; Raslan, R. Adaptive Building Envelope Simulation in Current Design Practice: Findings from Interviews with Practitioners about Their Understanding of Methods, Tools and Workarounds and Implications for Future Tool Developments. *Intell. Build. Int.* **2022**, *14*, 172–189. [CrossRef]
10. Taveres-Cachat, E.; Grynning, S.; Thomsen, J.; Selkowitz, S. Responsive Building Envelope Concepts in Zero Emission Neighborhoods and Smart Cities—A Roadmap to Implementation. *Build. Environ.* **2019**, *149*, 446–457. [CrossRef]
11. Sommese, F.; Badarnah, L.; Ausiello, G. A Critical Review of Biomimetic Building Envelopes: Towards a Bio-Adaptive Model from Nature to Architecture. *Renew. Sustain. Energy Rev.* **2022**, *169*, 112850. [CrossRef]
12. Juaristi, M.; Loonen, R.; Isaia, F.; Gómez-Acebo, T.; Monge-Barrio, A. Dynamic Climate Analysis for Early Design Stages: A New Methodological Approach to Detect Preferable Adaptive Opaque Façade Responses. *Sustain. Cities Soc.* **2020**, *60*, 102232. [CrossRef]
13. Carlucci, F.; Loonen, R.C.G.M.; Fiorito, F.; Hensen, J.L.M. A Novel Approach to Account for Shape-Morphing and Kinetic Shading Systems in Building Energy Performance Simulations. *J. Build. Perform. Simul.* **2022**, *16*, 346–365. [CrossRef]
14. Carlucci, F. A Review of Smart and Responsive Building Technologies and Their Classifications. *Future Cities Environ.* **2021**, *7*, 10. [CrossRef]
15. Casini, M. Active Dynamic Windows for Buildings: A Review. *Renew. Energy* **2018**, *119*, 923–934. [CrossRef]
16. Corrado, V.; Fabrizio, E. Steady-State and Dynamic Codes, Critical Review, Advantages and Disadvantages, Accuracy, and Reliability. In *Handbook of Energy Efficiency in Buildings: A Life Cycle Approach*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 263–294. [CrossRef]
17. Feng, F.; Fu, Y.; Yang, Z.; O'Neill, Z. Enhancement of Phase Change Material Hysteresis Model: A Case Study of Modeling Building Envelope in EnergyPlus. *Energy Build.* **2022**, *276*, 112511. [CrossRef]
18. Aburas, M.; Ebendorff-Heidepriem, H.; Lei, L.; Li, M.; Zhao, J.; Williamson, T.; Wu, Y.; Soebarto, V. Smart Windows—Transmittance Tuned Thermochromic Coatings for Dynamic Control of Building Performance. *Energy Build.* **2021**, *235*, 110717. [CrossRef]
19. Chidubem Iluyemi, D.; Nundy, S.; Shaik, S.; Tahir, A.; Ghosh, A. Building Energy Analysis Using EC and PDLC Based Smart Switchable Window in Oman. *Sol. Energy* **2022**, *237*, 301–312. [CrossRef]
20. Butt, A.A.; de Vries, S.B.; Loonen, R.C.G.M.; Hensen, J.L.M.; Stuiver, A.; van den Ham, J.E.J.; Erich, B.S.J.F. Investigating the Energy Saving Potential of Thermochromic Coatings on Building Envelopes. *Appl. Energy* **2021**, *291*, 116788. [CrossRef]
21. US Department of Energy. *EnergyPlus Engineering Reference: The Reference to EnergyPlus Calculations*; US Department of Energy: Washington, DC, USA, 2021. Available online: https://energyplus.net/documenta (accessed on 22 September 2024).
22. US Department of Energy. *Input Output Reference*; EnergyPlus: Doha, Qatar, 2021.
23. Nie, Z.; Chen, S.; Zhang, S.; Wu, H.; Weiss, T.; Zhao, L. Adaptive Façades Strategy: An Architect-Friendly Computational Approach Based on Co-Simulation and White-Box Models for the Early Design Stage. *Energy Build.* **2023**, *296*, 113320. [CrossRef]
24. Adilkhanova, I.; Ngarambe, J.; Yun, G.Y. Recent Advances in Black Box and White-Box Models for Urban Heat Island Prediction: Implications of Fusing the Two Methods. *Renew. Sustain. Energy Rev.* **2022**, *165*, 112520. [CrossRef]
25. Marion, W. *New Typical Meterological Years and Solar Radiation Data Manual*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 1978. [CrossRef]
26. Marion, W.; Urban, K. *User's Manual for Derived from the 1961–1990 National Solar Radiation Data Base*; US Department of Energy: Golden, CO, USA, 1995.
27. Wilcox, S.; Marion, W. *Innovation for Our Energy Future Users Manual for TMY3 Data Sets*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2008.
28. World Metereological Organization. *United Nations Environment Programme Climate Change 1992 The Supplementary Report to the IPCC Scientific Assessment*; World Metereological Organization: Geneva, Switzerland, 1992.
29. IPCC. *Climate Change 2001: Synthesis Report*; A Contribution of Working Groups I, II, and III to the Third Assessment Report of the Integovernmental Panel on Climate Change; IPCC: Geneva, Switzerland, 2001.
30. IPCC. *Climate Change 2007: Synthesis Report*; Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change; IPCC: Geneva, Switzerland, 2007.
31. IPCC. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In *IPCC 2014 Climate Change 2014: Synthesis Report*; IPCC: Geneva, Switzerland, 2014; ISBN 9781139177245.
32. IPCC. *Climate Change 2022: Impacts, Adaptation and Vulnerability*; Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; IPCC: Geneva, Switzerland, 2022.
33. Carlucci, F.; Negendahl, K.; Fiorito, F. Energy Flexibility of Building Systems in Future Scenarios: Optimization of the Control Strategy of a Dynamic Shading System and Definition of a New Energy Flexibility Metric. *Energy Build.* **2023**, *289*, 113056. [CrossRef]
34. World Meteorological Organization. United Nations Environment Programme IPCC Special Report: Emissions Scenarios. In *Summary for Policymakers*; IPCC: Geneva, Switzerland, 2000.

35. Uppala, S.M.; Kallberg, P.W.; Simmons, A.J.; Andrae, U.; Bechtold, V.D.; Fiorino, M.; Gibson, J.K.; Haseler, J.; Hernandez, A.; Kelly, G.A.; et al. The ERA-40 Re-Analysis. *Q. J. R. Meteorol. Soc.* **2005**, *131*, 2961–3012. [CrossRef]
36. Trzaska, S.; Schnarr, E. *A Review of Downscaling Methods for Climate Change Projections 2014*; Tetra Tech ARD: Adelaide, Australia, 2014.
37. P.Tootkaboni, M.; Ballarini, I.; Zinzi, M.; Corrado, V. A Comparative Analysis of Different Future Weather Data for Building Energy Performance Simulation. *Climate* **2021**, *9*, 37. [CrossRef]
38. Gao, B.; Zhu, X.; Ren, J.; Ran, J.; Kim, M.K.; Liu, J. Multi-Objective Optimization of Energy-Saving Measures and Operation Parameters for a Newly Retrofitted Building in Future Climate Conditions: A Case Study of an Office Building in Chengdu. *Energy Rep.* **2023**, *9*, 2269–2285. [CrossRef]
39. Hamdy, M.; Carlucci, S.; Hoes, P.J.; Hensen, J.L.M. The Impact of Climate Change on the Overheating Risk in Dwellings—A Dutch Case Study. *Build. Environ.* **2017**, *122*, 307–323. [CrossRef]
40. Hacker, J.N.; De Saulles, T.P.; Minson, A.J.; Holmes, M.J. Embodied and Operational Carbon Dioxide Emissions from Housing: A Case Study on the Effects of Thermal Mass and Climate Change. *Energy Build.* **2008**, *40*, 375–384. [CrossRef]
41. Andric, I.; Kamal, A.; Al-Ghamdi, S.G. Efficiency of Green Roofs and Green Walls as Climate Change Mitigation Measures in Extremely Hot and Dry Climate: Case Study of Qatar. *Energy Rep.* **2020**, *6*, 2476–2489. [CrossRef]
42. U.S. Department of Energy. *EnergyPlus^{TM} Version 9.6 Documentation: Getting Started*; US Department of Energy: Washington, DC, USA, 2022.
43. Loonen, R.C.G.M.; Favoino, F.; Hensen, J.L.M.; Overend, M. Review of Current Status, Requirements and Opportunities for Building Performance Simulation of Adaptive Facades†. *J Build. Perform. Simul.* **2017**, *10*, 205–223. [CrossRef]
44. Field, K.; Deru, M.; Studer, D. Using Doe Commercial Reference Buildings for Simulation Studies. In Proceedings of the SimBuild 2010 Fourth National Conference of IBPSA-USA, New York, NY, USA, 11–13 August 2010.
45. *ANSI/ASHRAE/IES Standard 90.1-2019*; Energy Standard for Buildings Except Low-Rise Residential Buildings. ANSI/ASHRAE/IES: Atlanta, GA, USA, 2019.
46. Deru, M.; Field, K.; Studer, D.; Benne, K.; Griffith, B.; Torcellini, P.; Liu, B.; Halverson, M.; Winiarski, D.; Rosenberg, M.; et al. *U.S. Department of Energy Commercial Reference Building Models of the National Building Stock*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2011.
47. Kim, H.; Park, K.S.; Kim, H.Y.; Song, Y.H. Study on Variation of Internal Heat Gain in Office Buildings by Chronology. *Energies* **2018**, *11*, 1013. [CrossRef]
48. Ministry of Economic Development Ministerial. *Decree 26/06/2015, Applicazione Delle Metodologie Di Calcolo Delle Prestazioni Energetiche e Definizione Delle Prescrizioni e Dei Requisiti Minimi Degli Edifici*; Ministry of Business and Made in Italy: Rome, Italy, 2015; pp. 1–8.
49. Brekke, T.; Isachsen, O.K.; Strand, M. *EPBD Implementation in Norway*; Concerted Action Energy Performance of Buildings: Copenhagen, Denmark, 2018.
50. Gagarin, V.G. Thermal Performance as the Main Factor of Energy Saving of Buildings in Russia. *Procedia Eng. Procedia Eng.* **2016**, *146*, 112–119. [CrossRef]
51. Danish Knowledge Centre for Energy Savings in Buildings. *Energy Requirements of BR18 A Quick Guide for the Construction Industry on the Danish Building Regulations 2018*; Danish Knowledge Centre for Energy Savings in Buildings: Roskilde, Denmark, 2018.
52. Schettler-Kohler, H.-P.; Ahlke, I. *EPBD Implementation in Germany*; Concerted Action Energy Performance of Buildings: Copenhagen, Denmark, 2018.
53. Carlucci, F. Responsive Envelopes Performance Analysis in Current and Future Climate Scenarios: Development of an Interactive Computational Platform. Ph.D. Thesis, Politecnico di Bari, Bari, Italy, 2023.
54. Yang, Y.; Javanroodi, K.; Nik, V.M. Climate Change and Energy Performance of European Residential Building Stocks—A Comprehensive Impact Assessment Using Climate Big Data from the Coordinated Regional Climate Downscaling Experiment. *Appl. Energy* **2021**, *298*, 117246. [CrossRef]
55. Bi, K.; Xie, L.; Zhang, H.; Chen, X.; Gu, X.; Tian, Q. Accurate Medium-Range Global Weather Forecasting with 3D Neural Networks. *Nature* **2023**, *619*, 533–538. [CrossRef] [PubMed]
56. Tabares-Velasco, P.C.; Christensen, C.; Bianchi, M. Verification and Validation of EnergyPlus Phase Change Material Model for Opaque Wall Assemblies. *Build. Environ.* **2012**, *54*, 186–196. [CrossRef]
57. Zastawna-Rumin, A.; Kisilewicz, T.; Berardi, U. Novel Simulation Algorithm for Modeling the Hysteresis of Phase Change Materials. *Energies* **2020**, *13*, 1200. [CrossRef]
58. Costa-Carrapiço, I.; Raslan, R.; González, J.N. A Systematic Review of Genetic Algorithm-Based Multi-Objective Optimisation for Building Retrofitting Strategies towards Energy Efficiency. *Energy Build.* **2020**, *210*, 109690. [CrossRef]
59. Granqvist, C.G.; Lansåker, P.C.; Mlyuka, N.R.; Niklasson, G.A.; Avendaño, E. Progress in Chromogenics: New Results for Electrochromic and Thermochromic Materials and Devices. *Sol. Energy Mater. Sol. Cells* **2009**, *93*, 2032–2039. [CrossRef]

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