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# Digital workflow for climate resilient building façade generation

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**ABSTRACT**

The contribution presents the results of an applied research aimed at developing an operative methodology and its corresponding data-driven and user-friendly computational workflow for the design of climate-resilient building façade (CRBF) able to adapt to the variation of the environmental conditions through morphology configuration. The research consists of an expansion of an already defined computational workflow proposed to design performance-based architectures and applicable in the early stage of the design process. As far as the façade design is concerned, the contribution foresees to obtain a series of intermediate objectives that contribute to the achievement of optimized design solutions for unitized multifunctional façades which presents different benchmark parameters in relation to the specific design phase and the climate zones in which the façade can be located. The research proposes a case study located in Abu Dhabi (sub-tropical, arid climate) to explore the relationship described above. The research was carried out in two consequential phases, early-stage and mid-stage, involving various benchmarks and different optimization processes that all together describe the complexity of building façade. The design of modular and parametrically façade demonstrates the reliability of the proposed methodology in ensuring benchmarks achieving and optimizing performative aspects, defined according to site's climate analysis.

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Climate-resilient façade; performance-based design; digital form-finding; brute force parametric analysis; genetic optimization

## Introduction

The use of data in performance-based design (PBD) represent one of the big opportunities offered by digital computation for design resilient buildings and façades. Unfortunately, due to methodology and software limitations, the performance evaluation through data analysis is not used as a generative element in the early-stage phase and as result we see the same identical archetypes applied in different climate zones. The computational approach offers the possibility to link a metadesign (Kolarevic, 2018), with quantitative data derived by simulation and allows to better understand of the relationship between geometry as well as materials and performative criteria defined as benchmark, from urban to skin scale. The metadesign describes the genotype of the project, that is its genetic makeup or rather the DNA. This DNA is represented by the parametric model that describes the geometry. The geometry requires careful consideration not only of its parameters, but the resulting parametric hierarchy, with parameters articulated at different levels, with a clear definition of interdependencies (Kolarevic, 2018). To fully exploit the design space, it is important to introduce the concept of phenotype as the set of morphological and functional characteristics of an organism, as they result from the expression of its genotype and from environmental influences. Through the approach proposed above, it is possible to define a different concept of resiliency and adaptation that considers façade design as part of the whole process and fully exploit the design complexity of the post-digital era enabled by digital computation and fabrication.

## Climate-resilient architecture: avoiding hypermechanical buildings through morphologies

The concept of resilience relating to architecture identifies its ability to absorb stresses to which it is exposed and to adapt to external changes in order to reduce the demand for primary resources consumptions and its subsequent environmental impact. It is possible to find a parallelism between the concept of resilient architecture and responsive architecture as in both cases the architectural organism assumes the ability to mediate and react dynamically to external inputs, acting as an interface between two complex systems: the internal space and the external environmental one, influenced by climatic and environmental factors (Turrin, 2014). In modern culture, 'Form follows function' represented the design paradigm

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that wanted to 'adapt an idea of homogeneous and isotropic space to an inhomogeneous and anisotropic energy field' (Bottero et al., 1984). Starting from this paradigm, the morphological considerations underlying the architecture of the past capable of adapting to different climatic conditions through the synergy between material distribution, spatiality and microclimate (Hensel, 2010) are replaced by mechanical principles that tend to standardize the behaviour of buildings compared to the change in comfort conditions. In the historical recourses of architecture, the response to inhomogeneous energy fields occurred through passive devices whose morphology is generated in accordance with the energy flows, following the principle of the 'form follows flow' (Naboni et al., 2015). This design approach has favoured the development of project cultures that, have given rise to architectural styles linked to particular climatic zones. The advent of mechanical devices, in this case, the invention of air conditioning, has accelerated what the industrial revolution had initiated, or a progressive approval of processes and products. The introduction of devices for air conditioning in architecture, shifts the design focus from form to mechanical devices, reducing the complexity of the spatial organization of the constituent elements of architecture. In order for this relationship to be resilient as in the historical examples, it is possible to exploit the potential of some technological innovations such as kinetic devices or based on the use of innovative and programmable materials. If the benefits deriving from their use are a fact, also critical issues such as the high cost and the difficulties of application at different design scale are obvious. In the last few years, information systems for PBD processes have been developed in order to optimize the design process of responsive buildings (Kolarevic & Malkawi, 2005) aimed at fine-tuning innovative operative methodologies based on which the formal generation process is informed by the performances that become design input rather than a mere quantitative parameter used to verify building performances (Figure 1). The visually dynamic responsiveness, obtained through the morphological reconfiguration of the systems, becomes static through the information of the design processes. Within this scenario, digital computation and parametric tools play a fundamental role by virtue of their ability to concentrate in a single data-driven workflow on the morphological generation processes, the simulation of phenomena and the optimization of the performance. The operative methodology foresees the definition of a metadesign (Kolarevic, 2015; Kolarevic, 2018), as defined above, through which to define the limits of the form finding and at the same time to stimulate the creative and explorative process. In light of that, is necessary to start a reflection on the design methodology and the related toolkit to be used in the design of CRBF. Working on the topic of resilience, as the intrinsic capability of places and buildings to restore the equilibrium of the system, allow to transform low performance – high carbon systems into high performance – low carbon systems (Coyle, 2011) that act and interact as natural organisms able to operate as conciliatory agents rather than as compromise agents between two opposing forces of activation and restriction.

## Data-driven strategy

As discussed before, the use of data in the design process represents one of the big opportunities offered by emerging technologies. The possibility to access an almost unlimited quantity of data, the growing ability to refine them to extract information useful for problem-solving processes and the cost-effectiveness of these operations inevitably change the way we design. Their influence in the construction sector has led to the definition of a new design paradigm that involves the use of data as 'fuel' to feed the creative process and increase the quality of the choices made by decision maker (Deutsch, 2015). This strategy can be defined as data-driven design (Proving Ground, 2015) and its application in the architectural practice is favoured by the use of generative and parametric design techniques and in general by the ubiquity of digital computing. In summary, the term data-driven identifies a process through which qualitative and quantitative data are used as driving parameters in order to make informed design decisions. Solving physical environmental problems in an integrated way increases the total quality and supports the design process. The Reference to *MacLeamy's* curve is evident as appropriate: the information of the design process in its early stage allows to maximize the impact of design choices in terms of performance and to decrease the costs related to their application. The application of the strategy described above at the early stage of the design of PB architectures has led to the development of numerous researches (Raji et al., 2017) mainly focused on the exploration of the relationship between form and energy or structural performances. Thanks to the data-driven strategy, the customization of the form can be linked to a responsive and adaptive interpretation with respect to local characteristics and regional variations (Yuan, 2015). Data-driven design totally relay on softwares and tools that allows to design in an integrated way, coupling geometry exploration with performance exploitation (Naboni & Havinga, 2019). In the following sections, an overview of tools available is made according to the aims of the research.

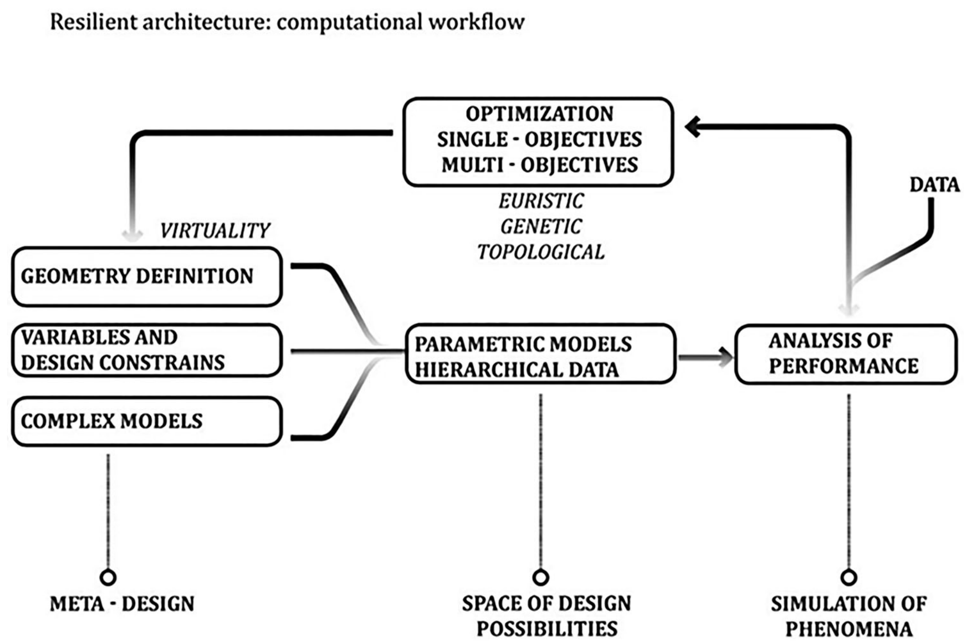



**Figure 1.** Resilient architecture: a computational workflow. Angelo Figliola.

## Performance-based simulation tools

Given the purpose of the research, it is necessary to analyse performance-based simulation tools available on the market to perform analyses at different scales. The tools that support designers in PBD can be divided into three main categories: stand-alone software for climate analysis, integrated tools in a CAD, BIM or NURBS modelling environment and stand-alone software that need a transfer model and related information from one platform to another. The subsequent classification can be made in relation to the type of analysis that such software can execute: climate analysis, energy and thermal analysis, daylighting, computational fluid dynamics analysis (CFD), simulation of the outdoor microclimate. About the first category, these are free tools developed mostly in the university environment and designed for educational purposes. Their field of application ranges from the climatic analysis of project sites starting from a climate file without providing for the import of complex geometries to the evaluation of the energy demand for heating and cooling, as well as to evaluate the temperature behaviour in buildings. Among the most used software, we can mention CasaNova, ArchiSUN, Climate Consultant, CBE Clima Tool. The most interesting category of tools is certainly that of software integrated into modelling environments that allow you to deal with almost all types of analysis in a single platform and to create data-driven processes starting from the schematic phase of the design. Among those most used in the academic and professional fields are Ladybug Tools, open-source and free, Climate Studio, OpenStudio, Sefaira and Autodesk® Green Building Studio (cloud computing). In the first two cases, the modelling interface is the NURBS Rhinoceros® modelling software while for Green Building Studio the BIM platform is Autodesk® Revit while the graphical interface of OpenStudio and Sefaira is Sketchup®. The latter exploit the flexibility of parametric models thanks to the Grasshopper applications in Rhino and Dynamo in Revit and allow to conduct most of the environmental and energy analyses up to the CFD and outdoor microclimate simulations (Ladybug Tools). Finally, the last category concerns stand-alone professional software that allow you to conduct energy and thermal analyses, daylighting, CFDs and simulations of the outdoor microclimate with extreme accuracy. For the energy and thermal simulation the available tools are IES, Transys, Design Builder, eQUEST; for daylighting: Diva, Radiance, Velux Daylight, Daysim; for the simulation of the outdoor microclimate: ENVI-met while for the CFDs analysis Autodesk® CFD, Ansys and Consol, OpenFoam. For their use, specific skills are needed and in most of the cases, they are extremely expensive. In the specific field of façade design, the software used can be divided according to disciplines of investigation and the different phases of the design process. The tools supporting the designers at early-stage and able to correlate different benchmarks (e.g. daylighting and energy analysis) are:

- Dalec;
- Comfen.

Other softwares are related to different fields of investigation:

- Dynamic Building Simulation: Energy plus, Open studio, Trnsys, Dynbil, Ies, eQUEST;
- CFD; Ansys, Comsol;
- Hygrothermal Simulation: Delphin, Therm, Heat, Anterm, Comsol;
- Window System Performance: Window, Frame plus.

These tools are mostly stand-alone and engineering-oriented and used by consultant to verify design decision previously done. Moreover, they are not so easy to use to model complex geometries and generate design options. With reference to the overview of the available tools, the research aims to innovate the design process by integrating into the early-stage design phase the assessment of different benchmarks in relation to the morphological variation. Why should we use analysis only to verify the performance of buildings and facades? Coupling analysis with generative processes allows designing specific solutions according to boundary conditions. An important part of the process described above is the optimization of performative benchmarks to be conducted with different strategies and tools.

## Optimization and brute force parametric analysis

Optimization of performance in architecture through the use of evolutionary algorithms (Coates, 2010; Worre Foged, 2015), genetic (Goldberg, 1988; Goldberg, 1989; Holland, 1992; Madeddu, 2011; Mitchell, 1998; Turrin, 2014) or morphogenetic (Dunn, 2012; Yi et al., 2019) is one of the methods through which guide decision making processes within the space of design possibility offered by parametric – associative models. There are different approaches to the theme of optimization and they can be summarized by defining three strategies:

- Heuristic optimization, exploiting the potential of the parametric model to visualize the different design options in relation to performances parameters defined as benchmarks;
- Genetic optimization, using genetic algorithms and solvers integrated into visual scripting programmes that allow to guide the formal generation through the construction of an initial population of individuals that describes the genotype and defines the variables of the problem and a selection process that provides the choice of the best individuals in relation to the objective function, fitness;
- Topological optimization (Yan et al., 2022), XESO, Extended Evolutionary Shape Optimization, based on the use of contour lines, defined as contour lines, to describe stress conditions related to surface portions with equal stress values, higher and lower than the limit values indicated in the optimization parameters.

The different approaches have similarities and a substantial difference: all three methods described involve the construction of an algorithm that presents geometric parameters and performance simulation within the same digital workflow, but only in the case of genetic and topological optimization the performance analysis guides the formal generation to achieve the optimal solution. Another aspect resides in the control that the designer holds on the creative process of formal generation, and therefore on the final result: the metadesign (Kolarevic, 2018), a tool at the base of genetic optimization and heuristic exploration, is the expression of a collaborative path between man and machine with the first one called to define the problem and to outline the limits of the digital form-finding process. Unlike the above, the impact of the designer on the creative process is lower in the topological optimization processes, as the problem setting, and the construction of the algorithm only provides for the definition of macro elements that describe the project. Recent researches on the field are expanding the design space of topology optimization processes combining it with environmental analysis and fabrication constrains (Feng et al., 2022; Yan et al., 2022). Nowadays, the available plugins for Grasshopper for solving optimization processes are (Wortmann et al., 2022):

- Galapagos, evolutionary genetic solver for single-objective (SO) problems;
- Octopus, evolutionary genetic solver for multi-objective optimization processes (MOO);
- Goat, linear solver;
- Silvereye, an evolutionary genetic solver for SO, based on the Particle Swarm Optimization (PSO);
- Opossum, evolutionary genetic solver for SO, based on direct search algorithm;
- Wallacei, evolutionary genetic solver for MOO process

A typical optimization process includes the following steps:

1- Numerical variables defined using a cluster and meta-design tool are fed into VARIABLES. The genetic solver used will automatically adjust variables, generate design iterations, trigger simulation toggles, and records all solutions;
2- Analysis of performance is defined according to design objectives. The numerical results obtained through the simulation are set up as fitness function. The objective or fitness function, or the value that wants to minimize or maximize to reach the optimal position;
3- A set of initial solutions are generated randomly with the performance evaluated. The number of generations – defined as 'max generation' and the number of solutions in each generation – defined as 'population size' – are set up by designers;
4- The solutions with better performance results are counted as the parents for a new generation and those with poorer performance are discarded. Only the most favourable solutions enter the next generation. The rate of the better performance in terms of 'diversity' (Rutten, 2010) is defined as 'mutation rate';
5- The loop will continue until the number of generations reaches 'max generation', or until the user stops the process.

In general, there are two approaches to solve MOO problems. The first one uses a 'weighted sum function': the various objectives converge into one single objective to be optimized. Weight factors are assigned for each benchmark. The other approach is to use 'Pareto optimization': a solution is said to be Pareto-Optimal if it is non-dominated. It means that there is no other feasible solution that can improve one objective without deteriorating at least another one, thus this set of non-dominated solutions is called 'Pareto frontier' (Machairas et al., 2014). The optimization process is a 'sensitive analysis' and requires a deep understanding of the problems. It is an understanding of why some design options are better than others and what parameters are most important or the most influential. Given today's complexity and the ever increasing need to set up integrated design processes, it is increasingly difficult to have optimization problems dominated by a single objective. At the end of optimization processes, designers need to decode the results obtained to define the weight of each individual optimization goal and understand the relationship with the variables of the parametric model. As an alternative to genetic solvers that employ various specific algorithms (Wortmann et al., 2022), it is possible to resort to the brute force parametric analysis which allows to analyse the entire space of design solutions generated through the definition of variable parameters in accordance with the analysed performance. In this case, we will not have an optimal solution but a design solution that mediates between the various benchmarks defined a priori. In addition, it is important to define building performance metrics according to the design objectives. This can be done building a diagrammatic map with macro-categories that helps designers finding relations and correlations between performative parameters. In the field of environmental and energy analysis, the category can be defined as follow: environmental impact; occupant comfort; monetary cost. Data visualization strategies are fundamental to fully understand the relation between design solutions and performative parameters and to inform the design decision. Moreover, heuristic optimization allows to save time and consequently money if compared with the genetic optimization processes which can lead to an overwhelming problem complexity (Wang et al., 2018).

## Research framework: computational workflow for climate resilient buildings and facades

The proposed research is part of an already developed design methodology, supported by a computational workflow, for climate resilient buildings and facades (CRBF) (Figliola & Rossi, 2018; Rossi & Figliola, 2019). The research proposes a toolkit that can handle the different scales of the design project (urban, building and facade) in different climate zones, based on a digital form-finding process and structured in three consecutive phases in which the output of the previous phase is the input for the next phase. CRBF intends to support the designers not identifying a single possible solution but rather a range of design solutions calculating for each of them the performance in terms of energy and the corresponding level of indoor and outdoor comfort. It is the designer who chooses from the range of possible solutions the one he intends to pursue and insert as input in the next phase using different tools and methods for exploring the entire design space.

Specifically, the CRBF objectives can be summarized as follows:

- To simplify the generative process through the proposition of an intuitive tool that allows to explore the space of design possibilities with the integration of thermal and energy simulations in the same workflow;
- To unite in a single workflow the main stakeholders involved in the design process in order to define

objectives, generate alternatives and perform analyses, evaluate options and make decisions;
- To simplify the decision-making process of design based on qualitative and quantitative parameters (defined as benchmarks);
- To limit the consumption of primary resources, the environmental impact and consequently reduce the vulnerability of the built environment.

CRBF foresees to obtain a series of intermediate objectives that contribute to the achievement of an optimized design solution that presents as benchmark parameters the reduction of energy consumption of the building [kWh/m$^2$a] and the improvement of indoor comfort conditions (PMV, Predict Mean Vote [-]) as well as outdoor (UTCI, Universal Thermal Climate Index [°C]) in relation to the different climate zones in which the project is located. Referring to the many and consolidated research paths on the issues of resilient architecture, the proposed workflow presents its innovative aspect in the multi-scalar and interdisciplinary approach as 'intelligent integration between technology and nature' (7Group, Reed & Fedrizzi, 2011). The integrative approach to the design process allows to work on the potential of the entire system starting from the awareness that optimizing every single phase of the project tends to worsen the performance of the system as a whole due to the complexity of buildings and performance requirements (Liu et al., 2022). To build up and explore a series of design options, the design team needs an intuitive toolkit through which it facilitates the collaboration between different professions and integrates the know-how at disposal on the different topics. Specifically, the proposed methodology forms the basis for a systematic, collaborative and iterative process that includes the following steps:

- Formulation of the range of design alternatives to be explored by the design team;
- Generation of alternatives, where the hierarchical structure of data is defined through parametric systems to produce digital catalogues of design solutions;
- Analysis of performance in relation to the parameters chosen as benchmarks;
- Data visualization and decision-making facilitation.

The computational workflow is organized according to the following project scales (Figure 2):

Micro-Urban scale – Starting from the requests of stakeholders, as the functional programme and the gross indoor surface area of the building (input), the toolkit generates a digital catalogue of design solutions of which it defines the volume and the orientation of the building in relation to the cardinal points (output) which provide a form factor, S/V, able to optimize energy consumption for the specific project site. Defined the volume and the orientation, the next phase will define the position on the building site (output) optimizing both the energetic consumption for heating and cooling and the level of outdoor comfort (UTCI).

Building scale – On the basis of the morphology of the building and its location on the site (input) as defined in the previous phase, the ratio between opaque and transparent surface (output) in the four façades is optimized in order to minimize the energy consumption for heating and cooling.

Skin scale – In the last step, the envelope is designed starting from the relationship between the opaque and transparent surface (input) and the orientation as determined previously. The performances of the different skin solutions are verified in a virtual test-room equipped with five adiabatic surfaces, insulated surfaces that do not exchange energy and matter with the external environment, and one with the façade to be evaluated. In the first phase, the different solutions are generated by diversifying the morphology of the building façade according to the metadesign defined by the designer. In the second step of the workflow, an optimization of the building façade it will be done taking into account the materials of the opaque and transparent parts acting on the energy consumption according to the climate zone.

## Computational workflow for CRBF

Unfortunately, performance evaluation through data-driven analysis in the façade design process is not used as a generative element in the early-stage phase rather as a tool for verifying the performances required by the legislation or by certification rating on an already defined design solution. In most of the cases, this approach totally relies on the use of mechanical systems, HVAC, to regulate indoor conditions based on outdoor environment. Because the performance of the building façades plays a particularly important role in this context (Hausladen et al., 2006), several recent research works take into account only this part of the building with the intent to develop a climate resilient building facade. This approach aims at having 'the ability to repeatedly and reversibly change some of its functions, features or behaviour over time in response to changing performance requirements and variable boundary conditions and does this with the aim of improving overall building performance' (Loonen et al., 2013). The

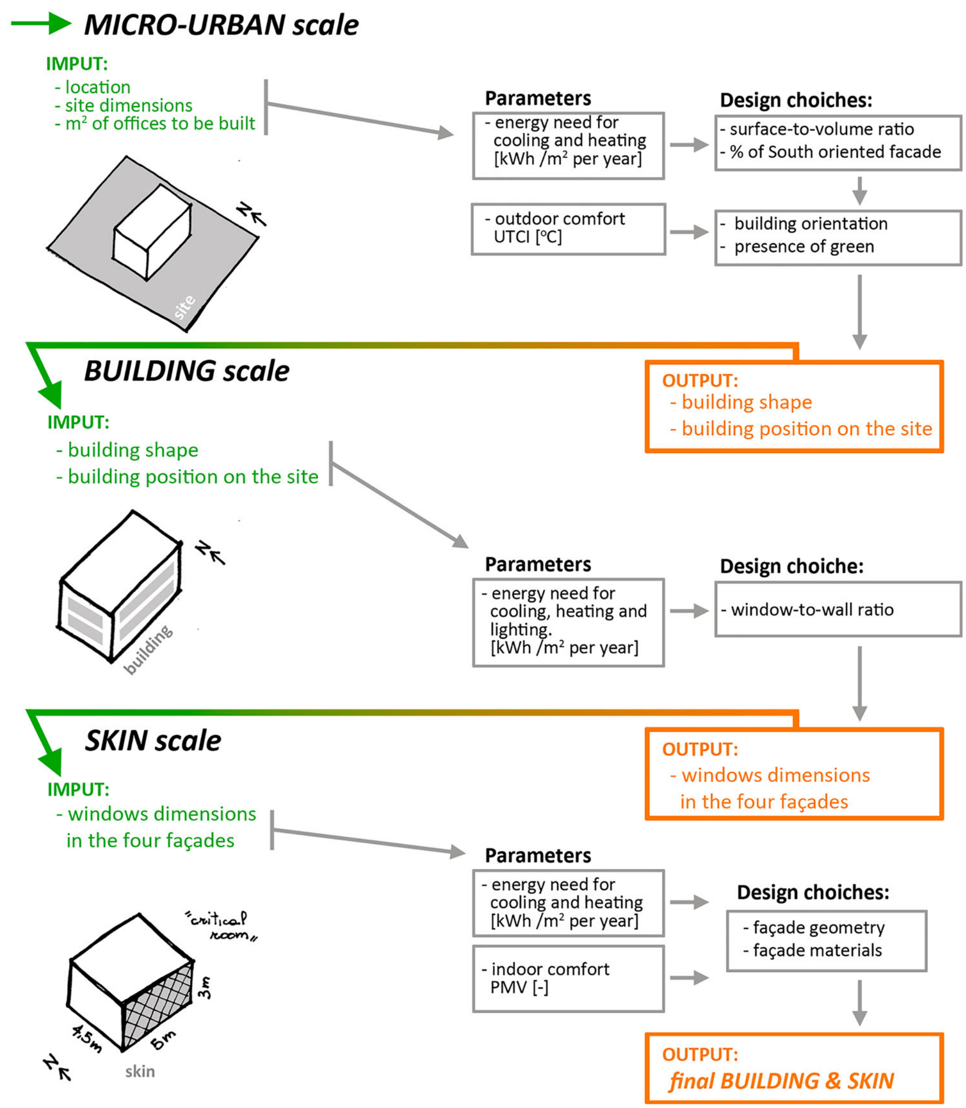



**Figure 2.** CBRF workflow through different design scales. Angelo Figliola & Monica Rossi.

adaptability of building façades can be realized pursuing different strategies. The first one refers to 'kinetic envelopes' (Fortmeyer & Linn, 2013; Alotaibi, 2015), which implies that the building skin can change its configuration via moving parts (solar shading, moving panels, lamellae etc.), using particular features or natural/engineered materials properties (Dierichs et al., 2021; Krüger et al., 2021). In the second case, the adaptability is realized via changes in thermo-physical or optical properties of building components and materials (shape-memory or temperature-responsive polymers, phase-changing materials PCM, photo-chromatic glasses, etc.) (Mohtashami et al., 2022). In this case, the building façade does not have a changing form, but is characterized by an optimized (for a specific climate zone) geometry able to maximize the dynamic properties of the used materials and components. The use of (innovative or traditional) materials – able to adapt their energy performance under changing environmental boundary conditions by means of phase change (Aridi & Yehya, 2022), thermal mass activation, etc. – can reduce the energy demand for heating and for cooling of a building. Research in this field, oriented at commercializing a specific material or component, is often conducted by the chemical or building industry and does not consider the whole building (Pinotti et al., 2017; Persiani et al., 2016). High-performance building skins cannot be designed separately from an appropriate and holistic design (Heusler, 2015) of the building at all design scales: micro-urban, building and façade. At the facade scale, the most important elements are skin geometry and materials. The skin geometry can optimize the energy flow between outside and inside (and vice versa) and consequently improve the level of inhabitants' comfort indoor. The design of this (changing or optimized) geometry is usually supported by computational design tools (e.g. Grasshopper combined with different appropriate plug-ins) in order to find the perfect form able to meet a predefined performance. This topic usually characterizes the academic works or some applications in specific experimental buildings (De Luca et al., 2022; Szentesi-Nejur et al., 2021; Shen, 2018). The above-mentioned three design scales, despite their strong influence on each other, are usually considered separately and often by different research/design organizations that do not communicate with each other (Liu et al., 2022). Another growing research area is the so-called 'optimization-based design exploration' (Liu et al., 2022). The application of this strategy in architectural practice is favoured by the use of generative and parametric design techniques in which qualitative and quantitative data are the pillars of multi-criteria optimizations (Ekici et al., 2021; Wortmann & Natanian, 2020; Wortmann & Natanian, 2021). As well represented in MacLeamy's curve: the 'information of the design process' in its early stage allows for maximizing the impact of design choices in terms of performance and decreased costs related to their application (Negendahl, 2015; Raji et al., 2017). Performance-based designed architectures have led to the development of numerous researches (Elbeltagi et al., 2017; Konis et al., 2016) mainly focused on the exploration of the relationship between form and energy performance, in relation to different climate zones. Several studies are conducted on the topic of façade optimization using genetic algorithms (De Luca et al., 2022; Fathy & Fareed, 2017; Gagne & Andersen, 2010; Liu et al., 2022; Rahmani Asl et al., 2014; Shen, 2018; Yi, 2019; Zemella & Faraguna, 2014). Many of these cited studies limited their scope to a simplified initial geometry and the optimization process was only limited to the size and position of these openings or to the positioning of shading devices. Although this may result in minimizing energy consumption and optimizing daylight distributions, they lack in considering architectural design values and aesthetics decisions taken by the designer client and manufacturer. In addition, variables and benchmarks are restricted due to the complexity of the optimization processes (in terms of time and costs) and consequently the design space of possible solutions is limited and difficult to decode. Most of the researches on façade optimization are developed based on a single-step method solved by SO or MOO with a problem-solving approach rather than as exploratory tool. Based on the critical discussion on the above-mentioned research works, this work aims to develop an innovative design methodology for CRBF that proposes optimization-based design exploration able to ensure the best performance by integrating quantitative and qualitative benchmarks in a two-phase design methodology involving different levels of complexity for ensuring the exploration of a vast design space. Based on what underlined by Danhaive and Mueller (2021) 'There is a need for methods that allow designers to intuitively explore chaotic design landscapes without resorting to automated procedures, given the importance of human factors in design', CRBF intends to expand design variables and performative benchmarks to be evaluated including biophilic principles and aesthetic perceptions according to designer, client and manufacturer requirements.

## Methodology of CRBF

The following sections detail the steps of the methodology and the computational workflow as:

- Toolkit;
- Metadesign: variables and constraints definition; Benchmarks;
- Energy performance simulation;
- Analyse design solutions;
- Select and optimize.

## Toolkit

The theoretical and methodological aspects previously mentioned were translated into a computational workflow using the 3D NURBS modelling program Rhinoceros©, and the open source add-on Grasshopper © (Gh).[1] Part of the same workflow is the climate analysis coupled with energy and thermal simulations. Those were performed through the open source and free plugins of Gh, Ladybug and Honeybee.[2] The first one, Ladybug, is used to decode and analyse the climate file related to the site where the project is located by importing or downloading the climate file in EPW format in direct connection with the World Meteorological Organization (WMO) website. Decoding the EPW file allows to make preliminary environmental analysis and also have a clear understanding of the radiation and sunlight hours. Honeybee is used to perform energy and thermal simulation as a graphical interface of the software OpenStudio ©, for the construction of climate zones, and Energy Plus © as a computational engine. The use of these tools does nothing more than simplify and make intuitive the process of simulation and analysis of performance by creating a feedback loop relationship between formal generation and quantitative parameters derived from the calculation. Using the plugins offered by the Ladybug Tools (LT) Suite for Gh is it possible to perform almost all the analysis, from climate to outdoor microclimate passing through energy and thermal simulations, without any geometry limitations. The toolkit (Figure 3) described above was chosen according to the aims of the research inasmuch it allows to perform a comprehensive analysis to start informing the design from the schematic design phase. Furthermore, using parametric software simplify the process of formal generation and the analysis of performance, making it accessible also to non-expert users or in any case not in possession of specific knowledge of digital computation. To summarize the advantages of using the toolkit in relation to the aim of the research:

- LT is built on top of several validated simulation engines such as Radiance, EnergyPlus/OpenStudio, Therm/Window and OpenFOAM;
- LT is integrated into 3D modelling software so all geometry creation, simulation, and visualization happen within one interface;
- LT is flexible across different stages of design;
- LT runs within parametric visual scripting interfaces, enabling the exploration of design spaces and the automation of tasks;
- By harnessing capabilities of CAD interfaces, Ladybug Tools produces a variety of interactive 3D graphics, animations, and data visualizations.

To explore the whole design space as a result of a brute force parametric analysis, the workflow uses Colibrì 2.0 a plugin for Gh through which all the design options can be 'recorded' and after analysed using a web platform called Design Explorer. The plugin generates an Excel sheet and a series of images according to the designer requirements. Finally, a genetic optimization solver was used in the second phase of the design process. Analysing the plugins available and previously discussed and according to the aims of the research, the Opossum plugin is used. It allows the search for many goals at once, producing a range of optimized trade-off solutions between the extremes of each goal using a model-based method (RBFOpt). Opossum was chosen accordingly for its efficiency and robustness and also for the speed in calculation compared to others genetic solvers (Wortmann, 2018).

## Metadesign: variables and constrains definition

The metadesign is a tool through which designers, clients and manufacturers (as main contractor or subcontractor) parametrically defining a geometric model (Figure 4) using Gh as the baseline for simulation and optimization. The tool is characterized by a variable defined by the designers taking into account the complexity of the architectural aesthetics and according to the client's requirements and the constraints derived by the manufacturing processes. Specifically, the constraints of the process are given by:

– the climate zone defined by site location and EPW files (weather data file saved in the standard EnergyPlus format) downloaded from a repository of free climate data for building performance simulation (Climate.Onebuilding.Org);
– design parameters defined in the previous phase of the research (Figliola & Rossi, 2018; Rossi & Figliola, 2019), such as glazing ratio and façade orientation;
– architectural characteristics of the test room such as depth (y), length (x), height (z), number of façade modules;
– The variables for the early-stage design phase include:
– geometric dimensions according to the morphology configuration of the unitized façade system;
– For the next step of the methodology, mid-stage design phase (genetic optimization):
– materials (e.g. typology, insulation thickness) and HVAC systems (e.g. typology, insulation thickness).

The range of the variables is defined based on design constraints. The hierarchical structure of data is defined through a parametric system, cluster, to produce digital catalogues of design solutions. This approach allows to visualize different design options by manipulating a simple slider that controls the geometric design variables. As the cluster is built with the synergic work of designers, clients and manufacturers, the entire design space will respond to all the requirements from the figures listed above.

## Benchmarks

Given the complexity of the design process for a building façade, the method starts with an analysis of the local environmental condition, indoor comfort needs, energy behaviour and predetermined design drivers, such as client requirements, architectural aesthetics, project budget and manufacturing constrain. The performance parameters to evaluate are defined according to different steps of the design process. Specifically, the workflow presents two main phases and the benchmarks are defined accordingly:

- Early-stage design phase: (based on concept design, schematic drawing): the benchmarks will be

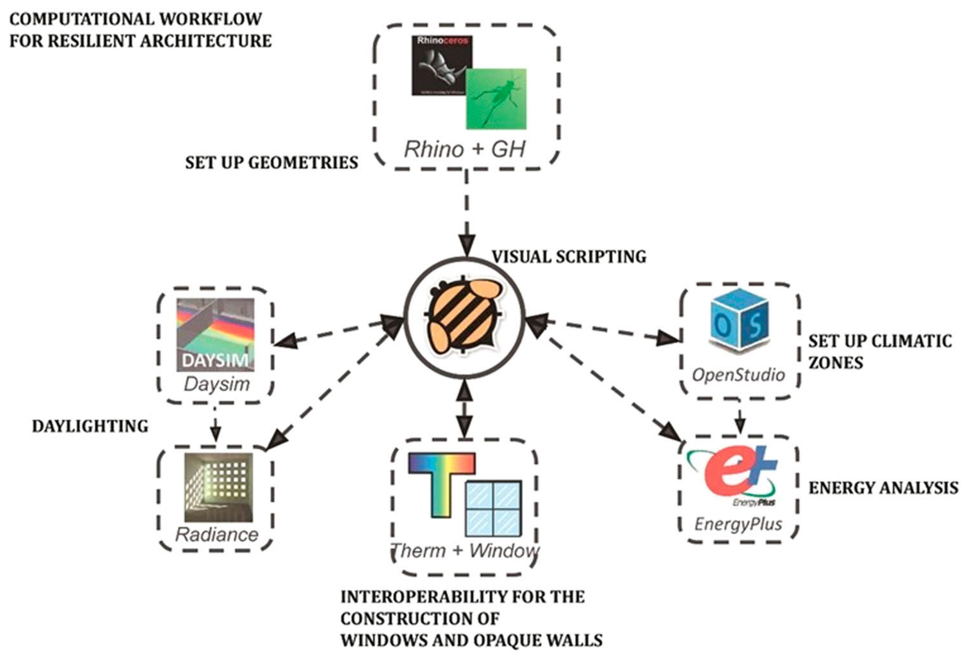



**Figure 3.** Computational toolkit for resilient architectures and building façade.

defined following the analysis of the climate conditions of the project's site and the performance requirements with reference to normative apparatus and certifications rating;

Mid-stage design phase and optimization: (design solution/s fixed, materials and, HVAC to be defined). At this stage, benchmarks are defined to ensure the best performance on energy consumptions and comfort perception according to climate zone. The application of the method described above ensure that in the first step each unitized cell will be able to adapt to the external conditions (environment) and the internal one (inhabitants) through an optimized geometric configuration. The overall geometry is defined by coupling geometric variables and performative criteria using brute force parametric analysis. This kind of analysis does not require an extensive computational knowledge so can be handled by a designer. In the second phase, the geometry selected will be enriched by materials and HVAC information using genetic optimization process that allows to minimize cooling demand.

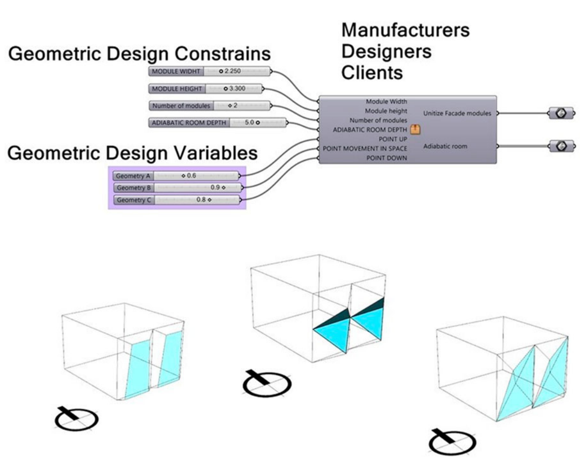



**Figure 4.** Cluster: defining design solutions through variables and constrains. Angelo Figliola.

## Energy performance simulation

About façade design, the BPD process includes daylight and thermal simulations using specific tools already described above. The process usually starts at the design development phase by testing how the facade design affects the energy consumption. In most of the cases, the analysis is carried out when the design principles are already fixed, and it is used to validate the designer's decisions previously made. Two simulation types are the focus of Environmental Performance Evaluation (EPE) and Building Energy Modelling (BEM). EPE is the primary type of the simulation in developing facade morphology which is impacted by daylight, solar, and thermal. According to the literature review, BEM in architectural practice usually starts at the design development phase by testing how the facade design affects the energy consumption (Shen, 2018). In the era of technological innovations and ubiquitous computing, we cannot avoid as designers and technicians to fully explore the power of digital tools. This means to completely change the way we design and learn from other disciplines as naval and aeronautical design where design is coupled with analysis in the early-stage. About that, parametric tools are more integrated with the design process and more intuitive to designers. The integrative parametric environment allows to consider different performative benchmarks in the conceptual design phase, coupling energy behaviour with comfort index. Specifically, the simulations are subdivided following the two consequential steps, early-stage and mid-stage (Figure 5). In the early-stage design phase analysis the simulations performed are:

– Daylight analysis using two metrics: Daylight Factor DF [%] and Spatial Daylight Autonomy sDA [%] – LEED V4. Daylight Factor can be used for fast calculation in a climate zone with a prevalence of an overcast sky;

**Daylight factor DF [%]:** the ratio of the light level inside a structure to the light level outside the structure.

$$\mathrm{FLD} = (\mathrm{Eint}/\ \mathrm{Eo})\mathrm{x}\ 100\%$$

$E_{int}$, value of illuminance on the internal work plane;

$E_o$, value of simultaneous illumination on a horizontal plane placed under the celestial hemisphere in the absence of obstructions and direct solar irradiation.

**Spatial daylight autonomy sDA [%]:** is the per cent of analysis points across the analysis area that meet or exceed the thresholds value (set to 300 lux for LEED) for at least 50% of the analysis period.

In 2013 IESNA coded the target values for X and Y = sDA $_{300,50\%}$ (IES LM-83-12): % of analysis points in which a DA ≥ 300 lux is recorded for at least 50% of the occupation time considering an employment profile: Mon-Fri 8–17 (8 h/day);

- nominally accepted: sDA $_{300,50\%}$ in at least 55% of the analysis points;
- preferred daylight sufficiency: $\mathrm{sDA}_{300,50\%}$ in at least 75% of the analysis points.
- ASE, Annual Sunlight Exposure [%] – LEED V4;

**ASE, annual sunlight exposure [%]:** % of the area of analysis that exceeds a specified solar direct illuminance level for an annual number of hours Y greater than a threshold X-ASE x, y.

In 2013 IESNA coded the target values for X and Y = ASE 1000,250 (IES LM-83-12):

% of analysis points in which a direct light illumination is recorded for at least 250 h during the occupation time:

– unsatisfactory visual comfort: ASE $_{1000,\ 250} > 10\%$;
– neutral: ASE $_{1000,250} < 7\%$;
– clearly acceptable: ASE $_{1000,250} < 3\%$.

This simulation produces both a spatial visualization of glare potential over the space as well as a temporal visualization that illustrates when the most glare is happening.

– Total Solar Radiation [Kwh/m$^2$a];

**Solar radiation [KWh/m$^2$a]:** total solar radiation falling on input geometry using a selected sky matrix.

- View Quality [%] – LEED V4;

**View quality [%]:** determine the Floor Area with a Quality View from inside to outside.

- Energy Analysis [Kwh/m$^2$a];

**Energy analysis [KWh/m$^2$a]. Cooling:** the cooling energy needed in kWh. For Ideal Air loads, this output is the sum of sensible and latent heat that must be removed from each zone. For detailed HVAC systems (other than ideal air), this output will be electric energy needed to power each chiller/cooling coil.

**Heating:** the heating energy needed in kWh. For Ideal Air loads, this is the heat that must be added to each zone. For detailed HVAC systems (other than ideal air), this will be fuel energy or electric energy needed for each boiler/heating element.

- PMV, Predicted Mean Vote;

**PMV, predicted mean vote:** PMV is a seven-point scale from cold (−3) to hot (+3) that was used in comfort surveys of P. O. Fanger. Each integer value of the scale indicates the following: −3: Cold, −2: Cool, −1: Slightly Cool, 0: Neutral, +1: Slightly Warm, +2: Warm, +3: Hot. The range of comfort is generally accepted as a PMV between −1 and +1. Exceeding +1 will result in an uncomfortably warm occupant while dropping below −1 will result in an uncomfortably cool occupant.

At this stage, materials, schedule and HVAC systems are defined according to the standard setup offered by Energy Plus based on the ASHRAE code.

In the mid-stage design analysis:

– Detailed Energy analysis coupled with daylighting.

The proposed workflow allows designers and non-qualified technician in the field of façade design and construction to include different performative

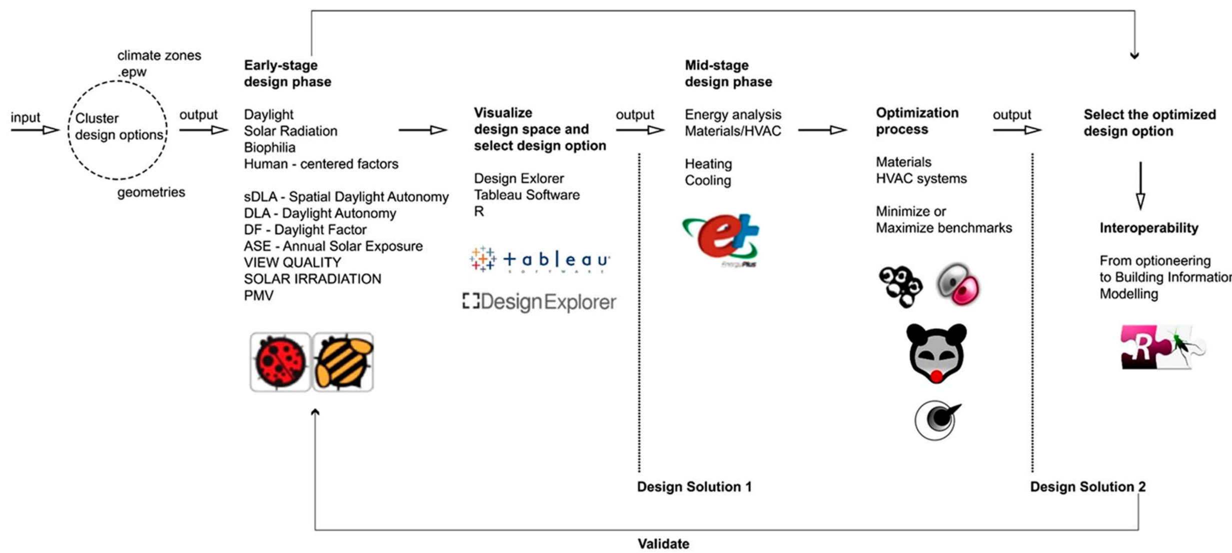



**Figure 5.** Climate-resilient façade methodology. Angelo Figliola.

parameters in the design process and to link shape generation with performance simulation. It represents also the opportunity to integrate into the early stage the requirements of certification protocols (e.g. LEED, BREEM, DGB) as suggested by best practices and to couple energy performance with human well-being and using occupant comfort as constraint.

## Analyse design solution

As mentioned above, the methodology and the early-design computational workflows are applied for shaping the geometry according to geometric variables using occupant comfort and energy behaviour as a constraint to empower the development of human-centred facades able to create more desirable occupant experiences and help to reduce consumption and $CO_2$ emissions. For the first step, the iterations are made using a brute force parametric analysis simply recording the simulation results and geometry variations. Through this methodology, the designers have the possibility to analyse the entire design space emerging from the correlations between geometry and simulations with a relatively fast digital procedure compared to time-consuming multi-objectives optimization processes that use specific genetic algorithms. To fully explore the design space, designers are required to evaluate as many solutions as possible exploiting the computational power. To carry out this process, it is necessary to correctly set up the algorithm as follows:

– define variables using the cluster input already defined by designers, manufacturers and clients;
– extract numeric values from simulations;
– define a procedure for recording design options and performative values (using Colibri a plugin for Gh).

To read the results different options are available. For this specific workflow, is used an opensource web platform called DESIGN EXPLORER.

## Select and optimize

Differently from optimization, brute force parametric analysis process will never end up with a single optimal answer, but it will represent the entire design space according to the metadesign. To select the design option for the next phase, the final step is to filter and sort the optimal solution based on the weighting criteria customized in the previous phase. Benchmarks for selecting design option are selected based on a literature review (Shen, 2018) and according to the climate conditions of the selected building site (Al-Shaalan et al., 2014). Traditionally, façade design proposals are evaluated in the early-stage based on their daylight and thermal performance. The proposed method tries to expand the performative parameters by introducing a biophilic[3] human-centred factor such as view factor and PMV. The design solution results of this stage are enhanced using genetic algorithms for single or multi-objectives optimization based on the use of Gh plugins. As the previous step, optimization requires a specific algorithm set-up based on:

– Definition of the project objectives, in this specific case the optimization of energy consumption for heating

or cooling according to the climate conditions of the sites;
- Definition of design variables based on meta-project and cluster, fitness criteria;
- Setting of energy analysis using Honeybee and Energy Plus, extension of the Grasshopper software modelling environment;
- Analysis of results through 2-D or 3-D pareto-front curve in case of MOO;
- Choice of the optimal design solution.

In the case of multi-objectives optimization, Octopus[4] allows to analyse a maximum of five design objectives and automatically visualizes the results of all the generations using a 3-D or 2-D visualization space. While all the solutions are distributed in the coordinate axis view cube, the best-fitted instances are shown on the pareto front curve. The optimized design option can be subsequently transferred from the Rhino/Grasshopper environment in BIM software Revit using Dynamo and Rhynamo.

## CRBF case study: an experimental output

Following an experimentation in the project of an office building located in Berlin (Rossi & Figliola, 2019) it was decided to further optimize and verify the workflow in a different climatic zone and in particular in Abu Dhabi, a desert or semi-desert climate area. In this second experimentation, the workflow is enriched with a simplified tool, able to facilitate the formal generation process as the used data is used as input in synergy between the different actors involved in the design process. The cluster consists of a simple parametric model that creates alternatives starting from design inputs, thanks to which the information is structured to generate the different design hypotheses and subsequently to conduct the energy-environmental analyses.

Micro-urban scale – Starting from pre-established data such as site dimensions, the gross useful area to be built and the climatic data of Abu Dhabi, the cluster is used to generate different design hypotheses (building morphology). The parametric model has been structured providing designers the ability to vary in an intuitive manner the geometric coordinates (x, y, z, radius and diameter) in the way that only buildable volumes can be generated. The morphology is defined by parameters such as the height and number of floors, the volume and the external surface. These parameters, defined in order to determine an optimal S/V shape factor for the chosen climate zone, can be partly set by the designer or allowed to be generated directly by the tool. In this first phase, five design hypotheses were analysed taking into consideration the parameters listed above and evaluating the energy consumption on an annual basis expressed in kWh/m$^2$a. In relation to the climatic of Abu Dhabi the S/V ratio does not represent an important parameter but rather data to be monitored in relation to energy consumption. The morphology which ensures lower consumption, given the design constraints, is a parallelepiped 40 m × 15 m × 33 m (10 floors of 3.3 m) and S/V ratio of 0.22. The morphology, output of the first phase, is preparatory to face the problem at the urban scale taking into account the requirements for the size of the building site equal to 60 m × 40 m and the open space of about 1000 m$^2$. Thanks to the intuitive nature of the cluster, the manipulation of geometric coordinates makes it possible to diversify the location of the building with respect to the four cardinal points and to evaluate its energy consumption. A new evaluation parameter is introduced at this stage: the different locations of the building on the site are also evaluated according to the levels of outdoor comfort considering the possibility of adding vegetation to mitigate the climatic stress deriving from high temperatures. The UTCI has been calculated considering the summer season, June–September, since the variation in temperatures is minimal throughout the year. The combination of the two evaluation parameters made it possible to select the optimal solution (Figure 6): the building is located in the north portion of the site with the main façades facing north–south. The presence of vegetation makes it possible to mitigate the thermal stress in outdoor spaces even if the comfort conditions are not guaranteed.

Building scale – Once the morphology of the building has been defined and the best location on the project site is identified, through the cluster it is possible to vary the ratio between opaque and transparent surface, glazing ratio, GR. In this phase, five different design solutions were analysed, varying the GR percentages of the four façades. The solution chosen as output shows a percentage of glass surface equal to 40% for the north wall and 50% for the south wall while the surfaces exposed to the east and the west are completely opaque (Figure 7). The choice made by informing the computational process has validated the indications of the relevant literature (Hausladen et al., 2011).

Skin scale – To explore the relationship described above specifically in the façade design process, the project work proposes a case study carried out on a test room with the size of a generic space in hypothetical office building. The room is an office for two occupants of 22 m$^2$ foot area. The room dimensions are 4.5 m length, 5.0 m width and 3.3 m height. The room has on façade of 14.85 m$^2$ facing south (test surface). The

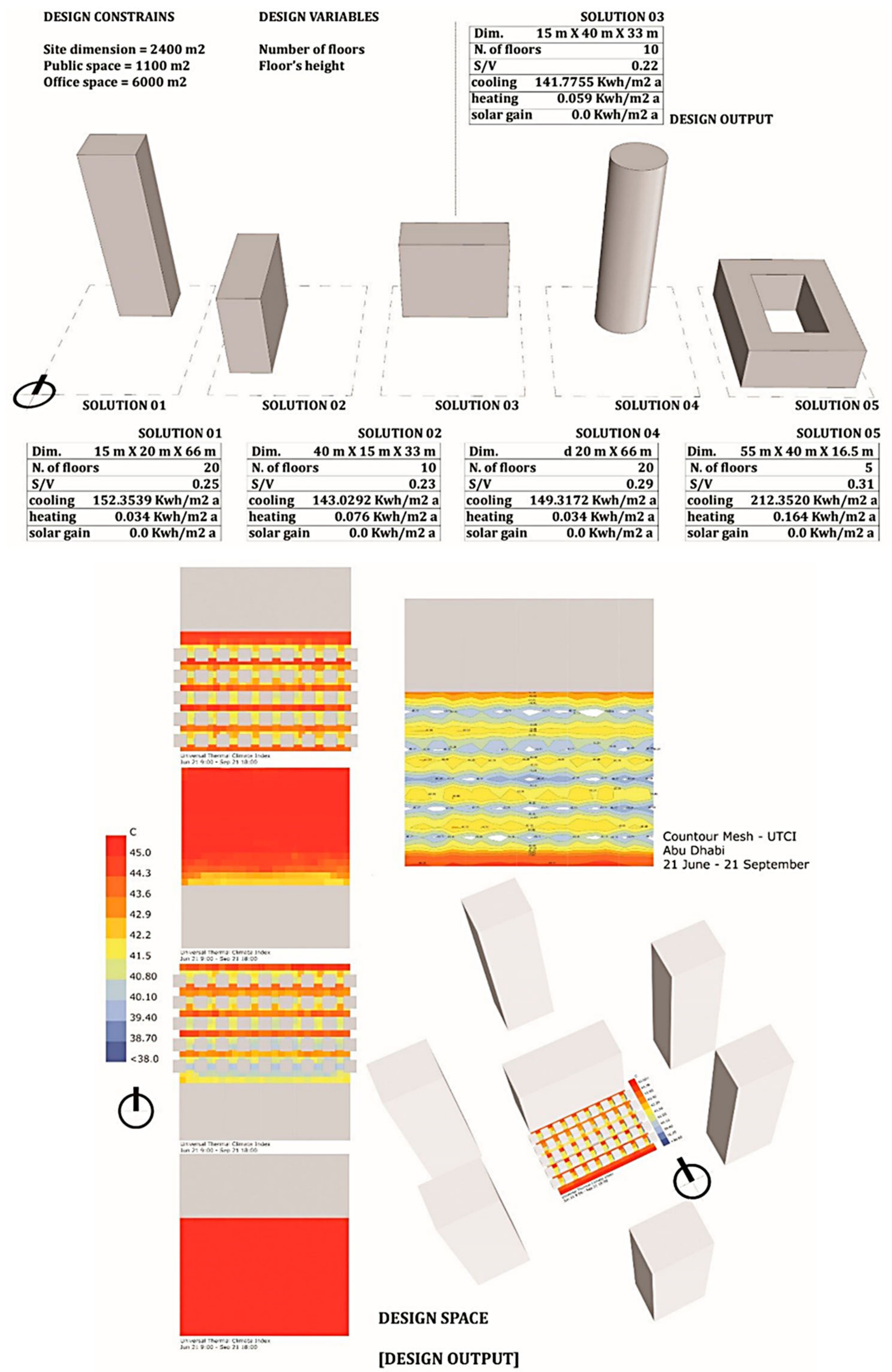



**Figure 6.** Micro-urban scale: design solution for the next step. Angelo Figliola.

other surfaces are considered adiabatic and adjacent to other heated/cooled spaces of the building. The analysis was carried out in two consequential phases involving different benchmarks that all together describe the complexity of building façade. The generation of alternatives of modular, parametrically designed façade, will allow to analyse performance in relation to the parameters chosen as benchmarks as well as understand optimization algorithms. Finally, a specific data visualization protocol will be studied to facilitate the decision-making process. As mentioned in the previous section, 'Metadesign: variable and constrain definition', the parameters listed above such us glazing ratio, test room depth, width and height are used to construct the simplified

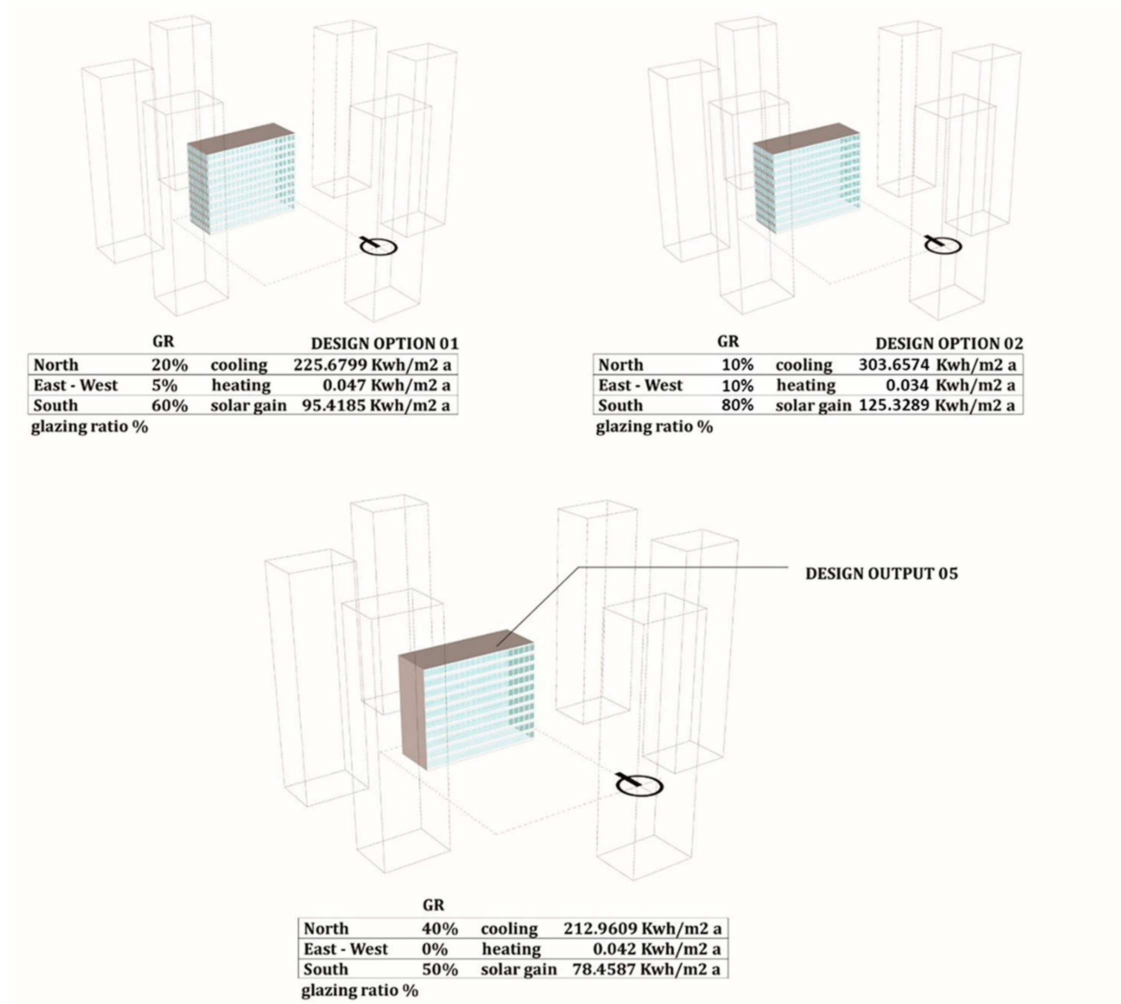



**Figure 7.** Design solution for the next step. Angelo Figliola.

cluster to be used in the façade design process. To complete the cluster, the south façade is designed according to aesthetics, client requirements and manufacturing constrains. For the Abu Dhabi case study, three cluster were prepared enhancing complexity and morphology exploitation defining variables and constrains. To carry on the research activity one of the clusters was chosen based on triangular meshes and folded panels. The cluster is composed as follows:

Constrains:

- Module depth 5 m;
- Module width 4.5 m;
- Module height 3.3 m;
- Glazing ratio: 50%;
- Orientation: south.

Variables (Figure 8):

- Geometry A, range from 0.4 to 1 m with 7 steps;
- Geometry B, range from 0.4 to 1 m with 7 steps;
- Geometry C, range from 0.4 to 1 m with 7 steps.

Based on the geometry defined through the cluster a simple parametric energy model is constructed to carry out the first analysis in the early-stage of the design process. The simulations are done following the methodology proposed: in the early-stage, the analysis conducted is about yearly daylighting penetration using DF and sDA, ASE, solar irradiation on the floor, view quality and solar irradiation falling on the potential PV surface. The study started with local climate and comfort analysis. Abu Dhabi is cooling dominated and adequate solar resource is available. Consequently, natural daylight, passive solar heat gain, seasonal solar shades, and Building Integrated Photovoltaic (BIPV) were primarily considered as the design metrics. To select one of the designs options the following benchmarks were considered:

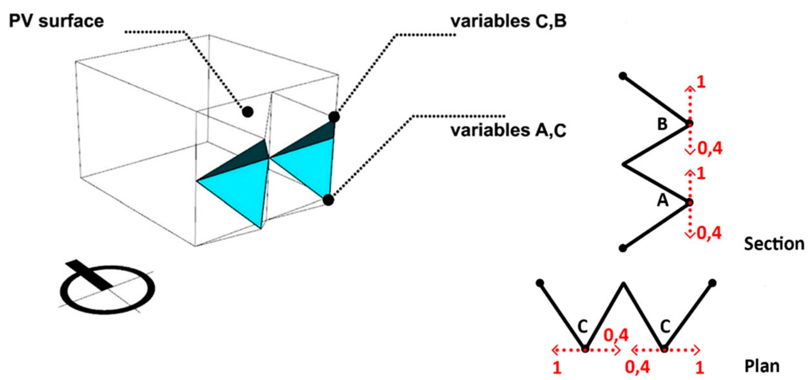



**Figure 8.** Design variables. Angelo Figliola.

- Daylight penetration using DF e sDA: the average of DF on the working plane at the level of 0.8 m should be maximum and the sDA should be over 50% according to LEED prescriptions;
- Solar radiation on PV surfaces should be maximum;
- Solar Irradiation (SI) on the floor should be minimum in spring-summer between March to September;
- Energy for cooling should me minimum all over the year.

The basics parameters are analysed coupled with human-centred factors such us view quality (biophilic parameters), PMV and ASE to avoid glare. At this stage of the design process, a standard material for External Wall (U-value 0.42 W/m$^2$ K) and External Window (U-value 2.3 W/m$^2$ K) was used according to Open Studio template. The simulations are conducted by interpolating the variables parameters and the results are recorded using Colibrì a Gh plugin that allows storing results in CVS format and jpeg images. Interpolating the variables previously defined produce 333 design options coupling geometry and performance to be explored (Figure 9). The analysis of the entire design space is conducted by the web platform Design Explorer ending with the selection of the design option that is able to satisfy the benchmarks fixed for the early-stage design phase.

Different solutions were analysed before selecting the design option to be further optimized. In the second phase of the methodology, a genetic optimization process is involved to further improve the performance in relation to energy consumption. At this stage of the process where a schematic design was chosen, the parametric model is implemented taking into account materials and HVAC systems. About materials, two systems are defined according to Open Studio setup: external wall (opaque) and external window. For the opaque wall a metal cladding is defined as a combination of the following layers:

– metal siding;
– air gap;
– insulation;
– metal siding.

To define the external window system is used a Honeybee component able to generate window system manipulating the three main values:

– U-Value;
– SHGC, Solar Heat Gain Coefficient;
– VT, Visible Transmittance

The analysis was carried out by varying materials properties of the opaque and transparent parts keeping the same morphological configuration previously selected by brute force analysis. Specifically, the objective of the optimization process is about to MINIMIZE the cooling loads of 120.82 Kwh/m$^2$a (FITNESS) using four parametric variables (GENOME):

– Insulation thickness – from 0.20 up to 0.30 cm;
– UV glass, coeff. – from 1.2 down to 0.4;
– SHGC, solar heat gain coeff. – from 0.9 down to 0.4;
– HVAC system among Packaged Single Zone – AC, Packaged Single Zone – HP, Packaged VAV w/ Reheat, Packaged VAV w/ PFP Boxes, VAV w/ Reheat, VAV w/ PFP Boxes Heated.

To run the optimization, it was used the genetic solver Opossum[5] as the Gh plugin, after a time of computing comparison with other solvers embedded in Gh. Opossum uses an RBFOpt algorithm for direct search using radial basis functions. After 60 iterations and simulations, an optimized solution was generated (Figure 10).

The optimized solution is characterized by the following geometric variables and materials properties:


**Figure 9.** Analysis of the design space over 333 design options Design Explorer web app.

– Geometry A, 0.5 m;
– Geometry B, 0.6 m;
– Geometry C, 1 m;
– Insulation thickness: 0.30 m;
– Window U-value: 0.5;
– SHGC, Solar Heat Gain Coefficient: 0.4;
– VT, Visible Transmittance: 0.7.

In the last step of the methodology, the morphology generated, and the materials specifications defined, will be translated from Gh to Revit using an open-source plugin for interoperability called Rhynamo.

## Results

Beyond the theoretical implication of the research that will be discussed in the next section, the case study demonstrates the reliability of the proposed methodology in ensuring benchmarks achieving and optimizing performative aspects defined according to site's climate analysis. In the first phase of the process, the entire design space was explored due to the use of brute force parametric analysis. All the different geometry configurations obtained through the connection among variables parameters and performance benchmarks was recorded and stored to be analysed in a web platform to simplify the decision-making process. Different solutions were analysed before selecting the design option to be further optimized which presents the following performance parameters (Figure 11):

– Daylight Factor DF [%]: 2,7;
– Spatial Daylight Autonomy sDA [%]: 62.50 – LEED V.4 prescription satisfied;
– ASE, Annual Sunlight Exposure [%]: 19 – LEED V.4 prescription satisfied;
– Solar Radiation on PV [KWh/m$^2$a]: 268544;
– Solar Radiation on the floor [KWh/m$^2$a]: 1319;
– View Quality [%]: 20;
– PMV, Predicted Mean Vote: −0.01
– Range of accepted COMFORT as NEUTRAL;
– Energy Analysis [KWh/m$^2$a] – Cooling: 121;
– Energy Analysis [KWh/m$^2$a] – Heating: 1.58.

In the second phase of the process, a genetic optimization solver was used to optimize cooling loads all over the year keep fixed the geometry and varying materials and HVAC systems (Figure 12). Starting from a value of 120.80 KWh/m$^2$a, the annual energy consumption due to cooling is minimized up to 60.976 kWh/m$^2$a with a PMV between 0.0 and 0.5 and only the 18% of people unsatisfied, extremely positive values compared to the standard of tower office buildings in the United Arab Emirates, UAE. According to literature review (Shanks & Nezamifar, 2013), a typical UAE office building simulated under generated annual hourly weather datasets has cooling demand of 165.8 kWh/m$^2$a and this value will increase over time. Due to the material specification of the façade component defined in this design phase, a further validation is made analysing how the materials affect the performance. Specifically, sDA e DF are analysed and the results show an improvement of the two benchmark parameters as follows:

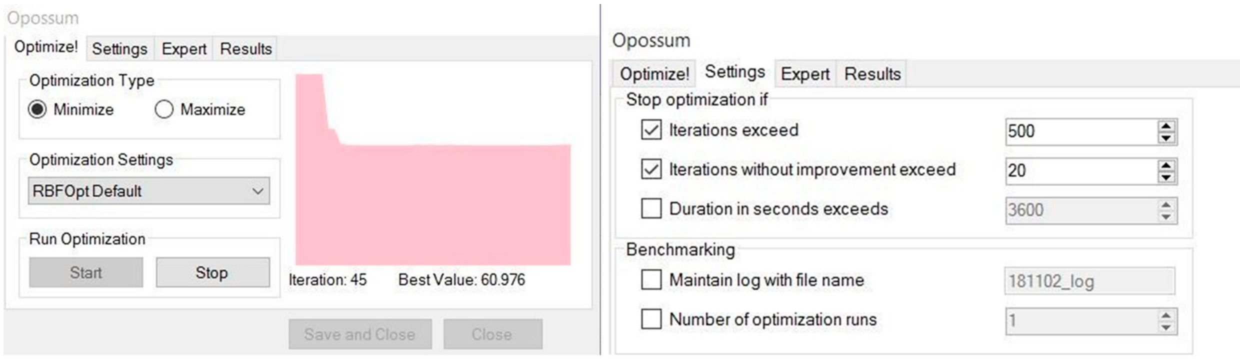



**Figure 10.** Optimization process using Opossum.

- sDA, 81.25%;
- DF, 3.2%.

## Discussion

The experimental application allowed us to test and validate the proposed methodology and the related computational workflow in the design process for climate-resilient building façades. From a comparison with the other design methods for PB building's façade it is possible to identify three innovative aspects related to practice and didactic: the first concerns the definition of two different phases of the digital form-finding process using different optimization's methods that allows to better understand the relation between geometries and performance according to a specific climate zone; the second is about the extension of the benchmark parameters and the multiscalar approach that go beyond the energy consumption and daylighting performance introducing human-centred factors such as view quality, glare control and PMV; the last aspect is the use of an open-source toolkit and a simple and intuitive cluster to guide the form searching process exploring the full space of design possibilities. The various phases analytically described above have shown that it is possible to transfer the design complexity of the digital space, derived from the processes of PB optimization, into the construction of climate resilient façade aimed at reducing the need for primary energy resources, increase energy production from PV surfaces as well as ensuring the satisfaction of indoor comfort conditions by introducing benchmarks such as PMV. The development of the case study has shown that a simple and efficient toolkit, defined as cluster, allows managing the entire design process even to users with non-specialist knowledge or to small-medium design offices while ensuring a high degree of customization of design solutions and a significant reduction in terms of time and investment on the necessary know-how. The parametric cluster allows to create a reliable connection among the professional figures involved in the process. The geometric parameters set as variable are defined to ensure the feasibility of the unitized façade unit and the complexity of the 3D shape was break down through a topology approach that works with line and points in space. To operate within this scenario the use of heuristic and genetic optimization algorithms it is essential to

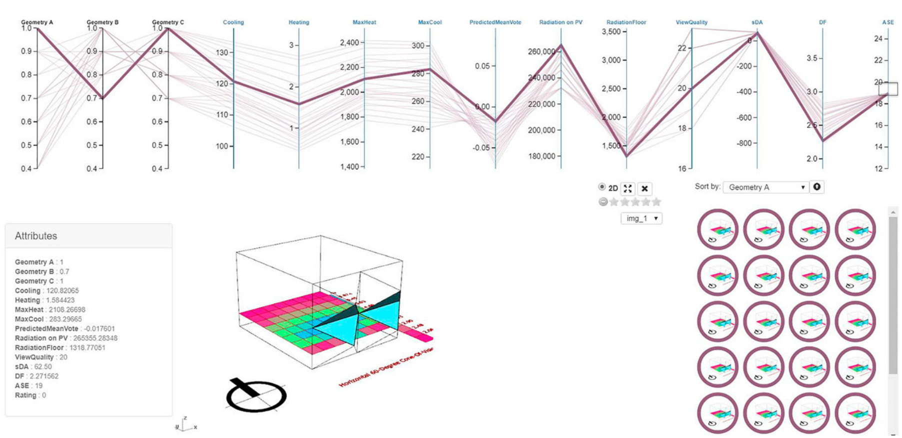
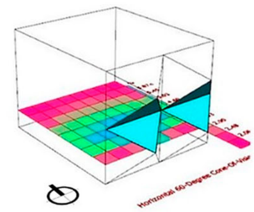


**Figure 11.** Design Explorer: selected design option and performance achievement.



**EARLY-STAGE DESIGN PHASE**

**Daylight Factor DF [%]:** 2,7
**Spatial Daylight Autonomy sDA [%]:** 62,50- LEED V.4 prescription satisfied
**ASE, Annual Sunlight Exposure [%]:** 19 – LEED V.4 prescription satisfied
**Solar Radiation on PV [KWh/m2a]:** 268544
**Solar Radiation on the floor [KWh/m2a]:** 1319
**View Quality [%]:** 20
**PMV, Predicted Mean Vote:** -0,01
Range of accepted COMFORT as NEUTRAL
**Energy Analysis [KWh/m2a] - Cooling:** 121
**Energy Analysis [KWh/m2a] - Heating:** 1,58

**brute force parametric analysis**

**MID-STAGE DESIGN PHASE**

**Daylight Factor DF [%]:** 3,2
**Spatial Daylight Autonomy sDA [%]:** 81,25- LEED V.4 prescription satisfied
**PMV, Predicted Mean Vote:** 0- 0,5
18% people unsatisfied
**Energy Analysis [KWh/m2a] - Cooling: 60,976**

**optimization**

**Figure 12.** Results of CBRF after the two iterations. Angelo Figliola.

ensure that performance does not become merely numerical parameters but a source of formal exploration and process information. The performance parameters, used as input to the design process, can be optimized in relation to a space of design possibilities defined by the designer himself by defining a metadesign described within the cluster. Resilience, as the ability to mediate between internal and external complex systems, is thus expressed through a specific morphological configuration informed by geometric parameters, functional characteristics and building site through the construction of the metadesign. The climate adaptation of the façade system can be tested with the same method applied to design south façade in different cities with different climate conditions. Nevertheless, a series of improvements can be made:

- The design variables can be extended in relation to the computational power;
- The early-stage analysis can be used to define benchmarks according to one of the certification protocols and consequently define better boundary conditions;
- Other design metrics need to be considered such as structural performance, construction cost and cost over the life cycle.
- One of the cons of the methodology is about dimensionality and the time need to compute the design space: more variables the designers introduce, and more time is needed to iterate the different parameters. That can be controlled by reducing the design variables based on design strategy or using a cloud computing to speed up the process and really exploit the all-design space. According to the research work conducted by Theodore Galanos, it is possible to have an idea of the relation between variables and time of computing. Just playing with facades: ORIENTATION (8) x WWR (7) x SILL HEIGHT (2) x GLZ SPECS (3) x WALL SPECS (3) x SHDG LENGTH (3) x SHDG ANGLE (3) x SHDG ORIENTATION (2) = **6,048** design alternatives **(50 hours);**
- Introducing climate parameters: x LOCATION (6) = **36,288** design alternatives **(300 hours);**
- indoor variables: x HVAC (4) = 145,142 design alternatives (1200 hours, 50 days); – massing: x SHAPES (4) = 580,608 design alternatives (4800 hours, 200 days).

## Future developments

The next phase of the research will concern the further implementation of performative parameters, genetic optimization (GO), machine learning and interoperability between different software platforms. Façade is a complex interface that need to fulfil different task related to energy consumption, structural stability and respect of life cycle assessment (LCA) prescriptions. All the performative parameters listed above can be implemented in the parametric code to expand the optioneering process and include all the aspects that characterize building façade. About GO, the improvement consists in the definition of multiple objectives instead of one single fitness criteria to fully explore the correlations between different performative benchmarks. Another aspect to be involved in the research is machine learning (ML) to fully embrace digital developments of our times. ML will allow us to do 'parametric design in generative scales'[6] and the focus can be shifted from goal-driven optimization to exploration and learn from the design space structure itself. Finally, a protocol of interoperability between visual scripting platform and BIM software will be studied to ensure a linear workflow, from conceptual design to building information modelling. If the optioneering process will be carry out in a visual scripting environment such as Gh the BIM platform will be fundamental to fulfil tasks related to coordination (e.g. fast interface checking), data analysis in relation to data structure and COBie compliance, scheduling and fabrication detailing.

## Notes

1. Rutten, D., Grasshopper, version 0.9.0072, http://www.grasshopper.com/.
2. Roudsari, M.S., LadyBug e Honeybee, http://www.ladybug.tools/.
3. The International Living Future Institute has defined the term Biophilia in the BIOPHILIC DESIGN INITIATIVE as follow: 'BIOPHILIC DESIGN IS THE PRACTICE OF CONNECTING PEOPLE AND NATURE WITHIN OUR BUILT ENVIRONMENTS AND COMMUNITIES'.
4. Octopus is a plug-in for Grasshopper for applying evolutionary principles to parametric design and problem solving. It allows the search for many goals at once, producing a range of optimized trade-off solutions between the extremes of each goal.
5. Opossum is a Grasshopper plugin for optimization that uses advanced machine learning techniques to find good solutions with a small number of function evaluations.
6. Theodore Galanos, Regenerative Design in Digital Practice – Conference – Malaga, 19/10/2018.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

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