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PARAMETRIC EXPLORATIONS IN ARCHITECTURE
FROM THE URBAN SCALE TO THE TECHNOLOGICAL DETAIL

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ABSTRACT
The social, environmental and economic changes that characterize the new millennium impose new challenges for the design of urban settlements, buildings and objects. In this context, the parametric architecture can become an innovative design support tool to favour smarter, more resilient, more adaptive, more sustainable projects. This work fits into this general framework and investigates the innovative potential of the parametric design process, applying it to three case studies on an urban, architectural and technological scale, highlighting its potential and limits.

KEYWORDS
parametric architecture, process innovation, production innovations, complexity

In 1973, Webber and Rittel proposed to classify some design problems as ‘wicked problems’, whose solution depends on the resolution of relationships between several contradictory factors, qualitative and quantitatively interdependent (Webber and Rittel, 1973). To solve them, an optimal solution doesn’t exist, but exist sets of better or worse solutions (Pratt and Bosworth, 2011). The complexity of wicked problems is similar to the architecture process complexity, which must aim to find the best solutions and that can only be pursued through an iterative process capable of assessing the interrelation between the various factors and, thus, decode the complexity of the process (Morin, 2008). Complexity that can be addressed, and solved, by promoting process innovations, capable of reviewing the sequences and organizational models, management and control of the process phases, and production innovations, capable of optimizing the various phases of the process through the application of appropriate and innovative functional tools (Losasso, 2018). Innovations that must be associated with an innovative training process for a 4.0 building industry (Sferra, 2018).

In this context, parametric architecture, defined as the description of the architectural organism through a set of logical-mathematical relationships (De Vita, 2009), can become a useful tool to address ‘wicked problems’. The parametric approach, by systematizing the design process in an innovative way, can contribute, in fact, to foster processes of design innovation in order to create responsive and adaptive, sustainable and resilient urban systems and buildings. Examples of the potential of this approach are expressed in the design field by the Singapore Opera House (Lopez Ponce de Leòn, 2016) and in the research field by several recent studies, which have analyzed different aspects, such as the environmental quality of open spaces (Bassolino and Ambrosini, 2016), the relationship with the urban project (Kenning, 2017), the potentiality for the design of buildings (Samuelson et alii, 2016), the potentiality for the design of shielding systems (Abouaiana, Mohamadin and Wagih, 2018; Mahmoud and Elghazi, 2016; Marroquin, Thitisawat and Vermisso, 2013; Wagdy, Mohamed and Hassan, 2014; Sherif, Sabry, Wagdy and Araf, 2015; Eltaweel and Su, 2017; Park and Dave, 2017).

The present work fits into this framework and aims to investigate potentiality and weaknesses of the parametric approach in the Architecture Project. Due to the complexity of the theme, the research is limited to a specific theme: the relationship Architecture-Solar Radiation. The work is structured as follows: introduction and state of the art; objectives, methodology and limits of the research; introduction of case studies and description of the three research scales; discussion of the results; conclusion and description of the potentiality and weaknesses of the parametric approach.

Methodology, objectives and originality – The work investigates the potentialities and weaknesses of the parametric approach in the Architecture Project. To aim this general objective, the research focuses its attention on a specific theme, analyzing the role that parametric approach can have in order to find the best solutions to solve the relationship between Architecture and Solar Radiation. In order to achieve this goal, the research is carried on by analyzing the parametric approach applied to three case studies characterized by different design scale: urban scale, building scale, technological scale. For all the case studies the parametric approach allows to find the best solutions for the identified problem according to the specific design scale. The work proposes an original parametric methodology for the analysis of specific case studies and a critical reading of the results. The research is directed to all construction sector stakeholders, bringing interesting observations ranging from the urban scale to the technological detail. The research presents first methodological results, then specific results for each case study, and finally critical-theoretical results nature. Methodological results describe the algorithms used to solve the faced problem. Specific results for each case study describe the best solutions identified through the parametric approach. Critical-theoretical results show potentiality and weaknesses of parametric approach.

Scope and tools of investigation – The research declines the theme of parametric design with respect to three specific case studies, representative of different design scales. For the urban scale, it was decided to study an area capable of representing the abandoned areas located within built urban contexts. For the architectural scale, it was decided to study the south facade of a tower building, capable of representing vertical shielding systems. For the technological scale, it was decided to study a horizontal roof located above a single-family monoplane house, capable of representing a horizontal solar shading system. For each case study, first will be described the objective liked to the parametric design, then the structure of the algorithm, and finally the solutions optimized by the algorithm. The research was conducted by applying the software Rhinoceros 6.0, using Grasshopper as an interface system and specific plug-ins to manage the individual issues addressed. The generative process of solutions responding to the objectives initially defined for each case study is managed through a multi-objective evolutionary algorithm (Octopus), which allows to produce a wide variety of alternatives and to optimize the results obtained.

Urban case study: objective, algorithm and results – The urban project involves the densification of an abandoned area within a 'typical city', through the creation of new mixed-use volumetries. The objective of this case study is to define an algorithm capable of creating multiple configurations of the same project idea (Fig. 1) and responding to specific design objectives: maximize the radiation on the facade of the new volumes, in order to optimize the energy supply in winter; minimize the radiation on the road, in order to reduce the urban overheating of public spaces; reduce the distances between buildings, in order to have a compact settlement. In order to simplify the algorithm's construction process in this first phase, simple geometries (volumes with a base of 30x30 and a height of 18 metres) were used for the design of the new buildings to be constructed.

The algorithm was developed within the Rhinoceros 6.0 software, using Grasshopper as an interface system and specific plug-ins, such as Elk for context modelling and La-

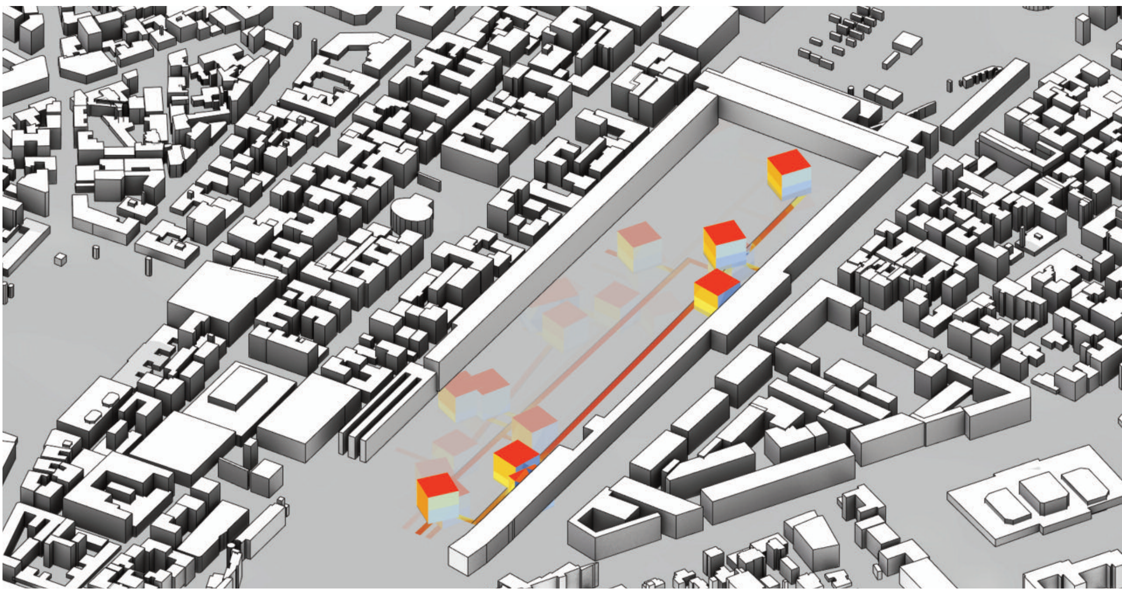


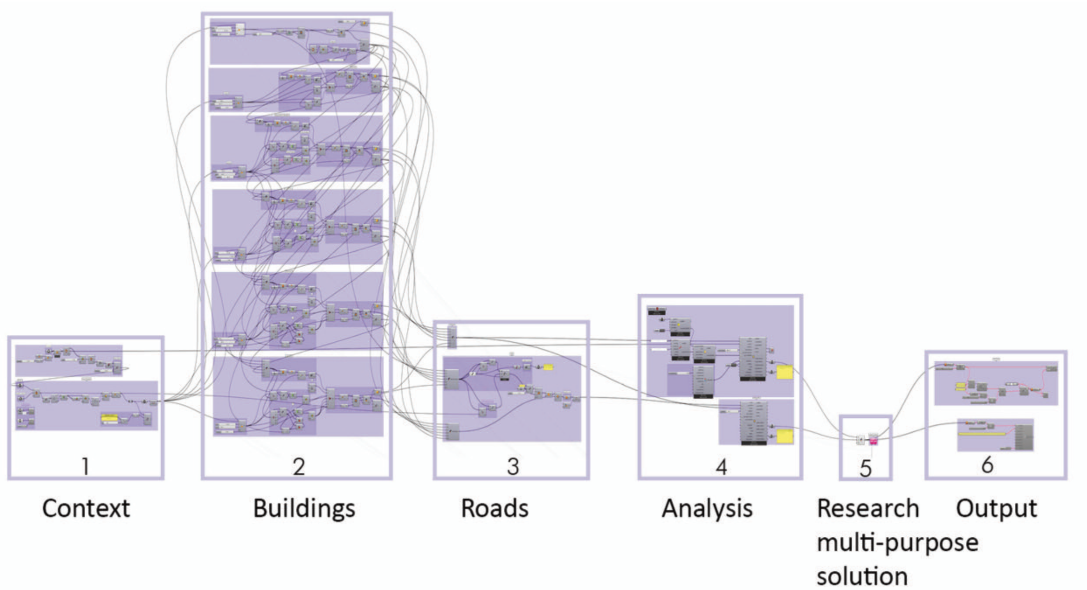
Fig. 1 - Analysis of solar radiation in the facade, overlaid with previous iterations.

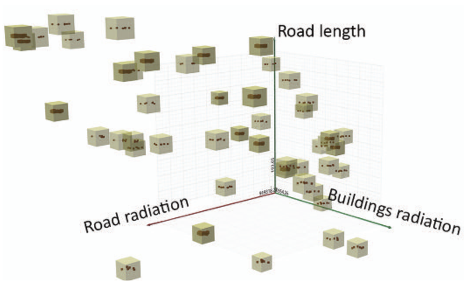
dybug as a tool for environmental analysis. The algorithm is defined by several macro-sections (Fig. 2), characterized by specific scripts created for specific objectives. The first section allows to describe the urban context, while the second section identifies the limit of action of the algorithm, extrapolating from the whole urban context the real project area. The third section allows to simulate several design configurations. In particular, the first part of the script allows to place the new architectural volumes within the project perimeter, one at a time avoiding intersections between existing and new volumes. In every iteration, the buildings will have a different position and angle. The settlement is composed by a main road that connects the volumes and secondary roads for the transverse crossing of the project area. Once the geometry is defined, the second part of the script allows to analyze, for the buildings and for the streets, the solar radiation.

The algorithm goals are to maximize the radiation on the building façade, and to minimize it on the road connection. The parameters used by the algorithm to determine buildings configuration are the coordinates of the volumes position and their angle of rotation. The algorithm works within the intervention area modifying distance between buildings and their rotation, respecting the limitation defined by the Local urban regulation, and optimizing connections length, aiming to minimize it. To achieve this goal, the algorithm is built to find a balanced solution between two discordant but interdependent parameters: maximum radiation; minimum possible distance. The entire generative process is managed by a multi-objective evolutionary algorithm (Octopus), which allows to produce a wide variety of alternatives and to optimize the results, presenting the final solution in a three-dimensional space (one dimension for each optimized parameter-objective) based on coordinates derived from parameters values of each configuration (Fig. 3). The evolutionary algorithm allows to build multiple design scenarios (Fig. 4) and compare them according to the defined parameters, offering to the designer a wide choice of design solutions. The same algorithm allows to identify, among all the solutions, the best solution according to the defined objectives. Analyzing the generated configurations, it's possible to observe how the results are aligned to the expectations, characterized by a distance between buildings that avoids mutual shading.

Architectural case study: objective, algorithm and results – The architectural project consists of a solar shading system, composed of elements of sunshades made with vertical strips, for the southern facade of a tower building. The objective of this case study is to build an algorithm capable of optimizing the inclination of this system in order to optimize the sunshade during the summer and maximize the solar contribution during the winter period. To simplify the algorithm construction process in this first phase, it was decided to keep the vertical slats fixed in size and position and leave their rotation on the vertical axis as a variable parameter.

The algorithm was developed within the Rhinoceros 6.0 software, using Grasshopper as an interface system and specific plug-ins, such as Ladybug, to perform an analysis of incident solar radiation, and Galapagos, for performance optimization. The algorithm





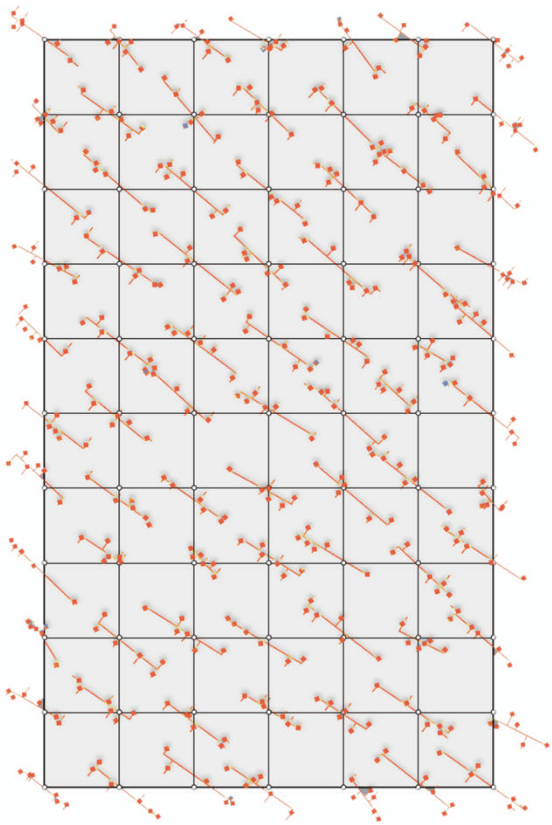


Fig. 2 - Visual representation of the script as a set of nodes and connections.

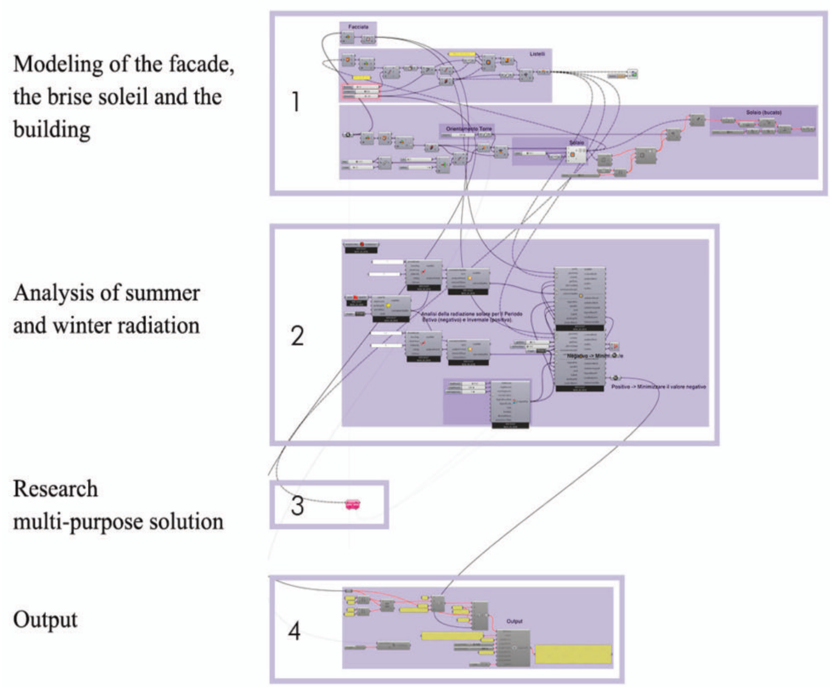
Fig. 3 - Representation of the space of the solutions.

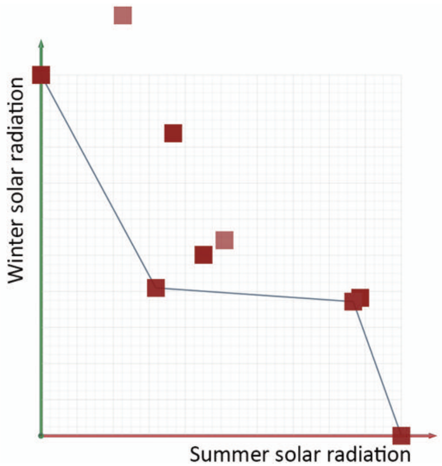
Fig. 4 - Plan view of some calculated solutions.

aims to find the best solution considering two conflicting objectives: to reduce the radiation during the summer period and to maximize the solar contribution during the winter period. The algorithm is composed by several macro-sections (Fig. 5), characterized by specific scripts created for each specific objective. The first section allows to design the geometry of the shadowing elements, which were parameterized starting from the subdivision of the façade basis and extruding at each point of subdivision a vertical element of 20x40 cm, ensuring them freedom to rotate on the Z axis. The second section allows to analyze the solar radiation that affects the façade considering as positive the solar radiation in winter (maximize), negative the solar radiation in summer (minimize). The evolutionary algorithm allows to build multiple design scenarios (Fig. 6) and to compare them. In this case, the obtained solutions are arranged on a Cartesian graph (Fig. 7) with the irradiation values as coordinates. It is interesting to observe how the results form a Pareto Front, a curve on which there are equal solutions in which there is no point that is simultaneously better than another for both objectives of optimization.

Technological case study: objective, algorithm and results – The technological project consists in creating, above a single-family building, a horizontal sunscreen, conceived as a large perforated sheet. The objective of this case study is to build an algorithm capable of optimizing the geometry of this shielding system and its holes, in order to maximize the diffused lighting, maximize the solar contribution on the photovoltaic panels located above the roof of the building, reduce summer radiation. The algorithm was developed within the Rhinoceros 6.0 software, using Grasshopper as an interface system and specific plug-ins to perform a lighting analysis, such as Honeeybee. The algorithm (Fig. 8) has been built in order to find the best solution considering two internal lighting quality criteria set by the LEED Protocol (US system for classifying the energy efficiency of buildings): the Spatial Daylight Autonomy (sDA) that describes how much space receives sufficient lighting (300 lux) for at least 50% of the occupancy time; the Annual Sun Exposure (ASE) that identifies areas that receive too much direct sunlight (1,000 lux) for over 250 useful hours each year. The algorithm is defined by several macro-sections, characterized by specific scripts created for specific objectives. The first section allows to build the geometry of the shading system. In particular, the width of the holes has been linked to the values of a Bezier curve, in order to ensure a progression between the areas with higher and lower density. The holes have been drawn using a Voronoi[1] tessellation on a surface.

The second section, made with Honeeybee and HBZones, allows to construct the holes of the façade. The analysis of the SDA was set on a grid of 0.9x0.9 m at about 0.7 m from the floor on which the lighting study is carried out. This study produces the percentage of the room surface where the lighting is sufficient (300 lux) for 50% of the occupation expected period. The analysis of the SDA was carried out thanks to an original algorithm, compensating the absence of a specific instrument within Grasshopper. The algorithm first calculates the direct lighting on the same SDA analyzed surface, then se-





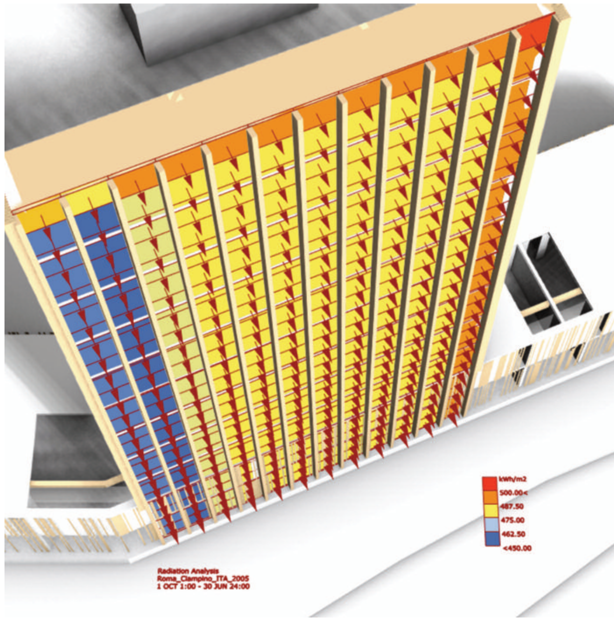
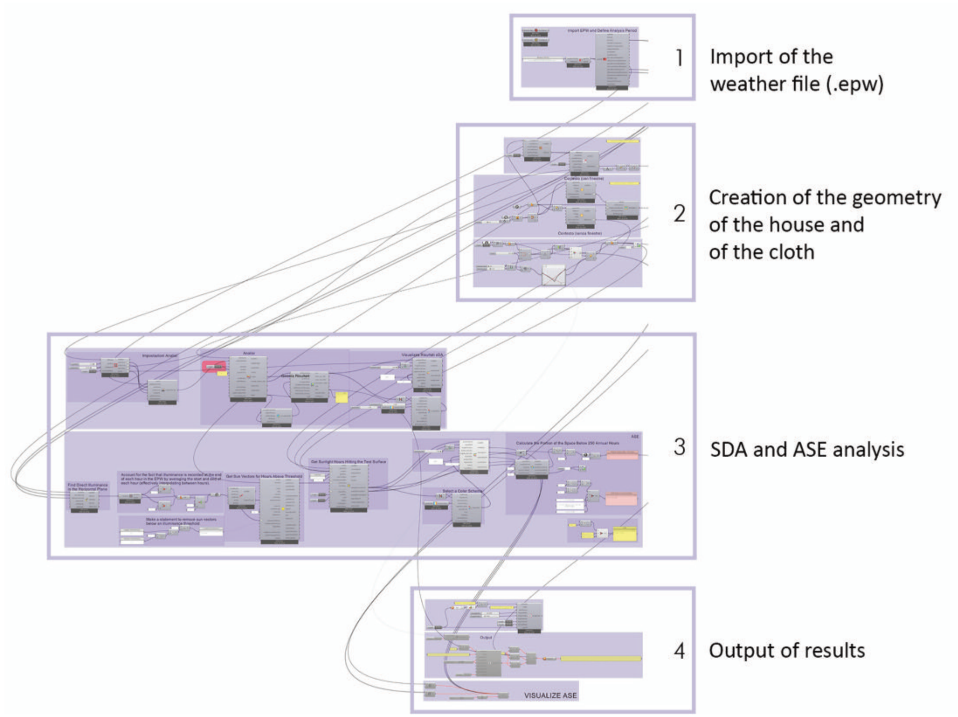


Fig. 5 - Visual representation of the script as a set of nodes and connections.

Fig. 6 - Representation of the space of the solutions.

Fig. 7 - Study of solar radiation on the south elevation.



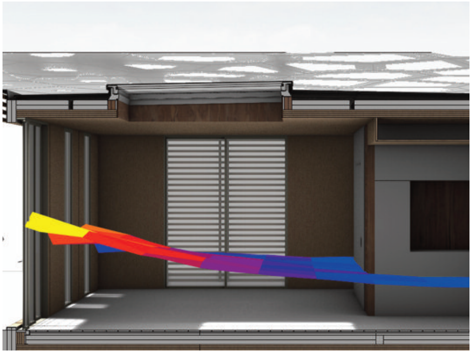


Fig. 8 - Visual representation of the script as a set of nodes and connections.

Fig. 9 - Axonometric view with the ASE values communicated through the relief and color of a mesh.

lects only the solar vectors above the limit of 1000 lux (threshold limit for the analysis to be carried out), finally, for each cell, calculates the number of direct sunlight hours exceeding 1000 lux, highlighting those that exceed 250 hours per year, the limit set by the LEED protocol. To facilitate the calculation operations, the ASE parameter, a parameter that is much more influenced even by small variations of the geometry. has been optimized first, Defined the ASE optimal value, the algorithm finds the solution with SDA value in accordance with the LEED limits.

The obtained solutions are presented as a single optimized numerical value, the values of light intensity per point can be represented by a mesh (Fig. 9) by a colored gradient that can be made three-dimensional by associating the height of the points to the lighting value in order to make it easier to identify critical points within the room. The evolutionary algorithm allows to find the best design solution considering the defined objectives. In particular, the calculations could converge to a single result that allows to obtain an optimal value for both measurements (sDA 86.11%, ASE: 2%).

Discussion – The work presents three examples of parametric design based on case studies characterized by different design scale, from the urban one to technological one. The algorithms, set and used in this research, aim to develop a standardized procedure for the analysis of visual comfort and energy saving, to inform the architect during the design process. In general, the work shows how this innovative methodology can offer interesting possibilities of supporting the design process. The potentiality and weaknesses, identified by the codified approach, are described below, according to the three scales of study.

At urban scale, the proposed algorithm allows to place fixed-sized volumes in a specific lot, maximizing the radiation on building façades, a parameter that would tend to increase the distance between the volumes, and at the same time reducing the length of connection elements (roads), a parameter that would tend to bring the volumes near. Best design results are characterized by medium dense settlements in which the buildings have different rotation angle in order to avoid shadow on the surrounding volumes. To facilitate the construction of the algorithm some limits have been imposed, such as the fixed size and height of the volumes and the analysis of the only parameter of solar radiation. Future developments will also analyze the performance of different settlements and volumes forms, not necessarily regular. The algorithm allows to produce multiple variations of the same design idea and for this reason it is extremely useful to explore multiple configurations, offering a wide range of possibilities to the designer. The designer's final task is to choose which solution to adopt from the optimal ones generated by the algorithm, evaluating objectives and design criteria for the project.

At the architectural scale, the proposed algorithm allows to find the best rotation angle for vertical shadowing elements on a south façade, considering the number and density as fixed parameters. To facilitate the construction of the algorithm some limits have been imposed, such as the size of the elements and their rhythm on the facade. Forthcoming developments will also analyze the performance of different shapes and sizes. The algorithm allows to produce multiple rotation configurations, evaluating the best combination considering the two indicated parameters.

At the technological scale, the proposed algorithm finds the best design configuration for horizontal sunshade system above a house, according to the internal lighting conditions defined by the parameters SDA and ASE (LEED protocol). During the algorithm definition, the description of the geometries that Honeybee can analyze can be the most complicated part, especially if the model is highly detailed. The proposed algorithm can also be applied to study other types of shading systems in order to further improve internal comfort.

Conclusions – The social, environmental and economic changes that characterize the new millennium impose new challenges for the design of urban settlements, buildings and components that must be necessarily designed to be smarter, more resilient, more adaptive, more sustainable. In this context, it's necessary to rethink the entire design process, identifying tools and methodologies capable of facing complexity and producing innovation in design, product and process. This work fits into this framework and investigates the role that new technologies such as analysis software, design and simulation related to digital, parametric, algorithmic and generative design can play. The work presents three examples of the application of evolutionary algorithms, automated parametric processes of construction of design variants capable of responding to precise pre-set objectives. The three case studies represent three different design scales: the urban scale, the building scale, the technological scale. For each case study, an evolutionary algorithm has been set up, capable of responding to precise quality objectives, identified in the maximum radiation of the façade of buildings for the urban scale, in the best energy balance for the southern façade of a tower building, in compliance with the ASE and SDA values for the technological scale. For each case study, the algorithms have allowed to produce multiple solutions and to order them according to their ability to achieve the defined objectives. For the urban case, the algorithm has produced multiple solutions that are comparable in terms of satisfying the objectives, leaving the choice of best the solution to the designer. For the architectural case, the algorithm has produced a set of solutions comparable in terms of performance. For the technological case, the algorithm produced an optimal solution according to the set objectives, offering the designer the best solution.

The work, based on the experimentation of three case studies, shows how the parametric approach, if well set up, can offer multiple possibilities and can be a valid tool to support the design, generating innovative design processes. The three case studies show, in fact, how the designer can, on the one hand, set the algorithm to find the best solution (technological scale), and on the other, set it to reduce the design possibilities, obtaining a set of solutions that respond in an equivalent manner to the pre-set objectives (urban scale and architectural scale). The work also highlights how to move from a 'discrete' to a 'continuous' design process, in which it is potentially possible to analyze all the possible variations of the same design idea, tracing, even visually, how an upstream decision affects the downstream result. The order in which the case studies are presented also suggests the possibility of connecting the three algorithms in order to analyze and optimize the three scales at the same time or in progressive steps for the same project. The work also shows that the parametric design process is not necessarily faster than the 'traditional' one. The resource 'project time', in fact, is distributed differently compared to the traditional project. Traditionally time for design and analysis of different alternatives is consistent, otherwise for parametric design, the most of the time is used in the description phase of the design idea through a complex system of scripts and algorithms, through which becomes very simple and fast to automatically obtain optimal combinations of design alternatives with respect to the predefined objectives.

If the potentialities of the parametric approach are clear, the work has also highlighted some limits. A first limit is related to the complexity of the control of the instrument, which requires specific training. A second limit is given by the complexity of the construction of the algorithm capable of responding to a wide range of objectives. A third limit is the need to have hardware capable of supporting complex calculation operations. Final limit is given by the absence of a tool that allows to identify the weight of each parameter on the result, to be able to concentrate on a smaller number of more influential parameters. These limits will be the subject of next research phases in which we will try to optimize the algorithms in order to optimize the calculation processes and to build algorithms capable of responding to a more complex framework of objectives and with a greater number of variables. In conclusion, the work highlights the potential of parametric design and the use of generative algorithms, underlining how these technologies, capable of generating innovative processes, can certainly be valid tools to support the design, but must be driven by a critical decision-making process that necessarily remains in the hands of the designer.

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NOTE

1) The Voronoi diagram, given a set of points on a plane, associates each point with a region of plane within which are contained all points closer to it than to any other point.

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