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A parametric approach to the bioclimatic design of large scale projects: The case of a student housing complex

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ABSTRACT

Advanced parametric processes enable the exploration of a wide range of design intentions and the generation of alternative project configurations. A novel parametric approach that integrates climatic and site data into a dynamic model of a large building project, to support architectural decisions in early design stages, is presented. Bioclimatic considerations that involve solar radiation analysis and computational fluid dynamic (CFD)-based wind flow simulations have been integrated into the parametric model, in order to explore the interaction of the geometry of the proposed buildings with the solar exposure and the prevailing winds in the area throughout the year. A new student housing complex on the campus of the University of Patras, Greece, was used as a test-bed for experimentation with the developed design algorithms that link local climatic data with the site topography and the basic geometric features of the buildings on the site. The parametric process and the design algorithms were particularly useful in the early design stage, during which various arrangements of the buildings on the site were studied, in order to optimize their environmental performance.

1. Background

The need to include sustainable design strategies among the major design parameters in building projects of all scales will certainly lead to new and in some cases identifiable building morphologies. Bioclimatic building design methods are among the recommended strategies for sustainable design [1]. These methods result in buildings that respond to the climatic conditions of their environment, are able to modify them and thus contribute to resources conservation while maximizing comfort [2].

The experimentation with the effect of environmental parameters on building design is greatly facilitated by the fast developing Computer Aided Design (CAD) tools in architectural research and practice. Advanced CAD systems that integrate computational tools, such as parametric design systems, make possible the interaction between a building's geometric form and physical or other parameters. Within this new field of building design research, *performative architecture* [3] explores new domains of architectural solutions by employing computational tools, which create simulation environments that emulate the physical phenomena that affect architectural form. Such simulation environments enable the integration of environmental parameters and performance requirements into the design process, and make possible the experimentation with sustainable design strategies that may lead to new and interesting building forms. In this regard, by reintroducing viable methods and strategies for climate control already utilized in historical architecture, such as bioclimatic methods, coupled with the fast developing generative and parametric design processes, may address current sustainability needs and eventually shape the future face of our cities.

Suburban sites, as well as university campuses, that are smaller in scale and inherently more open to innovation at all levels than urban centers, can easier serve as a test-bed for experimental approaches, before they are applied to actual urban sites. The design of a new student housing complex on the campus of the University of Patras, Greece, has served as a starting point for experimentation with a proposed design methodology that places emphasis on bioclimatic considerations and utilizes novel computational tools and processes.

The housing complex is to be built on a mountainous site that is easily accessible by public transportation from both the University of Patras educational and research facilities and the city of Patras. The selected site overlooks the impressive Rio–Antirrio Bridge, one of the largest cable-stayed bridges in the world. Additional housing complexes as well as athletic and other recreational facilities will be built on the same site at a later stage. The housing complex will consist of an arrangement of linear building modules placed with their long side facing south; each housing module will comprise studios, small family apartments and communal spaces organized in three levels.

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In addition to the programmatic requirements, the peculiarities of the site and the unique views, the climatic conditions in the area were taken into account in the design process of the proposed student housing complex. The climate of the broader area of the selected site could be characterized as moderate Mediterranean with mild wet winters and warm dry summers. The site also experiences relatively strong winter winds, summer breezes, and intense solar exposure almost all year long due to sparse plant coverage in the area.

A parametric design approach which incorporates site and climatic data, i.e. solar geometry and wind flow parameters was developed and applied to the preliminary design stage of the student housing project, in an effort to explore and optimize its environmental performance. At this early stage, very basic decisions with regard to the building massing, initial geometric configuration and placement on the site are to be made. As wind control and shading devices have a strong effect on the massing and morphology of a building, the earlier in the design process wind and sun data are considered, the more likely to be well integrated in the overall architecture of a project. The intention was to use a method that involves only a limited number of project parameters, such as site geometry, basic building component's form, distances between adjacent buildings etc., so that various alternate design solutions can be explored early on in the design process. Such a form exploration is significantly more difficult at an advanced design development stage, since the project parameters to be considered are usually too many and often conflicting, and numerous complicated simulations have to be performed [4]. The proposed method can be thus applied during the initial design process before other important design decisions, such as those that address constructability, material properties etc., have to be made. Once these parameters are introduced, as the design development progresses, the effect of environmental parameters, such as sun and wind, on the heating and cooling loads would also need to be evaluated. This step, however, is beyond the scope of the developed method.

A description of the approach taken with regard to solar analysis and wind flow simulation and their integration into a novel parametric methodology that involves the development of design algorithms is presented in the following sections.

1.1. Integrating solar data into the design process

The application of bioclimatic design strategies requires an understanding of solar path and sun angles expressed in terms of altitude and azimuth angles. This is critical to determining various design aspects, such as orientation of a building on a given site, selection of the appropriate shading strategies etc. At the same time, the utilization of sun control and shading devices is an important aspect of many energy-efficient building design strategies, as these devices can dramatically reduce a building's peak heat gain and cooling requirements and improve the lighting quality of the building's interiors.

Various commercially available software, which handle solar data, such as sun angles, solar analysis, shading devices dimensioning etc., already exist and focus on data collection, calculation, analysis and simulation. These software provide reports that are either readily available to the user, or that require further development and can be of use during various stages of the design process. For the proposed methodology a solar analysis software was required, which could be implemented early on in the design process and could be interfaced with CAD software, to allow designers to easily explore design alternatives and their performance early on in the design process. The selected software is the ECOTECT [5], which couples an intuitive 3D modeling interface with extensive solar, thermal, lighting, acoustic and cost analysis functions. Furthermore ECOTECT is compatible with the most widely used CAD software and its analysis functions use a wide range of graphing methods.

1.2. Integrating wind data into the design process

The effect of the wind on a compound of various buildings or a single building's features is hard to quantify, visualize, and manipulate. Numerical models based on Computational Fluid Dynamics (CFD) techniques are needed to simulate and visualize wind environments around buildings in urban and suburban areas. Such models require local wind data as initial boundary conditions, or for model validation.

Several research studies on the application of such methods in architecture have already been carried out. CFD-based wind simulations have addressed both indoor and outdoor environments. In most cases of CFD simulation studies for indoor environments, the objective was to study airflow for efficient cross ventilation and for reduced heat gains [6,7]. Several studies have also combined CFD with other physical parameters, such as solar parameters [8].

Other more recent studies pertaining to the use of wind data in the design process have tackled outdoor environments and urban scale projects [9–11]. In the outdoor environment, CFD models, which have already been used for estimating heat gains from air-conditioning condensers and building geometry, have also been utilized for determining the prevailing wind direction and speed at a given site [12]. Relevant studies suggesting city planning strategies that incorporate air paths with regard to the prevailing wind are also encountered in recent literature [13]. An important recent study in this direction, in which CFD results were verified against wind tunnel experiments, has shown that such techniques are particularly effective in predicting wind environments in pedestrian areas [14].

The need to include CFD simulations at the earlier stages of the planning and design processes has already been recognized [15]. However, the same studies, which also focus on the specifics of the available CFD software for architectural applications, its capabilities and limitations including user interface and ability to provide 3D visualizations, suggest that the application of a CFD model is very time consuming. In addition, in most instances reported in literature an analysis of wind data could not be performed before a virtual model of the architectural or urban project, at an early or an advanced stage, had been built.

In this study we developed a multi-parametric model of the design project, in which wind and solar data were integrated. The reason for the inclusion of a CFD model for wind flow simulations was to enhance our understanding of the airflow patterns on the site and their interaction with building core and envelope features at a very early stage in the design process. It should be noted that the effect of air flow towards the reduction of heat gains was beyond the scope of this study; it may be addressed at a following stage.

The CFD software used in this study, named WindSim [16], is designed for wind flow and resource calculations specifically for wind energy projects. The selection was based on the software's relative ease of use, visualization capabilities, exportability of results, and a bibliographic review of validation applications and case studies.

WindSim is based on a mesh system of modeling the terrain and wind velocity field. It uses a 3-D Reynolds Averaged Navier–Stokes (RANS) Equations solver, based on the finite volume method, to resolve the wind conditions in each of the cells in the mesh system [17]. The Reynolds Averaged Navier–Stokes (RANS) Equations are "time averaged" Navier–Stokes equations and are primarily used when modeling turbulent flow, such as wind flow. The derivation of these equations is based on the decomposition of e.g. the wind velocity into the mean component (a time averaged component) and the fluctuating component:

$$u(x,t) = \bar{u}(x) + u'(x,t),$$

where $x = (x, y, z)$ is the positional vector, $\bar{u}$ the time averaged component and u', the fluctuating component. A turbulence model is needed to model the relationship between fluctuating and time averaged components. WindSim uses the k-epsilon (k-ε) two equation turbulence model, common in CFD applications [17]. As opposed to a time step approach to solving flow calculations, this solution starts from the initial boundary conditions specified by the user and arrives at a steady state solution (which reflects a time averaged solution).

The primary scope of WindSim's simulation engine is the assessment of the energy potential of complex wind park layout configurations and thus it is very efficient in the calculation of wind fields over both complex terrain and using complex climatology [18]. Although WindSim is mainly used in the wind energy industry, the ability of the solver to handle complex digital terrain models in association with local meteorological data makes it particularly effective in the study of suburban or rural sites of variable topography. As will be discussed further on, the incorporation of the wind flow simulation data in the parametric model of building projects is to be used for the preliminary study of the airflow over the site and its interaction with one or more buildings.

2. Parametric design methodology

Advanced parametric processes enable the exploration of a wide range of design intentions and the generation of alternative project configurations.

In this study, a novel parametric approach is proposed, which combines climatic and site data with a dynamic model for the study of the environmental performance of building projects. For the development of the model the prevailing wind direction during each season is considered, in addition to the solar position, necessary for estimating self-shading and/or complete exposure configurations. For this reason, the geometric representation of two significant environmental features resulting from the environmental analysis of the given site is obtained, namely a) the critical sun path and b) the prevailing summer and winter wind directions in the area.

Since the topography of the site and the built context of a proposed building are critical in determining the movement of the wind in the area, the development of a 3-D wind grid is needed in order to properly describe the prevailing wind directions. The developed wind grid is associated with both the topography of the site and the geometry of the building /buildings and can be updated each time a new building module is placed on the site.

Hence, the main steps of the developed process that aims to optimize the environmental performance of a building project are the following:

- To conduct climatic analysis, and to develop a digital database of the local climatic features.
- To develop a parametric model that links the climatic analysis databases to the building geometry.
- To develop an algorithm to explore the geometry of the building at hand. The algorithm utilizes the parametric model that links the climatic analysis databases to the building geometry and to the site features.

A flow chart describing the proposed methodology is shown in Fig. 1.

A more detailed description of the steps of the proposed methodology and their application to the housing project on the campus of the University of Patras follows.

2.1. Solar analysis

For the climatic analysis of an area, local meteorological data are needed. The available raw data are processed to produce an hourly typical meteorological year (TMY) file, a format readable by most environmental software packages. This file can be consequently converted and analyzed using the Autodesk Ecotect Analysis software [5]. The Ecotect Analysis Weather Tool can display the prevailing climatic conditions in the area (direct & indirect solar radiation,

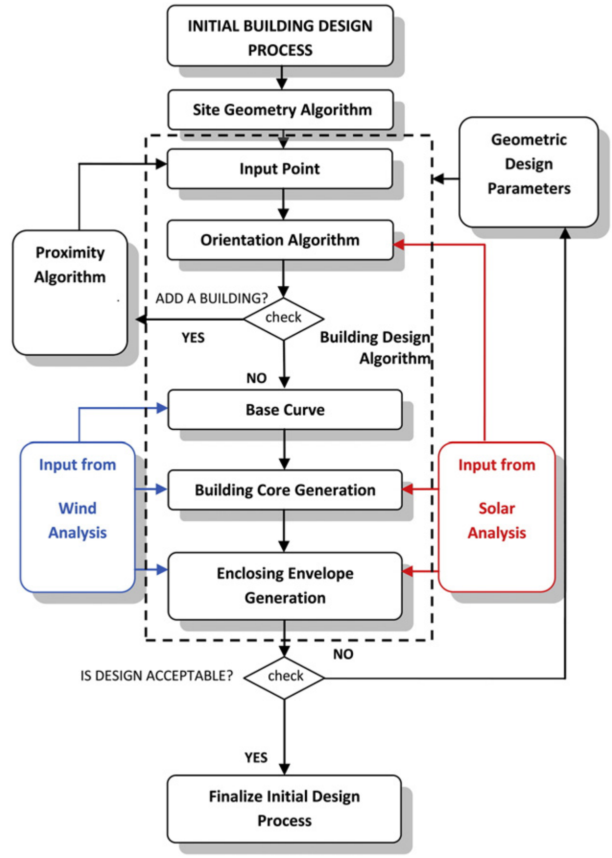

Fig. 1. Flow-chart of the proposed parametric design methodology.

precipitations etc.) in an hourly, weekly and yearly basis and their deviation from the thermal comfort conditions in each instance.

Regarding the University of Patras campus site, the only available data for either the specific location of the housing complex, or the campus area at large were the data collected during the last 10 years by the Laboratory of Atmospheric Physics of the University of Patras, which operates a meteorological station in very close distance to the studied site. Although the time span of the measurements was not significantly large, the close proximity of the meteorological station to the studied area suggested that the collected data were representative of the local climatic conditions of the study site. These data, sampled in 10-minute intervals, were processed to produce an hourly TMY file that was analyzed using the Ecotect Analysis software.

With the assistance of the Ecotect Analysis Weather Tool graphs displaying the prevailing climatic conditions (direct and indirect solar radiation, precipitations etc.) on an hourly, weekly, and yearly basis and their deviation from the thermal comfort conditions in each instance are generated. These deviations determine changes in the thermal strategy throughout the year and lead to a critical sun path that is derived from the combination of the solar paths on the critical dates of thermal strategy change. The critical sun path is incorporated into the parametric model. Relevant graphs for the University of Patras campus area depicted in Figs. 2 and 3.

2.2. Wind data analysis

The analysis of the raw wind data is done with the use of a powerful wind data analysis tool named Windographer [19]. The data time series are processed and visualized in monthly and yearly wind rose diagrams to determine the prevailing winter and summer wind directions on the site. Such diagrams for the University campus are

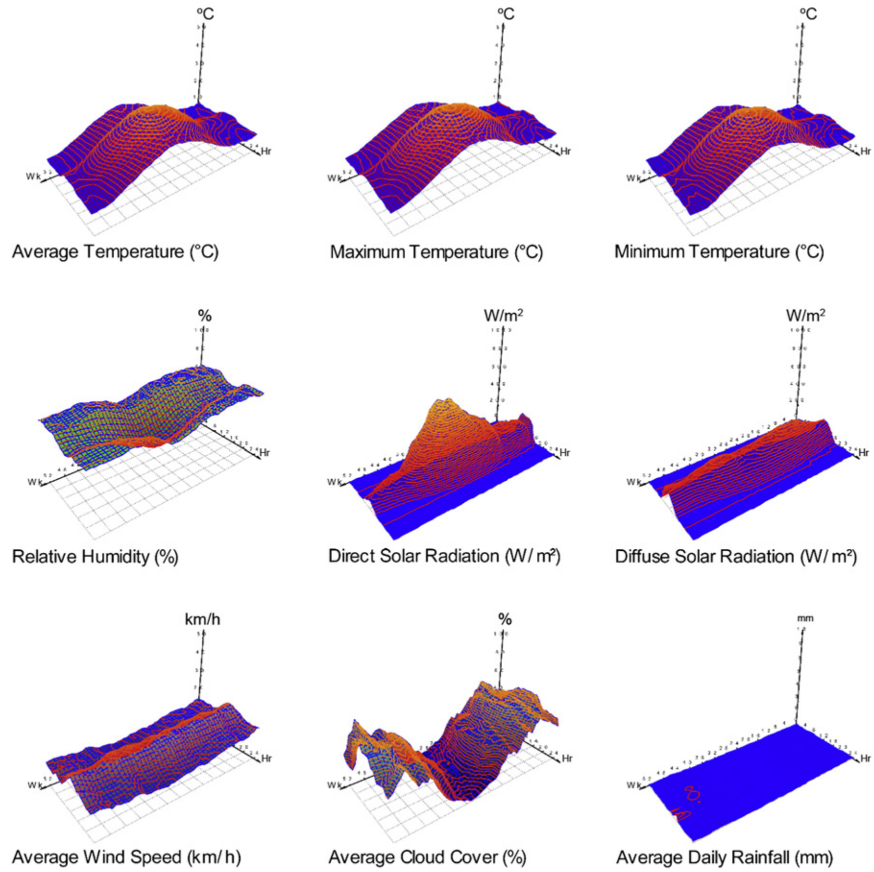

Fig. 2. Prevailing climatic conditions at the University of Patras site—Annual plots per week and hour of day of average, maximum and minimum temperature, relative humidity, direct and diffuse radiation, wind speed, cloud cover and rainfall.

depicted in Fig. 4. Windographer is also used to export the processed wind data in a suitable format in order to be used as a climatology data input file for WindSim's CFD calculations.

The prevailing wind directions are described by wind grids, which are produced by the CFD simulation, as it will be described next. The wind grids are associated with the buildings on the site as they affect the wind's direction between them.

For the University of Patras campus the wind analysis diagram indicates the winter wind directions that need to be avoided, and therefore driven away from the buildings. On the contrary, summer winds could be driven through the building modules to provide for natural cooling. Directing the air through decreasing openings between the buildings can also decrease the wind's temperature due to the Bernoulli effect. To take advantage of this effect, the building modules

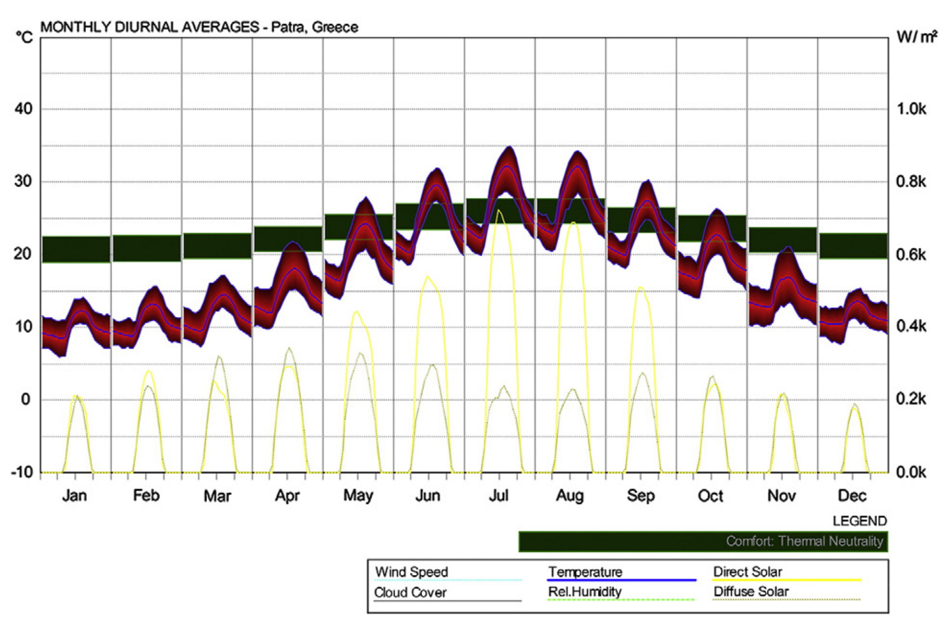

Fig. 3. Prevailing climatic conditions at the University of Patras site—Monthly diurnal averages and comfort (thermal neutral) range.

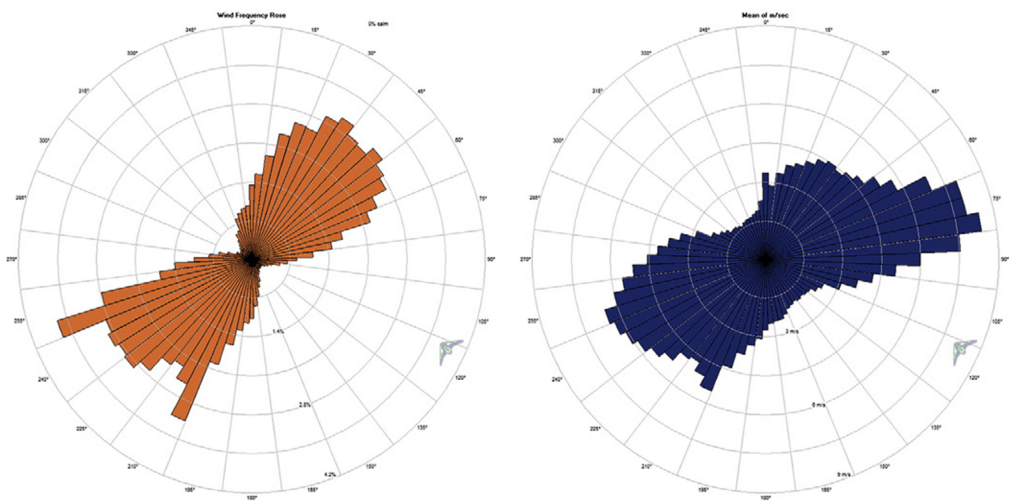

Fig. 4. Wind frequency graphs generated by the meteorological data for the University of Patras Campus—Wind frequency and mean velocity per direction.

were placed in an almost parallel direction to the summer winds while the distance between adjacent buildings was decreased.

2.3. CFD wind flow simulations

In order to determine the prevailing wind direction and intensity with respect to each building on a site, the effect of the site geometry on both the direction and the intensity of the wind has to be assessed. WindSim is used to simulate the wind flow over a specific terrain, based on a three dimensional digital terrain model and the local climatology file produced by the wind data analysis. Specifically, wind flow simulations are conducted for the prevailing wind directions, as defined by the wind data analysis, and a 3D vector field is exported, based on the resulting wind velocity vectors for each grid cell.

This process was followed for the wind flow analysis over the complex terrain of the University of Patras campus. A 3D model of the greater University area was developed (Figs. 5, 6), and wind flow simulations were conducted for the prevailing winter and summer wind directions. The CFD domain used was expanded 100 m above the ground. The boundary condition used was of the ‘fixed pressure’ type and the mesh resolution was 10 m. The resulting wind velocity vectors for each grid cell, taken at an elevation of 5 m above ground, are presented in Fig. 7.

The resulting vector field is imported into the parametric model and associated with the building design algorithm. Specifically, for each possible position of a building on the site, the closest wind vectors for the prevailing summer and winter directions are selected from the wind grid by the algorithm and associated with the building's geometry.

The CFD model can be updated each time a building is generated to reflect the changes in the site's wind flow.

2.4. Shading studies

The study of the solar path during the critical days can be used to determine self-shading and/or complete exposure configurations.

For the housing project at the University of Patras campus several shading studies were done to assess the effect of changes in the building modules' geometry. These studies were used to define the optimal overhang for the building core as well as for the shading louvers.

The extreme deformation positions of a building's core by the algorithmic process can be investigated to assess their effect on the shading parameters. The shape and position of the openings of the buildings can be also studied to ensure maximum solar gain in the winter and minimum solar load in the summer, in relation to the critical sun path and the shading configuration (Fig. 8).

The resulting shading parameters derived from the studies of the thermal strategies for the winter and summer seasons are incorporated into the design algorithms.

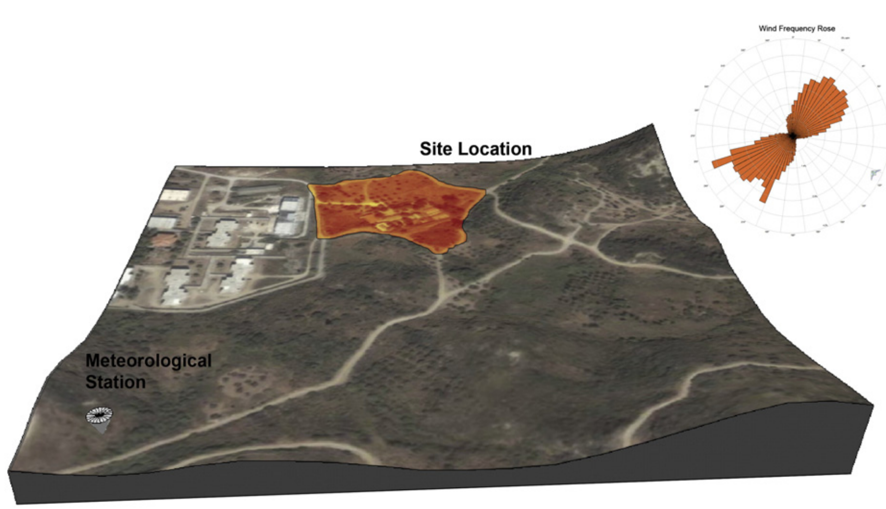

Fig. 5. Grid mesh of the terrain model used in the CFD study for the University of Patras campus with indicated height contours.

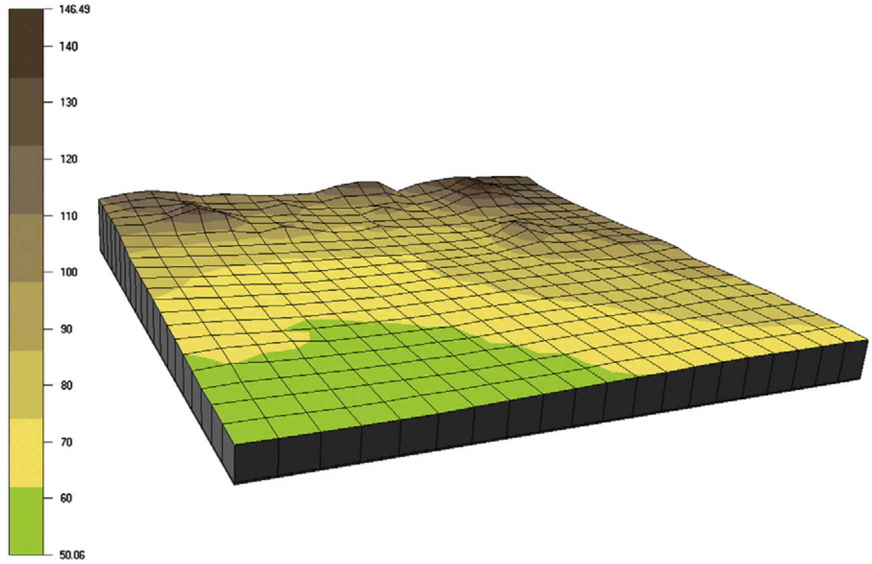

Fig. 6. Digital terrain model of the University of Patras Campus, site location and respective wind frequency rose.

To define the orientation of the buildings for optimal solar access the Ecotect Weather Tool can be used. The under-heated and over-heated periods are defined according to the study of the weather data and in relation to the deviations from the thermal comfort zone.

For the housing complex study case the resulting optimal orientation angle (165 degrees South) was used as a baseline for the configuration of the building modules. Shading from the adjacent hills that would lead to reduced passive heating during the winter was also taken into account through the association of the orientation of the building modules on the site to their distance from the closest hill.

Finally, the study of the critical sun path can also generate the minimum distances between adjacent buildings so that the best solar insolation can be achieved. For the housing project on the University of Patras campus, different adjacency configurations were studied to ensure solar access during the winter for all building modules, and throughout the range of solar movement for the under-heated period.

The orientation and proximity parameters are incorporated into the orientation and proximity algorithms of the parametric model as shown in the application for the University of Patras housing project (Figs. 9, 10).

3. Building design algorithm

The software that has been used for the development of the parametric model and the design algorithms, which associate the building form to the climatic features of the site, is Bentley's Generative Components [20]. As noted by the developer of this software, *parametric design systems, such as Bentley's Generative Components, model a design as a constrained collection of schemata where constraints are useful in expressing specific designer intention*s [21].

The development of the algorithm involved a step by step process. For each step of the algorithmic process, a *feature* type is generated in the Generative Components parametric environment, which is stored and can be used whenever needed in the process. The collection of these features forms the entire building algorithm that automatically generates all components of a building, and is used to experiment with various building configurations on the site. For any given point of origin on the site, the building algorithm generates sequentially the building components, according to the parametric associations of the building to the local climatic features on the site.

The first step of this process was to determine a basic curve which becomes the basis for joining the parametric geometry of the building module to the site geometry and the climatic data. The orientation and the tangent directions of the start and end points of this base curve are associated with the primary climatic features of the site.

For the housing complex study case the orientation of the curve was derived from the optimum orientation in relation to the adjacent hills while the two tangent directions of the curve were derived from the closest vectors of the summer and winter wind grids respectively (Figs. 11, 12).

After the base curve has been placed on site, the building components are built with a hierarchical dependency upon this base curve. These components include the core of the building, and a number of

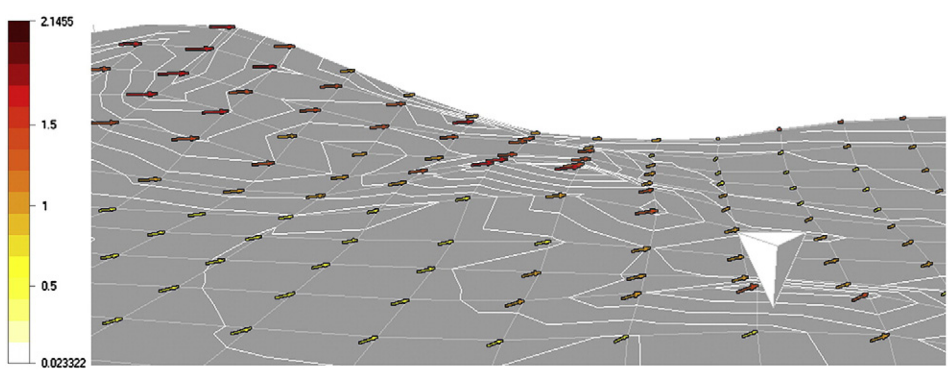

Fig. 7. Wind velocity vector field at 5 m above ground level generated by the CFD simulation for the University of Patras campus.

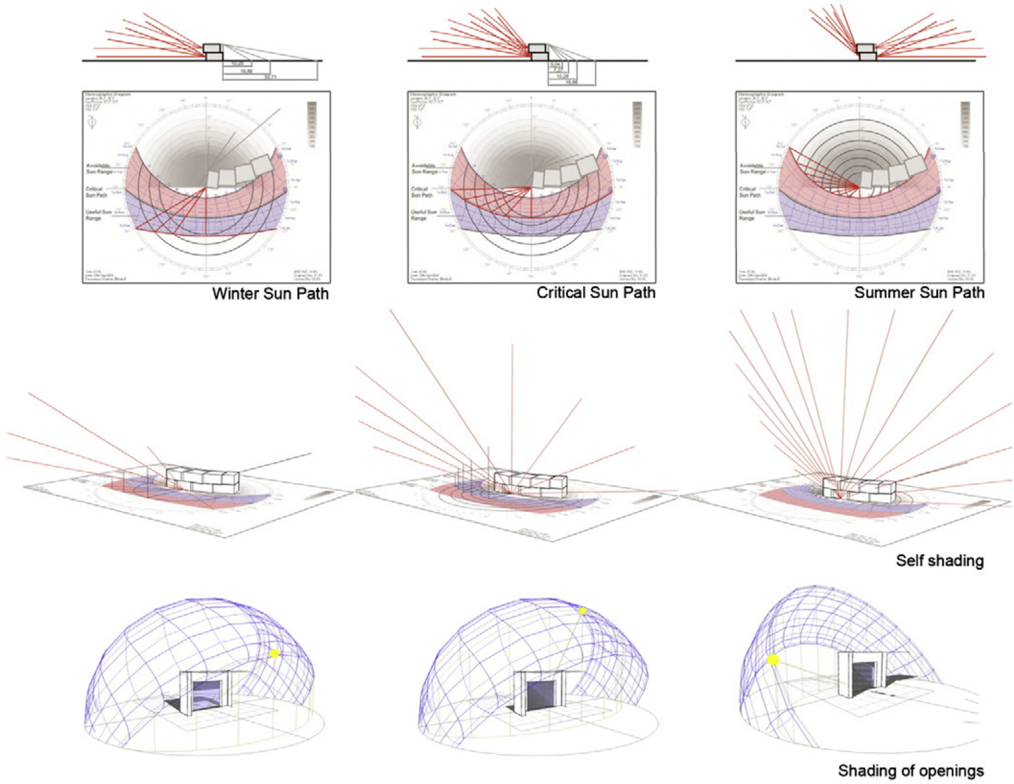

Fig. 8. Self shading study of the basic building geometry, its deformation and its openings for the winter and summer solstice and the critical sun path.

secondary components that form the external envelope of the building used to fine-control weather characteristics in the area. The parametric description of the core of the building is developed in association with the shading parameters and the prevailing wind directions.

For the housing complex at the University of Patras, in an attempt to create a first level of climatic control, the core of the module, which encloses the primary space units, are offset both vertically, to provide self-shading according to the shading parameters, as well as in the horizontal plane and normal to the direction of the prevailing winds to direct the wind away or through the modules during the winter and summer months. At a following stage, an envelope that aims at providing a second layer of control of the climatic features was developed. This envelope was created by a series of curves which were constructed by a set of points which were associated with the climatic features. At first, the set of points was created at an offset distance from the core volumes, which was derived from the shading parameters. This set of points was further offset by a combination of sine functions to create a wave-like enclosing shape that surrounds the core volumes and which is designed to drag the winter wind away and the summer wind through the module's core. The parameters of this offset were also associated with the closest wind vectors on the site (Figs. 13, 14).

To determine the optional orientation of the buildings and the distance between them in the case of more than one buildings on a site, it was necessary to develop additional algorithms. These are:

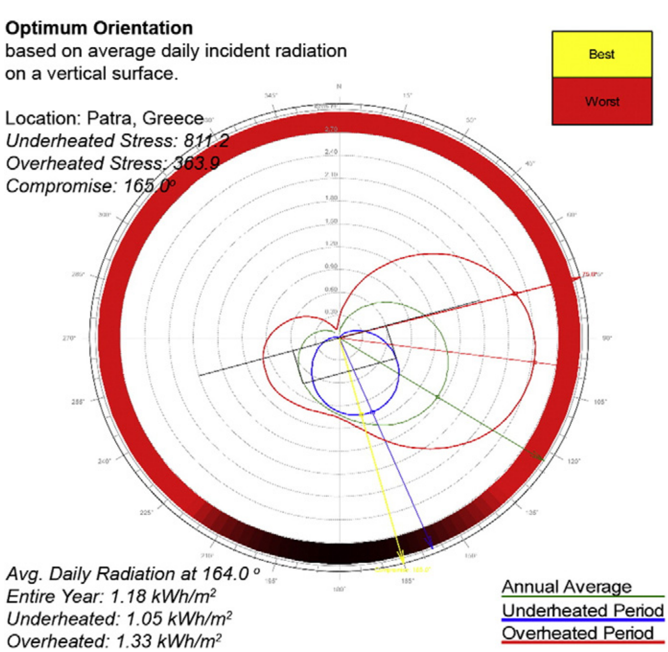

Fig. 9. Optimum orientation based on an annual calculation of solar gains in relation to thermal comfort, generated by the Ecotect Weather Tool.

3.1. Orientation and proximity algorithms

To experiment with different building arrangements on a given site, the *orientation* and *proximity* algorithms have been developed and are linked to the 3D digital model of the entire site. The digital terrain model of the site is imported into the Generative Components' environment and is associated with the climatic features, the winter and summer wind vector fields, which are also imported into the model. As already mentioned, the orientation algorithm links the site topography with the optimal orientation of the buildings on the site to optimize the solar access, while the proximity algorithm generates the minimum distances between adjacent buildings so that the best insolation is achieved. These relationships are mapped as features in the Generative Components' software to facilitate the spatial planning studies on a site.

For the housing complex case, an optimal configuration of several building modules was generated at any point on the site, through the

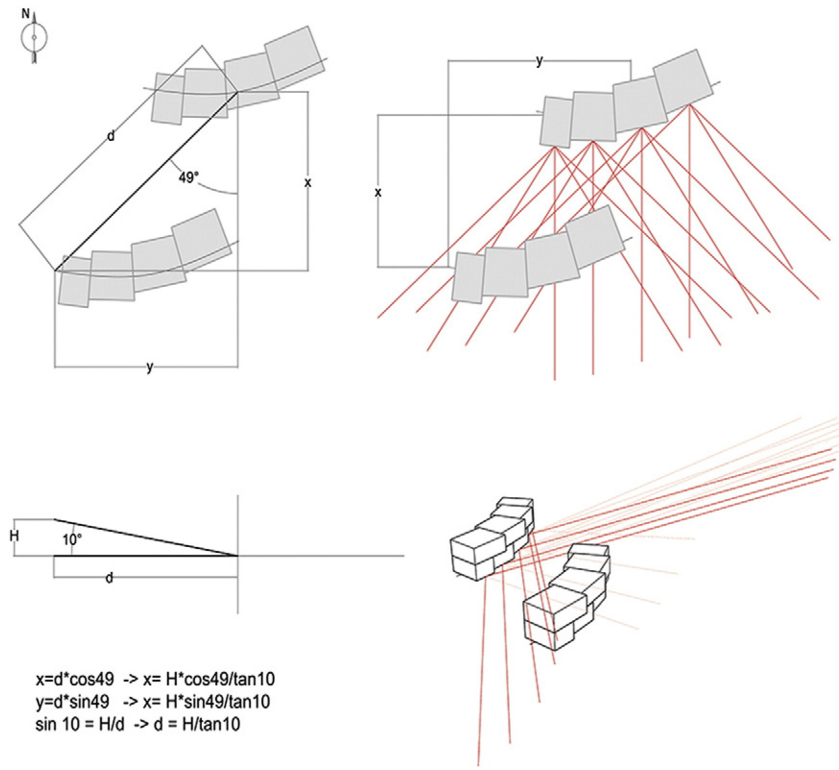

Fig. 10. Building proximity study to ensure maximum solar insolation during the underheated period.

implementation of the developed algorithms, providing an effective overview of the possible configurations of the housing modules on the campus site (Fig. 15).

3.2. Site geometry algorithm

An algorithm that links all the other algorithms and generates the geometry of the buildings on the site has been developed. This algorithm provides geometric relationships such as the exact placement of a building on a given site, the proportions and sizes of the building components and their orientation which satisfies the set environmental performance. Once a second building is introduced, the proximity algorithm is activated to determine optimal distances between the two buildings, while the form of the new building is generated by repeating the process already followed for the first one.

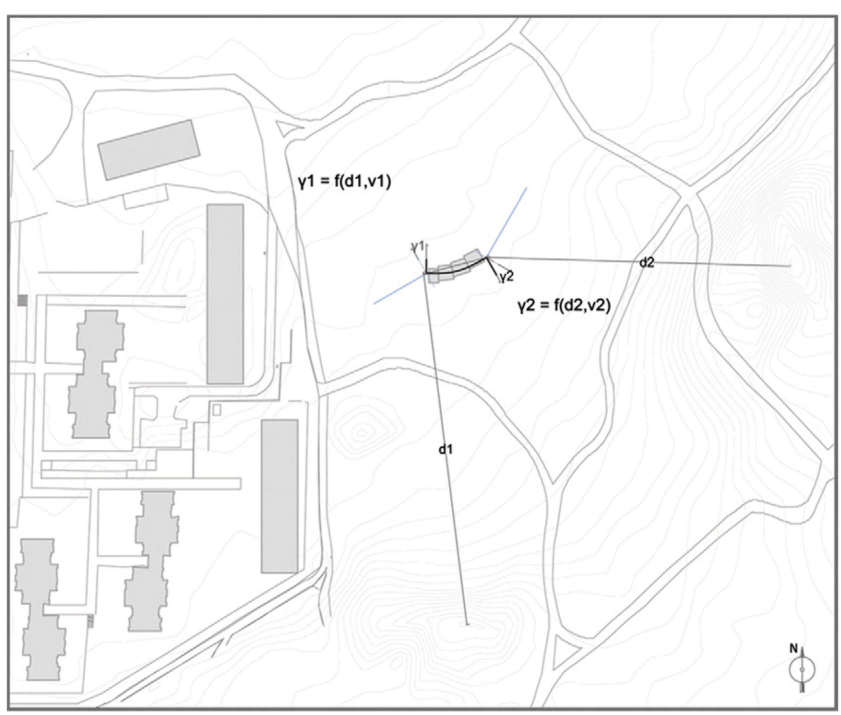

Fig. 11. Association of the summer and winter wind velocity vectors and the adjacent hills' distances with the tangent directions of the base curve.

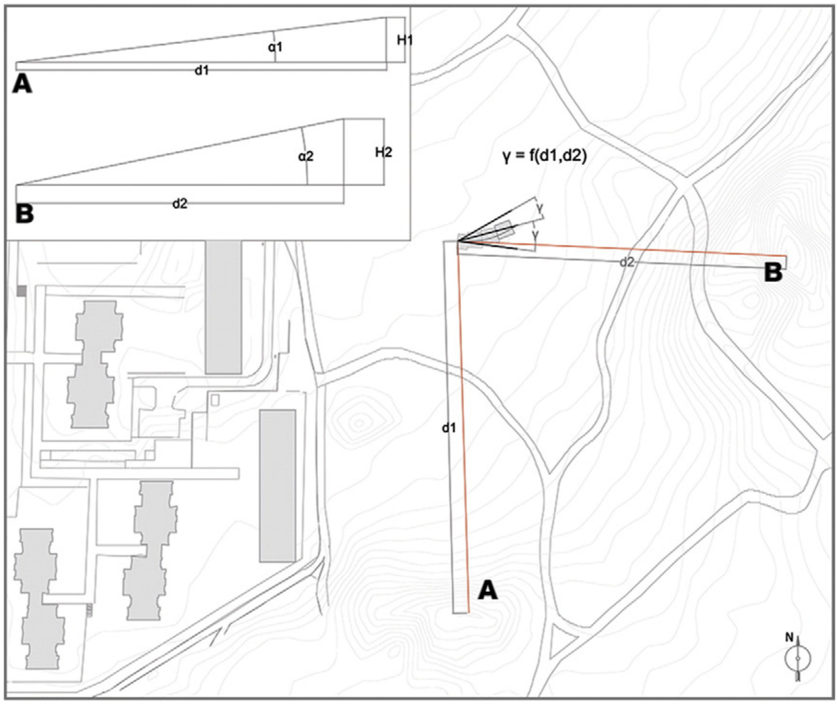

Fig. 12. Association of the optimum orientation with the adjacent hills to ensure maximum insolation.

The sequence of the generation of a building module arrangement on the University of Patras campus site is shown in Fig. 16.

The parametric solutions that are automatically generated by the algorithms allow for experimentation and study of many different design options. The resulting 3D geometries of the solutions can be exported and drafted into a Building Information Modeling (BIM) software (Graphisoft Archicad) in order to produce detailed drawings and 3D visualizations of the building complex.

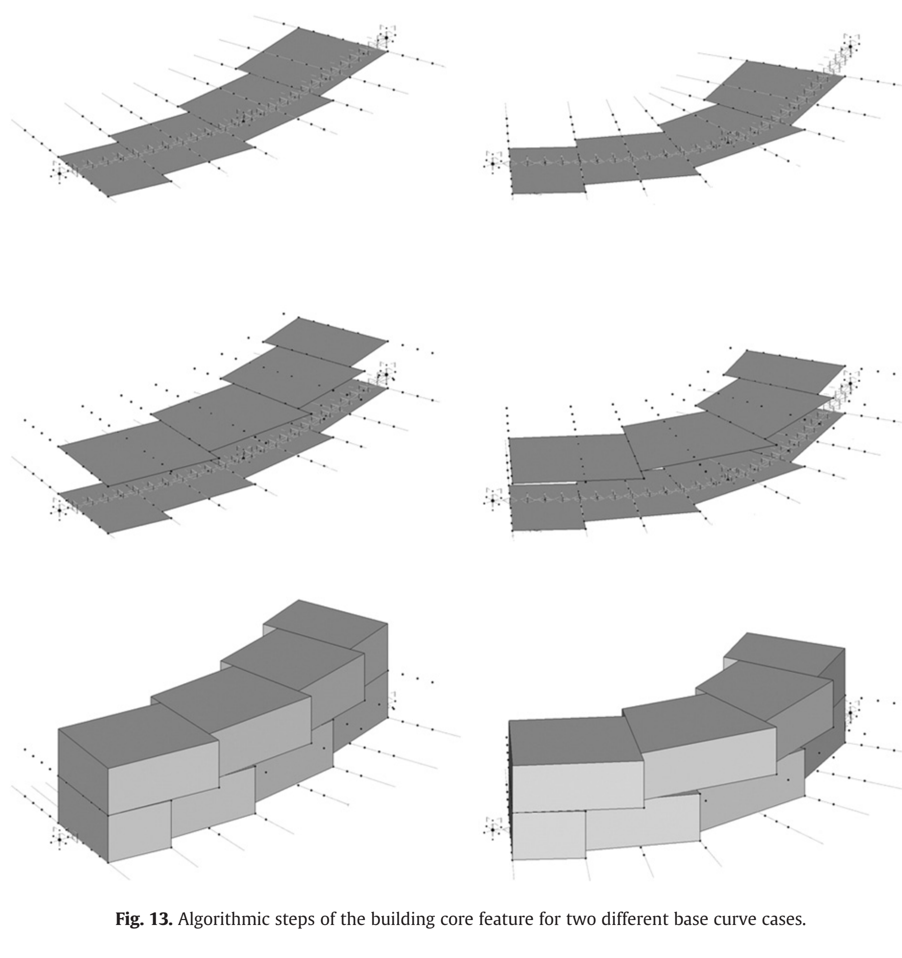

Fig. 13. Algorithmic steps of the building core feature for two different base curve cases.

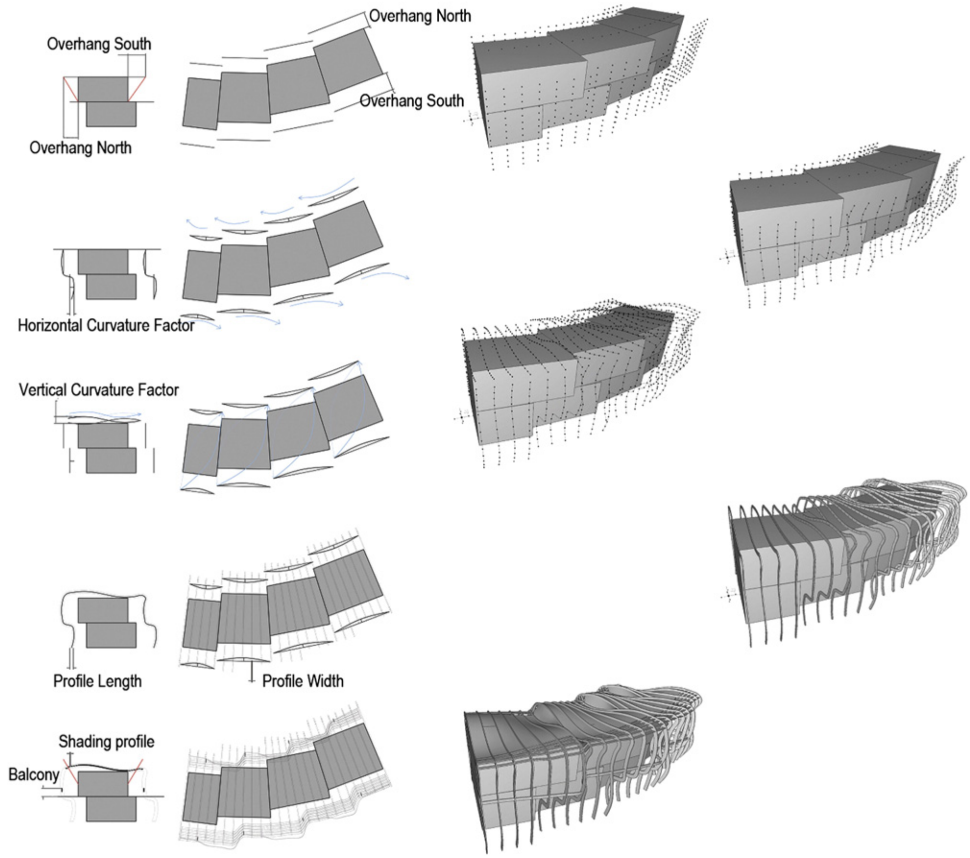

Fig. 14. Algorithmic steps of the enclosing envelope feature.

This process has been followed during the preliminary stages of the design of the student housing complex at the University of Patras (Fig. 17).

Conclusions

A novel methodology that integrates environmental analysis and site data into a powerful parametric design model for large scale building projects is proposed. Sun control and wind simulation algorithms have been incorporated into the parametric model of a building project so that the project can satisfy bioclimatic design criteria.

The proposed methodology allows for experimentation during the initial design stage with various design parameters and various arrangements of buildings on a given site.

This method facilated the bioclimatic design of a new student housing complex at the Campus of the University of Patras, Greece.

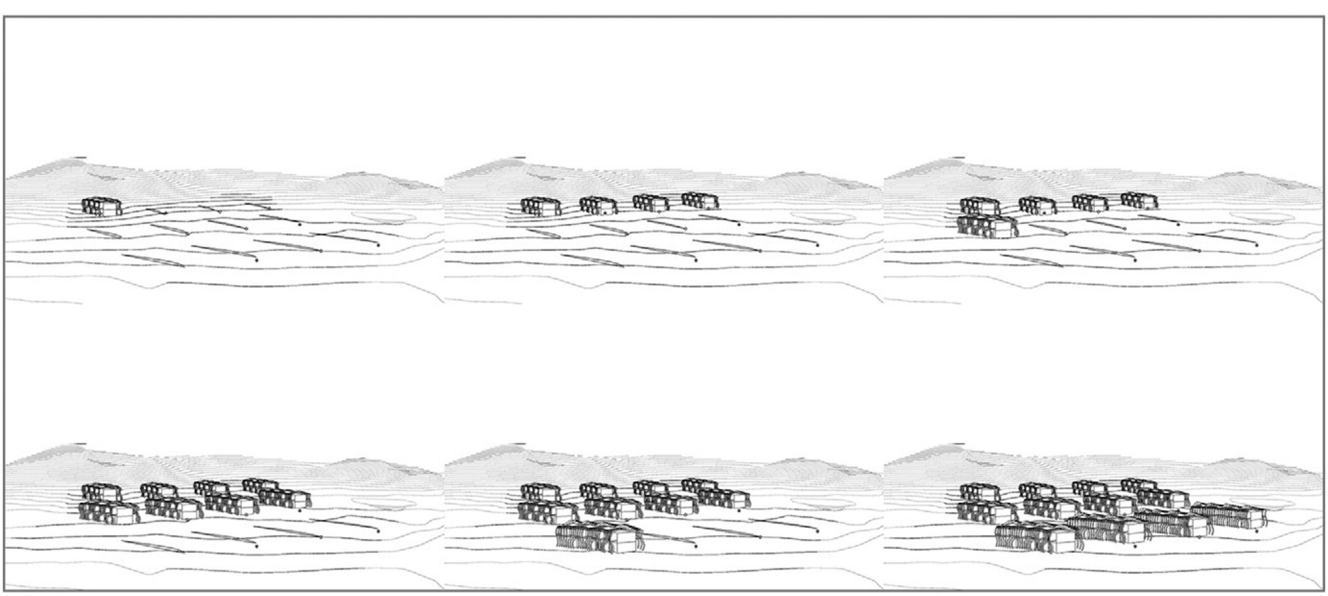

Fig. 15. An arrangement of building modules on the University of Patras site generated hierarchically by the site geometry algorithm.

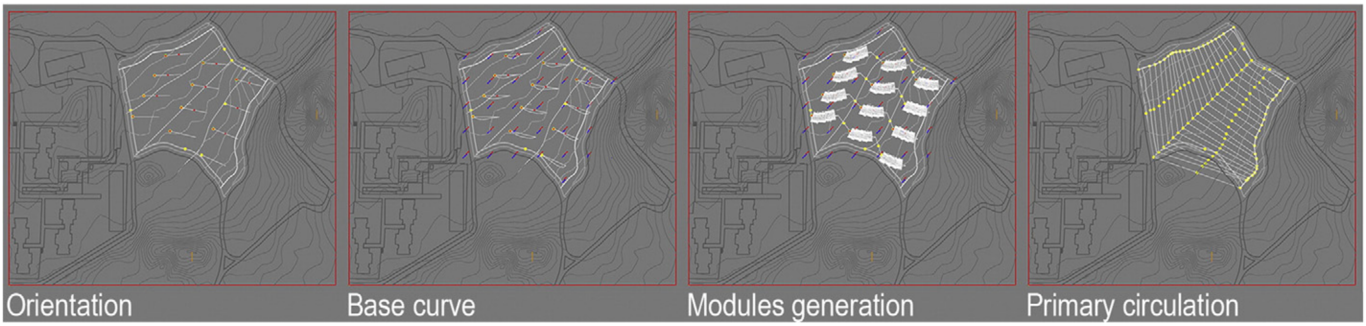

Fig. 16. Sequence of the generation of building modules on the University of Patras campus by the site geometry algorithm.

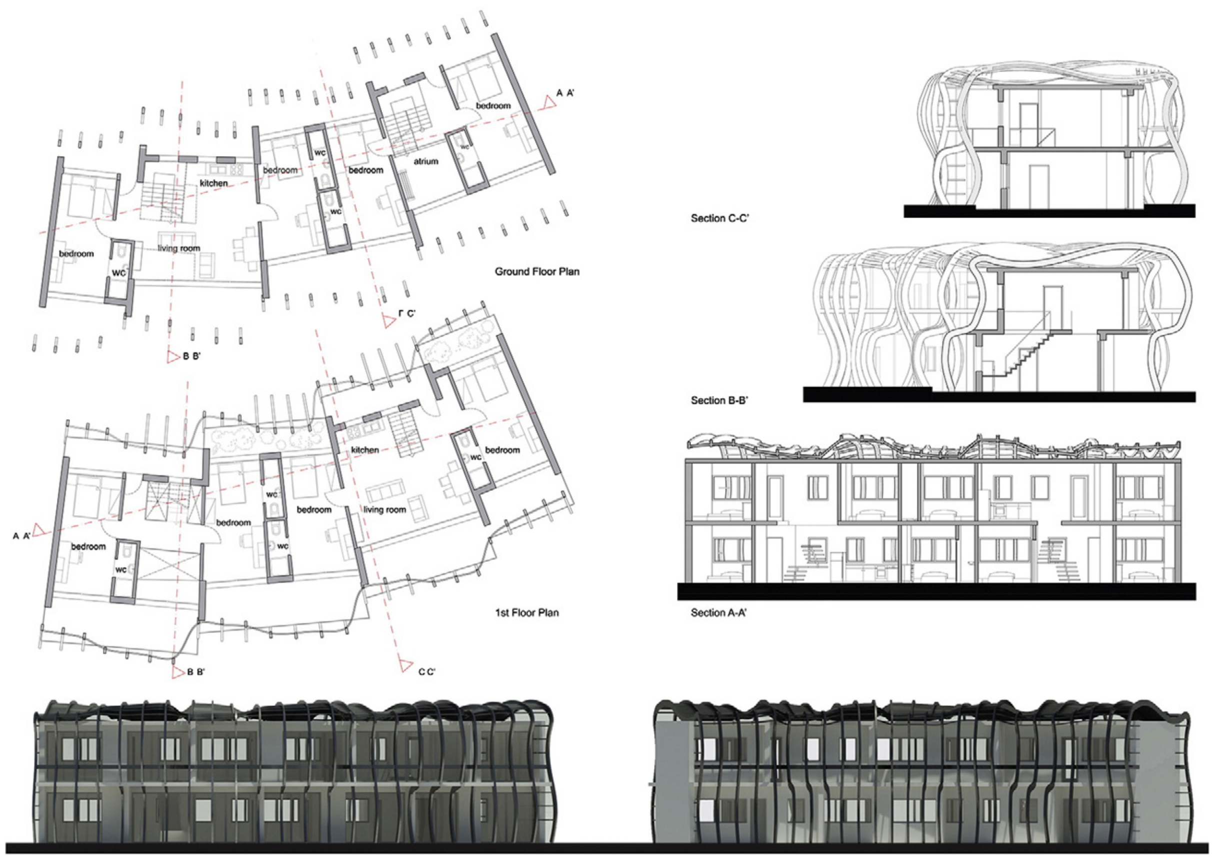

Fig. 17. Early form exploration studies for the student housing complex at the University of Patras—plans and renderings.

The parametric description of the design project enabled control over the range of alternate building configurations and the arrangement of several building modules on the site, highlighting the relation of the geometric form of the building to its environmental behavior. Hence, the process has provided valuable insight in both the performance objectives and the morphological exploration of the problem.

It should be mentioned, however, that, at a later stage, proper validation of the environmental performance of the project will be needed. Once additional parameters are entered into the design process, such as material properties and constructibility, the effect of the environmental parameters on the heating and cooling loads will need to be evaluated.

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