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Parametric Design for Ecological Purposes – Case Studies and Algorithm Examples

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Ecological architecture, which is often confused with low energy architecture, is some kind of energetic compensation for environment which is also giving a new direction for developing of new technologies and architectural solutions. The problem of global human population growth, demand for building materials, electricity, fossil fuels and water - systematically raises environmental standards which have to be met by modern architectural objects - whose construction, operation, maintenance and disposal today consume 60% - 70% of the world's energy. This issue becomes important also on a larger scale which is the urban and spatial planning - creating a vast area of research and the profession for contemporary design thinking. Software engineers develop tools which allow designers design in accordance with the doctrine of ecology and sustainability. At the forefront of this technological race, there are parametric and generative design programs - giving designers extraordinary opportunities to shape the form of buildings based on the assumed ecological parameters. This article will talk about the Bridge Pavilion in Zaragoza (2008), 30 St Mary Axe in London (2004), Al Bahar Towers in Abu Dhabi (2012), City of Culture of Galicia in Santago De Compostela, (2000-2013), Free Railway International Competition in Posen (2015). **Beyond the theoretical consideration of the specifics of the presented objects, the article defines practical algorithmic sequences for generating forms of these objects. Sequences presented in the article were created in the Grasshopper Software and illustrate methods of creating specific buildings, with special attention to their environmental properties.**

KEYWORDS: ecological architecture, digital technologies.

Introduction

Ecological architecture, which is often confused with low energy architecture, is some kind of energetic compensation for environment which is also giving a new direction for developing of new technologies and architectural solutions. The problem of global human population growth, demand for building materials, electricity, fossil fuels and water - systematically raises environmental standards which have to be met by modern architectural objects - whose construction, operation, maintenance and disposal today consume 60% - 70% of the world's energy. This issue becomes important also on a larger scale which is the urban and spatial planning - creating a vast area of research and the profession for contemporary design thinking. Software engineers develop tools which allow designers design in accordance with the doctrine of ecology and sustainability. At the forefront of this technological race, there are parametric and generative design programs - giving designers extraordinary opportunities to shape the form of buildings based on

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the assumed ecological parameters. The article presents key objects representing a concept of parametric design, whose form and technological excellence embody the idea of ecology.

KEYWORDS: parametric design, generative design , ecological design, collaborative design

Methods

The aim of the research was to create a base of parametric algorithms useful in ecological design, performed at the Faculty of Architecture at Poznan University of Technology.Conducted the study proceeded according to the scientific method of research "Research by Design".

The first research stage was selection of proper parametrically designed objects - which form and way of functioning are a manifest of ecological dogmas. Important was also to find a lot of information about this objects - to explain and understand unique ecological characteristics.

Criteria for selection of the objects are:

- environmentally friendly high properties, low energy consumption, LEED certifications
- parametric method of creating forms
- availability of project materials - plans, sections, elevations etc.
- expression of form, unique elevation
- international acclaim and recognition

The second stage of the research was deep analysis of plans and sections, buildings and architectural details. After that author started to work on a parametric algorithms which are imitating real solution from presented objects. At the end an special algorithm was created and used during architectural- urban international competition.

Parametric Design For Ecological Purposes

A broad scope of possibilities and universality of algorithmic design sequences enable both the effective use of environmental energy and efficient management of the energy surplus. Below-presented skyscraper shows how to use solar energy when needed and how to avoid it when arduous.

Al Bahar Towers – captured the energy of the sun

Innovative and dynamic façade of Al Bahar Towers opens and closes depending on the sun's path. Two-layer outside wall protects work stations against intensive insolation, which makes it difficult to maintain comfortable microclimate indoors as the air temperature in the United Arab Emirates often reaches 50° degrees.

Al Bahar Towers are 25-story skyscrapers with the area of 32,000 square meters of office space and 21,000 work stations. Tops of the buildings are enhanced with a deck providing a broad view on the gulf and the urban landscape of the far-off city center. The deck constitutes a kind of an orangery, comprising a number of spatially configured floors intended for thermophytes as well as water tanks and watercourses. Partially protected by a moving sun shade, the deck is a great place of relaxation. It is covered by photovoltaic panels adjusted to the sun rays incidence angle so

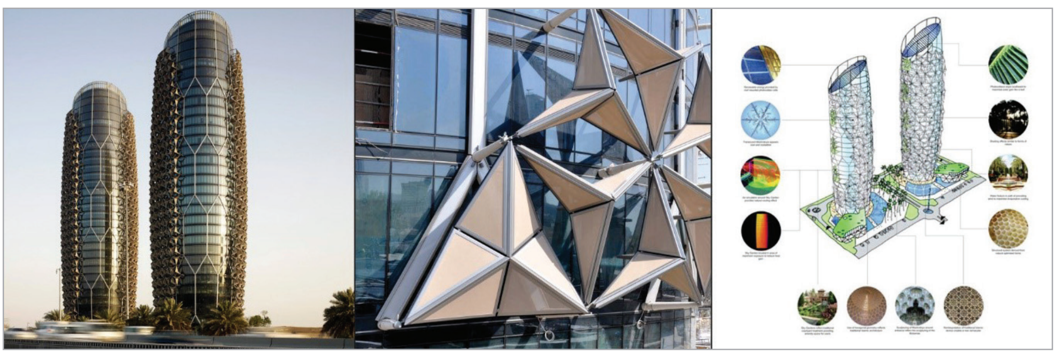

Fig. 1
Al Bahar Towers – form, detail and ecological systems diagram (www.aedas.com)

as to guarantee optimum performance. This small power plant provides over 5 percent of energy necessary for the building's operation, and in particular for water-heating and LEED Silver lighting supply. The consumption of water was reduced owing to the so called grey water cycle consisting in the re-use of water for, among other, flushing toilets. Moreover, on the south of each office floor there is a small garden with a water surface. Here, the floors are open, protected only by membrane sun shades, adjustable to the needs of plants and users. The introduction of pro-environmental solutions helped to reduce annual CO2 emissions by 1,750 tons. The basement consists of two-story car park for 750 vehicles, conditioned by gravity ventilation consisting in the use of air shafts, which are traditional for the region and ensure natural exchange and cooling of air. The shape and style of Al Bahar Towers are based on traditional Arabic architecture. Designers took advantage of the principles of geometry applied in the Islamic architecture since ages. Following the initial arrangements with the ordering party and site exploration, Aedas designers developed the form of towers using parametric digital techniques in order to generate already defined geometry. The design began with two cylindrical towers on a circular plan. A circle provides maximum efficiency in terms of a wall-to-floor relation. The form of the towers was sculpted with regard to wind loads, which can be initially determined by means of a digital program - Computational Fluid Dynamics. Following the analyses, the towers became cylindrical, wider around the intermediate floors and narrower at the base and at the top, resembling cigars. Due to high temperatures dominant in the Persian Gulf, the contractors performed daily thermal analyses. For the purposes of the design it was assumed that the average daily temperature equals approximately 40°C and the annual precipitation totals less than 100 liters/sq.m. In such extreme conditions, unfavorable shape would entail real costs generated by maintenance of the building in the future. Floor plans based on a circle were divided in a way reducing the southern exposure by means of gardens. The external wall of the object constitutes a non-standard self-supporting structure. After defining the geometry, designers could shape the façade to generate its structural grid and a grid mounting glass panels. A steel, hexagonal-patterned lattice on the façade was optimized by digital generative tools. Development of its virtual model made it possible to envisage difficulties associated with the execution of some of the nodes. Owing to parametric modeling techniques and associative geometry, fast and flexible introduction of changes was viable. Just as the form was in the stage of development, designers debated on how to protect the buildings against excessive insolation-triggered heating. The Arabs managed to develop methods, which are still applied today such as open-work wooden screens with a geometrical pattern called mashrabiya. Mashrabiyas were used in desert dwellings as screens or barriers and in urban settlements in windows or on protruding window constructions. Adeas designers developed a new, contemporary version of mashrabiya – moving spatial structure mounted to the façade. It consists of different components, which open and close like umbrellas, depending on the sun's path. Each component has its own activator, i.e. a mechanical device, which based on a command signal generates an input signal putting the object in motion. These miniature devices are placed in rods fixing components to the façade. It was also necessary to provide for the possibility of "manual" control of the construction by users – opening or tilting an individual screen, independently of the globally controlled system. The method of generating the simplified model of an office block exterior shell is demonstrated by the below drawing:

The algorithm starts with determination of a grid of hexagons and designation of angular points and center points (Fig.2). The next stage involves drawing two circles for each hexagon – the first one is drawn on the hexagon and the second, smaller one is placed inside it. On each circle the algorithm places three points at equal distances from each other – next stage envisages connecting the points into planes but before that it is necessary to program the attractor's function (Fig.3). The attractor consists in the creation of codependency between the equation values – in this particular case being the distance of individual circle centers from a drawn parabola. The pa-

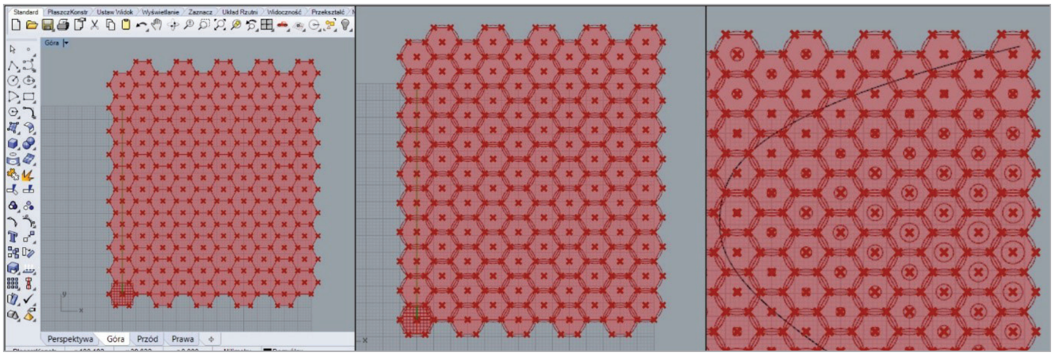

Fig. 2
Mashrabiya algorythm – part I (developed by M. Giedrowicz)

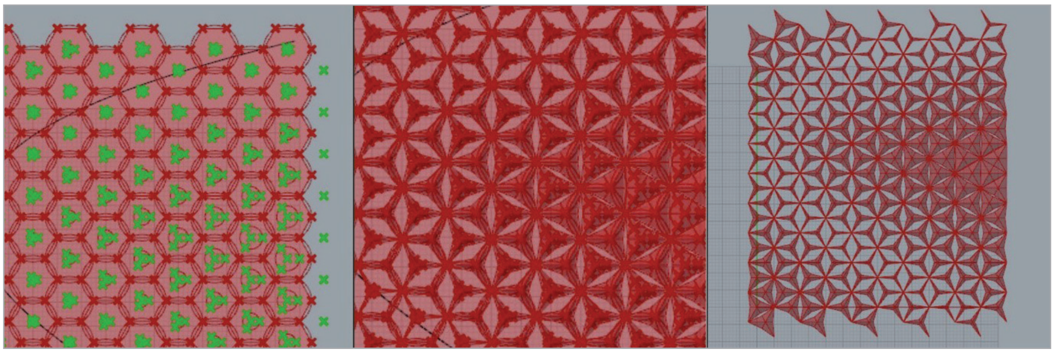

Fig. 3
Mashrabiya algorythm – part II (developed by M. Giedrowicz)

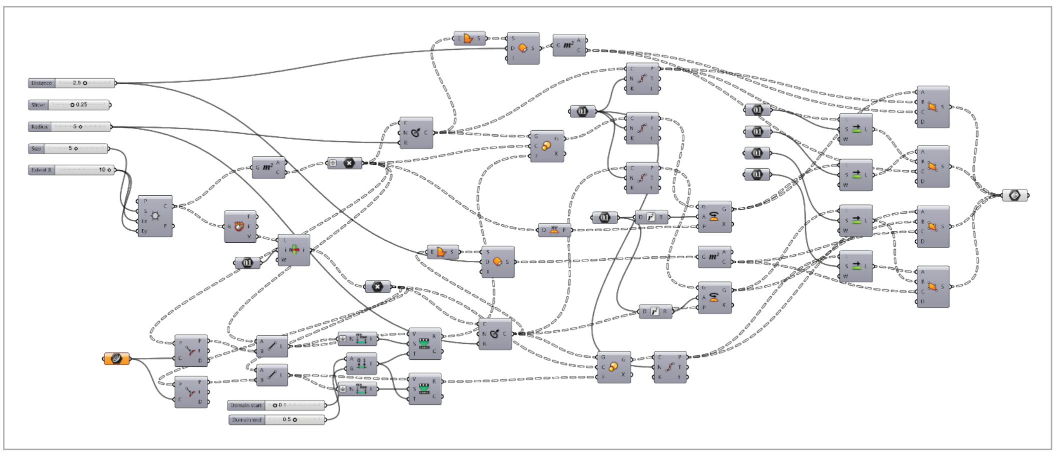

Fig. 4
Mashrabiya algorythm – all – screen shot from Grasshopper (developed by M. Giedrowicz)

rabola represents an insolated part of the building façade. Therefore, the procedure consists in the establishment of relations between the distance of each inner circle center and a drawn parabola, and then transposing the distance to the value of a given circle. This operation gives rise to the principle „the closer the smaller, the farther the bigger". Inner circles are subject to scaling against the proximity of the source of light, whereas connecting points previously fixed on circles creates the mashrabiya plane.

Modules cover approx. 75% of the building façade, leaving the northern part uncovered. The part to be covered was determined based on digital simulations of the path of sun rays incidence angle. The towers consist of almost 2100 modules of unfolding „umbrellas", each measuring approx. 4x6 meters and weighing 600 kilos. Each module in controlled independently by the central system. Dynamic mashrabiya reduced electricity demand of air-conditioning equipment by 20 percent. It also reduced the interior solar gain by 50%, improving comfort of employees. Designers are convinced that the towers will receive a silver LEED certificate. This is the first time in the history of architecture that a moving skin has been constructed, and already on such a grand scale. Dynamic mashrabiya constitutes a completely performative structure, which operates in a defined way while performing a specific task. It was created in response to environmental conditions and quality of materials it was constructed of. Moreover, two Al Bahar Towers are a great example of how to adapt latest technologies to a cultural context. Traditional Arabic architecture has helped people to survive in extreme weather conditions through ages. Observations of the sun and air movement allowed for the development of climate modulation systems used in residential interiors, commonly used souks and mosques. The analysis of these solutions leads to the development of new solutions based on simple ideas. Abu Dhabi is moving towards cultural integration by means of sustainable development.

Bridge Pavilion in Zaragoza - the use of local wind

The Bridge Pavilion designed by Zaha Hadid Architects and Ove Arup Engineers at the EXPO'08 in Zaragoza constitutes an excellent example of the energy consumption reduction caused by the use of forces of nature."We designed an envelope for the Bridge Pavilion that encloses the exhibition spaces yet can be permeated by natural elements. The internal micro-environment varies with the external climate and requires minimal cooling or heating infrastructure" says Hadid. " In particular, we considered the local Cierzo wind when designing the Bridge Pavilion's skin. A variety of openings convey and direct air into the building's interior – cooling visitors in the heat of the summer". The form of the bridge was created by digital generative tools that mimic the natural shaping processes Digital surfaces have been investigated when designing the Pavilion's exterior skin. Shark scales were fascinating paradigms both for their visual appearance and for their performance. Their pattern can easily wrap around complex curvatures with a simple system of rectilinear ridges. For the Bridge Pavilion, this proves to be functional, visually appealing and economical. The design capitalizes on the ambiguous nature of the original brief, maintaining both the aspect of a traditional bridge (open to the environment with the steel structure being the dominant visual element) and that of a more conventional exhibition pavilion where climate and light permeability are controlled. This bridge, with a length of 275 m, was also a pavilion of an Austrian company Rieder, producing construction concrete Fiber-C. On the surface of 6,415 m², the designers created an interactive exhibition space with an area of 3,915 m² and 2,500 m² for a sidewalk designed to cross the river in the shortest possible way. This bridge was in fact the main entrance to the EXPO'08, providing capacity for pedestrian traffic up to 10 thousand. persons/hour. Two pods housing exhibitions are enclosed with minimal acclimatization. The remaining two pods are clad by a single-layer skin which leaves the grid structure visible from the inside. These two pods include small triangular apertures, with larger openings located at lower levels, allowing for the greatest degree of visual contact with the river and the Expo.

City Culture of Galicia – excellent typing in location and local building materials

The City of Culture of Galicia in Santiago de Compostela is a unique building with a unique task. Based on an international competition of architecture announced in 1999 by the Parliament of Gali-

Fig. 6

Bridge Pavilion in Zaragoza – form and construction (wikipedia.org) cia, from global participants the Jury chose a sole winner – Peter Eisenman. The choice was justified by the uniqueness of his design and exceptional blending of the object with its surroundings – a picturesque hill stretching over the medieval city center, as well as the implementation of ecological and sustainable development objectives. The object gave rise to many expectations. The Capital of Galicia - the least economically developed region of Spain, has struggled with a high level of unemployment and limited inflows to municipal treasury. The situation was expected to reverse owing to the famous „Bilbao effect" – i.e. fast and effective development of the city as a result of the construction of an architecture icon, which was supposed to promote the city on a global scale, attract tourists, investors and foreign capital, soon returning the high cost of the investment.

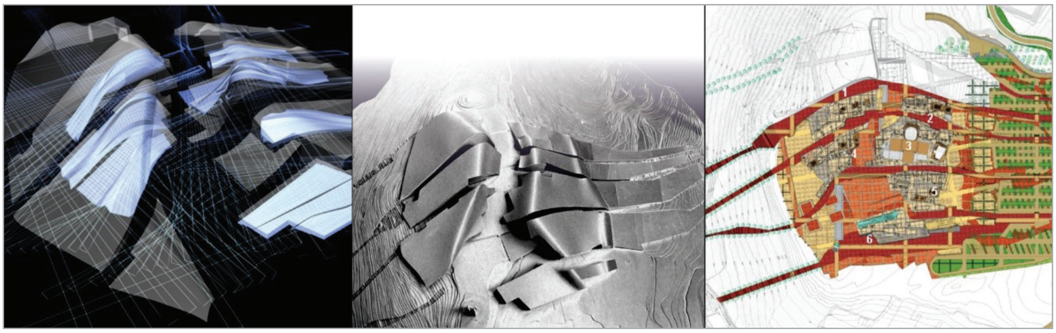

Fig. 7

City Culture of Galicia – form which is a result of solid substraction of Mound Gaias and plan of mediaval city Santiago de Compostela (www.archinect.com)

The construction is challenging and expensive asthe design of the buildings involves high degree contours, meant to make the buildings look like rolling hills. Nearly every window of the thousands that are part of the external façade has its own custom shape. Eisenman began with the outline and street plan of the medieval city of Santiago de Compostela based on the shape and ridges of a scallop, the emblem for the shrine. He then placed a similar street pattern on the top of Mount Gaiás to separate the original eight buildings and let the site's topography mold this medieval pattern. Then he overlaid the plan with a Cartesian grid while finally digitally warping the result with a computer-modeling wire frame to generate, as he says, "dimension and direction". Shotcrete was applied in the implementation of curvilinear forms of the City of Culture of Galica, according to Peter Eisenman's design. The construction is challenging and expensive as the design of the buildings involves high degree contours, meant to make the buildings look like rolling hills. The challenge was to create curved roofs with pitches ranging from 30 to 70 degrees. The task was to prepare the right concrete mixture, the composition of which would prevent the concrete from running off the roof of a steep plane. The mixture was tested on the model of the steel structure of the roof. A new formula was developed, which had never been used before. However, the first tests on the model did not produce the expected results – the mixture, instead of solidifying on a steel reinforcement, ran off the structure completely. The contractor was forced to treat the mixture directly on the site. As a result, the application of the concrete was performed by spraying, applying subsequent layers of concrete, until the desired thickness was obtained. At the next stage of work, the concrete layer of the roof was covered with thermal and water insulation. The conceptual design chosen in the competition assumed covering the roof with grass according to the green roof technology. However, calculation of costs associated with maintenance of the roof with such a vast area shed new light on a final form of the object. Going back to the initial idea related to the construction of the building, which will harmoniously blend with the surroundings, the architect decided to replace grass with local stone. A quarry providing the stone is located only few kilometers from the city. Therefore, the cost of stone winning, processing and transport was significantly reduced and the building was enriched with traditional, local material.

Cut into 60 cm2 blocks of stone (with blocks at the edges specially trimmed), it was mounted on a steel armature of curved box beams (or steel girders in the archive) plus steel cross-bracing. The

Fig. 8

Local stone on the roof (www.wikipedia.org)

ventilated chunky roof surges over an under layer of concrete deck, waterproofing, and protective insulation. The interstitial space between the two layers also houses mechanical equipment. The side walls of mortarless quartzite panels with stainless steel reveal stand out from the buildings like a rainscreen against galvanized aluminum.

St Mary Axe – double skin and gaps in floors

An interesting example of an efficient use of generative design technology for pro-environmental purposes is 30 St Mary Axe in London – better known as Gherkin. The 42-story office tower, which became a coherent part of the city's skyline as one of the most recognizable London skyscrapers. The energy saving technologies applied in the building reduced energy consumption by half - comparing to similar skyscrapers of the same height. Gaps in each story create six shafts constituting a natural ventilation system of the building – taking the form of a spiral moving up the building. An external façade forms a double skin of the building, which is filled with air and acts as a ventilation system and thermal insulator.

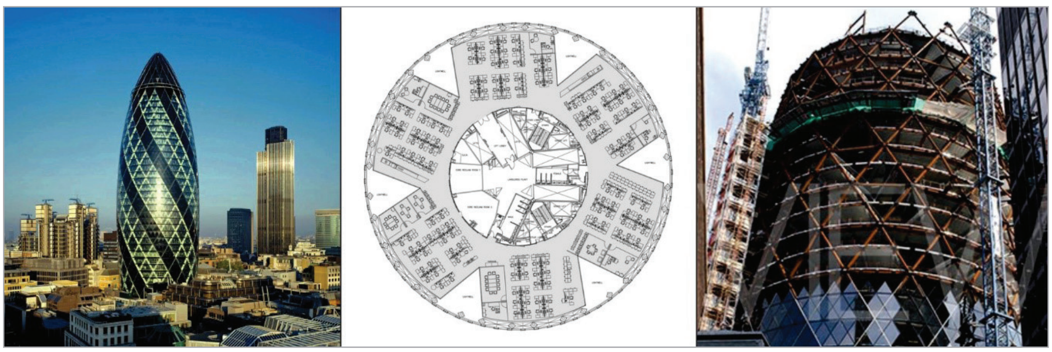

Fig. 9

30 St Mary Axe – form, floor plan and construction (www.wikipedia.org)

Building geometry was developed on the basis of the parametric methods of design – first stage of the building construction is a combination of three circles with a common center – the first one is responsible for the external shell of the building, the second for depth of ventilation channels and the last one for width of a communication core (Fig.10). After correct division of circles into points and connecting them in a right order we can see the shape of the building floor.

The next stage of the construction is the upward duplication and rotation of the previously obtained floor shape at a fixed angle, performed at the same time. The action results in the formation of ventilation channels, spiraling towards the top of the building (Fig.11). Then the floors have to be scaled – individually, by means of the Bezier curve – wide at the bottom, narrowing upwards with the entasis in the lower part – providing the building with a unique shape. The next stage of construction involves determination of floor thickness for each floor, generating a communication core and a double glass shell with a supporting construction. At any stage of the construction, the designer can immediately change the form of the building by altering any parameter. The process takes place automatically,

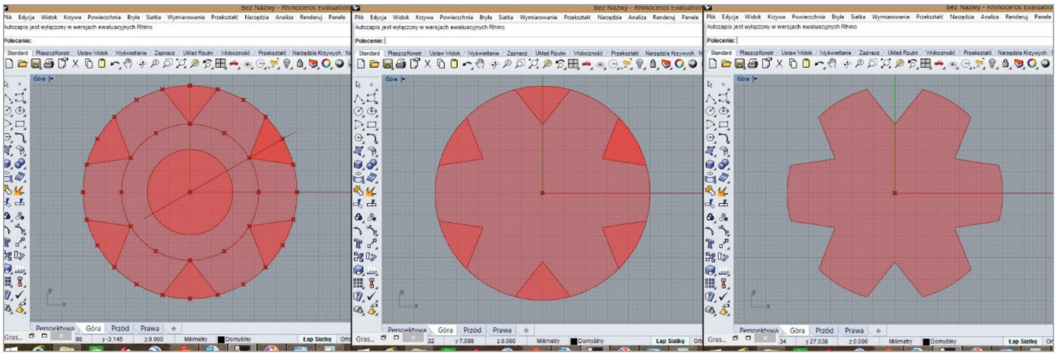

Fig. 10
30 St Mary Axe algorithm – part I (developed by M. Giedrowicz)

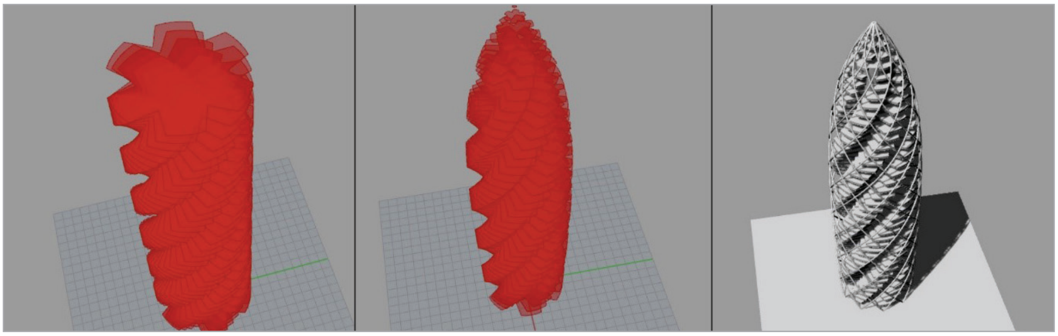

Fig. 11
30 St Mary Axe algorithm – part II (developed by M. Giedrowicz)

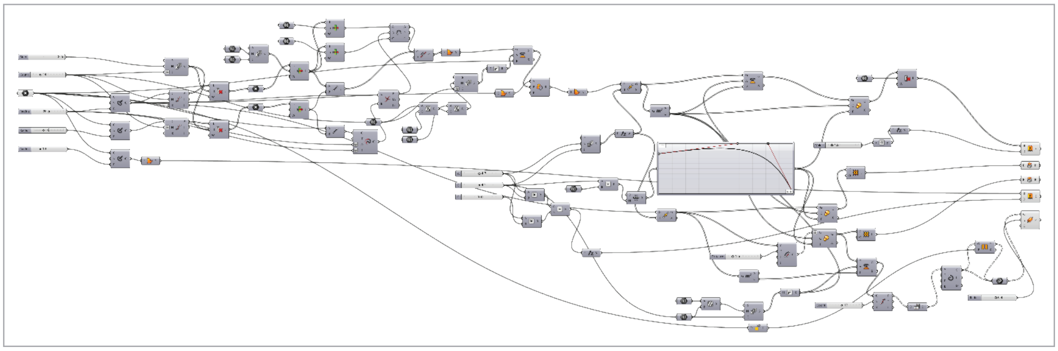

Fig. 12
30 St Mary Axe algorithm – whole sequence – screenshot from Grasshopper (developed by M. Giedrowicz)

not requiring a long and manual method of modeling. Additionally, during the design process, the algorithm continuously updates data concerning the usable floor area of the building, quantity of necessary building materials, construction dimensions and many other important aspects.

In order to create an external shell of the building, the designers used a double glass wall. Owing to that the shafts remove warm air from the building during the summer time and insulate the object in winter by means of passive solar heating. Moreover, the shafts enable the access of sunlight into the building, thus ensuring more friendly work environment and reducing costs of lighting. According to designers, the object has very high aerodynamic parameters and the shape of the building is so streamline that it is protected even against very strong gusts of wind. The use of adequate calculation algorithms brought another benefits – external shell of the building was optimized using triangulation that it does not require any additional strengthening to obtain the expected rigidity. Façade panels are made of flat elements – with the exception of a single, curved glass panel at the very top of the shell.

Free Railway Tracks – parametric management of green areas

At the beginning of 2015, the Poznań City Hall announced the city planning competition for the development of a broad area inside the city center – in the industry environment known as the Free Railway

Tracks [Wolne Tory]. Free Railway Tracks is the former railway rolling stock repair center – strongly industrialized area with numerous sidings, junction points and plants closed since decades. The competition jury will select the area development concept with the inner-city character, numerous workplaces, office and service premises and residential units – surrounded by vast green areas. The competition assumes that green areas should be in harmony with the existing municipal greenery – which in Poznań takes the form of three rings with wedges of greenery concentrically arranged on east-west and north-south axes. The percentage share of green areas and other municipal elements located on the developed land are precisely specified in program guidelines and competition regulations. The competition project prepared by the author of this article will be used to present the method of application of algorithms to design the park pursuant to standards specified by the investor. The first stage of design consists in drawing of park borders and covering the designated area with a grid of squares (Fig.12. The grid was rotated so that its angle is compliant with the majority of quarters located in this city area. The adopted size of squares was supposed to ensure an interesting floor plan, flexibility in the creation of plantings, small architecture and convenient pedestrian passageways. The next stage of the algorithm creation involves development of a logical test – grid fields within the borders are subject to further calculations and the rest of them is rejected. Then, some of the fields inside the park borders are randomly deleted, creating an interesting pattern. The number of deleted fields is closely associated with standards defined by the competition panel – algorithm sums the remaining fields and converts them into percentages of the whole area. This is a simple way to manage the quantity of green areas in an urban concept of a new district of Poznań. Additionally, the sequence of randomly deleted fields can be changed on an ongoing basis, which allows for the creation of numerous different versions of the park composition within several seconds.

During the next stage of the park development (Fig.14), the algorithm created co-dependency between height and thickness of greenery and an attractor, here the railway tracks – the closer to the tracks the shorter and thicker the greenery whereas the farther from the railways the greenery is higher and thinner. The process aimed at the obstruction of access to dangerous tracks and their total exposure.

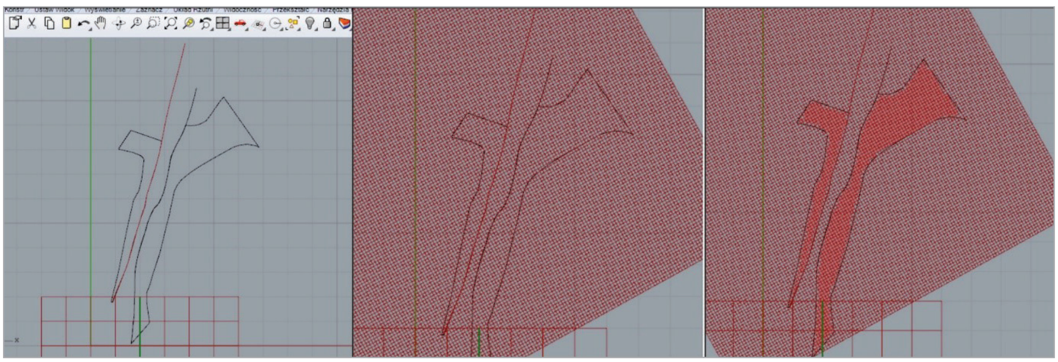

Fig. 13

Railway Park algorithm – part I (developed by M. Giedrowicz)

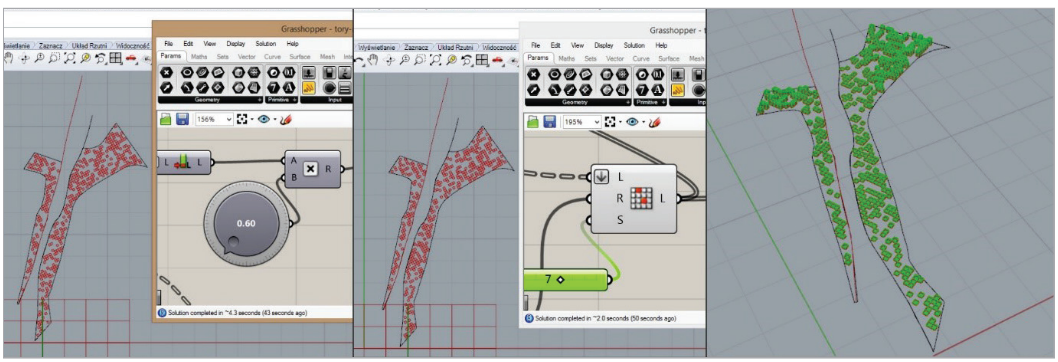

Fig. 14

Railway Park algorithm – part II (developed by M. Giedrowicz)

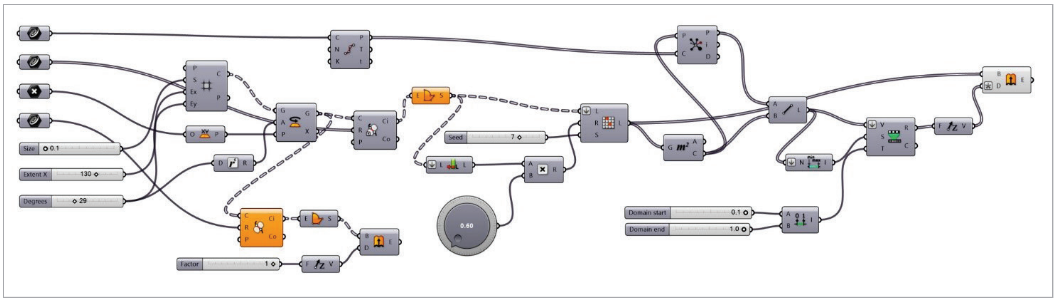

Fig. 15

Railway Park algorithm – pattern sequence (developed by M. Giedrowicz)

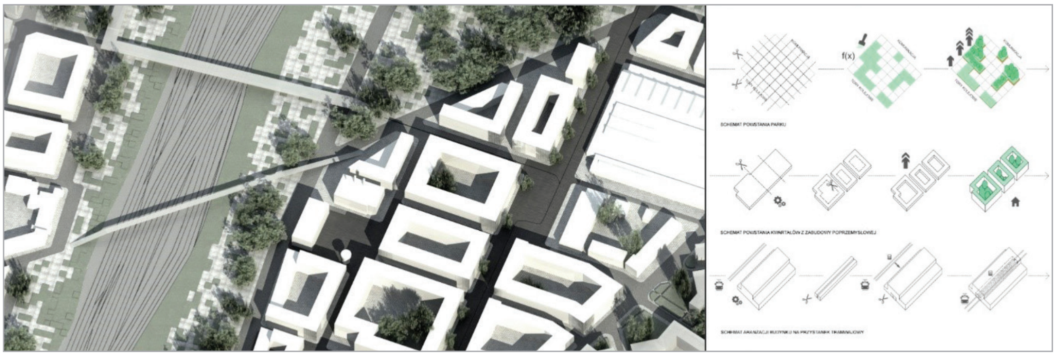

Fig. 16

Sample of Railway Park Project (developed by M. Giedrowicz)

Conclusions

The objects presented in the article show explicitly how parametric and generative designing tools change the view of the pro-environmental dimension of today's architecture. When adopting CAD/CAM technological solutions the architects re-solve the relation between the form of buildings, materials used, energy management systems and pro-environmental properties. The synergy of latest technologies with natural, traditional and environment-friendly solutions has gained the unprecedented recognition. Environmental objectives such as the use of local renewable materials, low embodied energy, water and energy saving, low maintenance costs, environmental protection – are effectively implemented at an increasing scale. Environmental construction supported by latest digital technologies may soon constitute a bridge between huge urban structures and natural environment, satisfying the needs of both sides. The conducted study shows that the use of parametric and generative design methods leads to achieve high ecological parameters. Analysis of the objects shown that these methods solve the full spectrum of environmental issues in contemporary architecture. The solutions can be used on all geographical widths. Created forms outside the environmentally friendly properties also has intriguing form - combination of these two features, as well as the structure and function issue, is considerably simpler using the software Grasshopper. Parametric design methods allow you to very quickly generate dozens of variations on a project problem, keeping imposed by the investor environmental standards.

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