Algorithmic Design and Low-Energy Buildings

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Introduction

This paper offers a short introduction to algorithmic design and highlights its corresponding fields related to architectural design. It explains how algorithmic architecture can be used to design energy-conscious, cost-efficient buildings that fully respond to the location and climate, while complying with all codes, regulations and fully accommodating all required functions. A case study presents real-life design scenario illustrated with actual design workflow steps using computer software applications.

What is Algorithmic Design?

Wikipedia provides this answer to the question: "Algorithmic design is a technology that mimics nature’s evolutionary approach to design." ¹

Figure 1: Mumbai Airport Terminal with algorithmic roof canopy optimized against summer overheating; the lotus-flower shapes reflect vernacular motifs.
Courtesy of SOM, photo: Robert Polidori, © Mumbai International Airport, India.

We may quote architect Arturo Tedeschi for a more in-depth definition: "Algorithms-Aided Design (AAD) allows designers to explore accurate, free-form shapes and provides computational techniques to develop and control complex geometries, parametric modeling, digital fabrication techniques, form-finding strategies, environmental analysis as well as building energy- and structural optimization."²

To better understand algorithmic design, let's take a closer look at the core differences of conventional- and algorithmic design, and highlight the benefits they offer for practicing architects.

**Conventional design workflow scenarios** - using "classical geometry" -- may also be known as "explicit": the architect imagines, investigates, considers and eventually describes every volume, space, element relationship, as well as every detail in the future building. Individual forms and their proportions may be taken from Nature, yet the final design is carefully and consciously created by design professionals alone. This "exact" design workflow describes how buildings -- as well as most objects and man-made forms -- were historically created. The Golden Proportion and Golden Mean were specifically applied to individual objects and their parts to create pleasing forms.

The ancient Greek Euclid (365–300 BC) describes the "Golden Ratio" in the historical record entitled Elements: "a straight line is said to have been cut in extreme and mean ratio when, as the whole line is to the greater segment, so is the greater to the less." Ancient architects used "golden ratio" proportions in various parts of their design to achieve beauty, harmony and balance in their designs. Medieval architects used ideal numbers and proportional series -- that were discrete and could be fractionally divided -- when designing gothic cathedrals.

![Image of Golden Ratio and Modulor](image)

Figure 2: The "Golden-Ratio" and the "Modulor": both are based on explicit proportions and applied to adjust the shape, form and proportions of the design.

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Vitruvius, Leonard da Vinci and Leon Battista Alberti made attempts to apply exact mathematical proportions in the human body to improve the appearance and functionality of architecture. Swiss-born French architect, Le Corbusier (1887–1965), based his "Modulor" on the height of a man with his arm raised and describe it as a "range of harmonious measurements to suit the human scale, universally applicable to architecture and to mechanical things".

It is the responsibility of the designer to consider and evaluate all internal and external design factors that many times contradict each other, such as municipality regulations, architectural design expectations, client's wishes, construction and maintenance costs, structural and energy-related considerations, and so on. In such design scenarios, computer applications are only used to handle, store, document and collaborate based on the decisions made by the architect.

**Algorithmic design workflows** may also be referred to as "parametric", "computational" or "generative": an algorithmic design workflow scenario uses constraints, rules and relationships represented by mathematical formulas. The architect is responsible for defining the formulas based on all design considerations, yet the actual and exact outcome of the design is not fully-determined by the designer. Instead, it is calculated by the computer applications using mathematical rules.

The **parametric** term may be applied when a set of different parameters are used to define forms and shapes. The **algorithmic** term typically refers to the design process to create complex shapes using various mathematical formulas. The **generative** term describes the process of using Nature's evolutionary approach to create forms. **Computational** design may refer to that segment of generative design that can be used well in architecture. Algorithmic, generative and computational design approaches use second and third degree shape functions, rules and conditions to generate forms.

"We should not copy Nature's form, but we could borrow Nature's processes, extract its algorithms and use these to create truly new shapes and forms beyond imagination. Nature's main process of creation is splitting one cell into two cells. Through this very simple process, we may create an astounding variety of forms. Using a computer, we are able to split any volume or fold any surface a million times faster and create thousands of variations. Using the computer to apply different folding algorithms to different parts of a simple column made of three stacked cubes, we're free of any physical constraints: a surface may become incredibly small or intersect themselves. Surfaces may become porous; they can stretch, they can tear. This allows us to generate forms and shapes that otherwise could not be possible to make: forms beyond imagination."
“Splitting a simple cube 16 times using difference ratios and locations ends up with 400,000 surfaces and shapes that are beyond imagination. Please remember: I did not design the form, I only designed the process that generated this form. To find the right process is not easy because 99.9% of the time the change in the folding ratio generates only the geometrical equivalent of noise.”

Rules, parameters and algorithms define certain aspects of the design and determine certain relationships and ratios of individual design elements. Modifying the algorithms and rules will instantly affect the entire design project. This is one of the main advantages of algorithmic design over conventional design: by adding and freely configuring design rules, parameters and algorithms ensure the ability for truly

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complex, yet still real-time design iterations. Now, let's see how algorithmic design scenarios are applied when designing low-energy buildings.

**Algorithmic design and architecture**

Algorithmic (also referred to as parametric or generative) design scenarios and techniques have been used by architects -- with the wide-spread use of personal computers -- since the 1990’s, giving designers the ability to create and maintain hierarchical systems or rules incorporating various design considerations.

"Parametricism is my term for a new, global style of architecture, including all the design disciplines; urban design as well as furniture-, graphic- or even fashion design. All the elements of architecture have become parametrically malleable. We are looking at Nature: its complex, variegated order and its endless forms."  

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**Figure 5: Algorithmic urbanism: Kartal Masterplan, Istanbul, Turkey © Zaha Hadid Architects**

In parametricism, there's always action and reaction between the correlated substances. The design strategy moves from a single system differentiation -- e.g. a swarm of facade components -- to the scripted association of multiple sub-systems: envelope, structure, internal subdivision, navigation void.

For instance, the load-bearing skeleton of a high-rise building must be differentiated from the ground moving up because the structural forces are much heavier close to the ground. The structural engineering team -- using final-element stress analysis -- may design a load-bearing skeleton that reflects this natural phenomenon.

Based on this skeleton, the shape of the building as well as the size, orientation and position of the openings may be determined. The floor-slabs will also react to the above by their shape and by pulling away from the openings. The strengthening load-bearing-ribs react to the shape and position of the slabs and recesses are

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4 The Autopoiesis of Architecture by Patrik Schumacher (Zaha Hadid Architects)
determined as a result of the interaction of the core with the outer envelope of the building.

The creation of all these sub-systems are a result of actions and reactions. The very same applies to the passive solar system as well, e.g. the orientation, transparency, internal and external shading of the transparent surfaces are determined as a result of the openings, the orientation of the building and its surroundings, and so on.

Algorithmic design schemes therefor may be efficiently used to optimize building shell and geometry-related passive solar design concepts for a specific project, incorporating all given properties of the site, weather, micro- and macro climate as parameters. By using curved building envelope - and reducing external edges on the building shell - the energy used for heating or cooling may also be reduced.

![Figure 6: The essence of parametricism is taken from Nature](image)

The essence of parametricism is taken from Nature; it describes how natural vegetation correlates to topography, climate and microclimate, orientation, etc. It's easy to read the topography through the vegetation and even find a river, because Nature is well ordered, structured, elegant and truly beautiful. The very same essence is applied to architecture and the built environment through algorithmic design schemes.
The world-renowned, Iraqi-born, British architect, Zaha Hadid, is acknowledged as one of the first masters of algorithmic architecture. Since the late 1980’s, they follow strict design principles and avoid rigid forms, simple repetitions and collages of isolated, unrelated elements. They use soft forms, differentiated and correlated systems to create unique, beautiful, never boring yet always ordered, energy-conscious, legible and navigable projects, whether it’s the Kartal masterplan for Istanbul, the Heydar Aliyev Cultural Center in Baku, the BMW Central Building in Leipzig or the Chanel Contemporary Mobil Art Container.

Algorithmic processes for energy-conscious designs

The algorithmic design processes -- all borrowed from Nature -- are not limited to creating astonishing building shapes, interior forms and urban layouts, but can be efficiently used in corresponding design scenarios as well. A generative design workflow always starts by defining a set of concrete objectives to achieve and a set of rules to consider. Such may be the required annual energy consumption of a building in a given climate, the shadow-mask and sky-conditions on the actual building site, the construction and maintenance costs of the future building, and so on.

"We invested a lot into cutting-edge technology: digital modeling, analyses and file-to-factory fabrication processes. We also use innovative materials, such as thermal-formed glass created by molds, extracted from the digital models. Computer applications lets us create and analyze building information models without making physical models. These tools are there to manage the complexity of the projects, to make these predictable, quantifiable, feasible."  

"If you’re in the business of the future, you can’t ignore sustainability. It’s crucial. We make the architecture express this sustainability - not just by putting some solar panels on the roof, but by actually forming the entire shape of the building. In the KAPSARC center we managed to achieve 42% reduction in the annual energy consumption of the building. This reduction value is compared to the performance of an ordinary "box-like" building in the same climate."  

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5 Shajay Bhoosan, Computational Design Group, Zaha Hadid Architects
6 DaeWha Kang, Associate, Zaha Hadid Architects
The KAPSARC research center is similar to a living, organic scheme where expansions grow and multiply like cells, creating a network of three-dimensional six-sided cells, rising above the desert of the Arabian Peninsula, emerging as a cluster of crystalline forms, which evolve in response to environmental conditions. The spatial program of the design ensures that each component is suited to the function it serves. The exterior’s shell-like façades conceal the porous interior, where sheltered courtyards bring natural daylight into the center of the scheme. These buffer zones allow a gradual temperature transition between outdoor and indoor volumes.

**Algorithmic design tools for low-energy buildings**

Several computer applications have already been developed to help implement various levels of algorithmic capabilities, such as Solidworks and Catia by Dassault Systèmes, Generative Components by Bentley Systems, Dynamo by Autodesk, and Marionette by Vectorworks. Generic algorithmic applications alone won't provide an adequate architectural design and documentation environment.

Architectural design and collaboration with consultants, engineers, clients and municipalities requires professional building information modeling (BIM) platforms. Some software vendors started to develop their own generative extensions to their BIM application; however, these algorithmic plug-ins are not yet matured and still have limited capabilities.

Today, Grasshopper is the most advanced and most widely-used graphical algorithm editor. Developed by Robert McNeel & Associates, it is tightly integrated with Rhinoceros (or Rhino) -- a versatile 3D modeler -- developed by the same company. Grasshopper is the choice of design professionals and students around the world for algorithmic design, because it requires no knowledge of programming or scripting, yet it still allows designers to build form generators from the simple to the awe-inspiring.
"Our favorite design tool currently is Rhino; this, however, is not a BIM solution. To overcome this problem, we’re currently working together with GRAPHISOFT to provide a plugin for both ARCHICAD and Rhino so that we’ll be able to link geometry and building information throughout the whole project."  

"ARCHICAD is a professional BIM application developed by GRAPHISOFT. The Grasshopper-ARCHICAD bi-directional software tool is already available and provides architects the "best of both worlds": advanced algorithmic design capabilities while enjoying all the documentation, collaboration and analytical capabilities provided by a professional BIM platform." 

Case Study

The following case study presents an architectural design workflow to create responsive and optimized shading panels on a free-form, high-rise project. This project was created by Michele Calvano and Mario Sacco at ArchiRADAR and won first prize in the "Algorithmic Design Meets BIM" design competition announced by GRAPHISOFT.

The initial free-form, conceptual shape and geometry of the building was created using Rhinoceros. Rhino provides all the tools necessary to efficiently work on double-curved surfaces of NURBs using graphic control-points, enabling convenient, real-time 3D editing.

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7 Jakob Andreassen, BIM Manager, Bjarke Ingels Group, www.big.dk
8 Laura Baróthy, Product Designer, Graphisoft, www.graphisoft.com
9 www.archiradar.it
Grasshopper is a software add-on to Rhinoceros, and enables designers to use a graphic interface when adding parametric functions and other generative capabilities to the Rhino model.

Grasshopper was used to overlay a mesh surface on the previously constructed NURBs; as a result, the complexity of the double-curved surface was reduced to evenly distributed planar squad panels grouped in clusters. This practically ensures that not all panels have different geometry; instead, the building skin is covered by a series of equal elements to increase manufacturing efficiency and decrease construction costs.
Another great design advantage of Grasshopper and Rhino is that all design updates and changes are handled in real-time. For instance, any change in the NURBs in Rhino will cause an instant update of the mesh surface generated by Grasshopper, while keeping the file size as low as 200KB.

The next step is to convert the previously generated mesh surfaces to parametric solar panels that may individually change their position, according to actual sky and sun conditions. Thanks to the live, bi-directional Grasshopper-ARCHICAD connection, smart, parametric sun-shading screens (brise-soleil elements) are created from the mesh surfaces. This robust, live, two-way connection is available throughout the entire design development project phase.

Any changes made in the ARCHICAD building information model will be reflected in Rhino, and any changes initiated in Grasshopper or Rhino will be instantly reflected in the BIM project as well. The ARCHICAD file size of the presented project -- including all shading elements -- is still only 13MB, ensuring an extremely responsive design environment even on average hardware.

As the design evolves, designers may benefit from ARCHICAD's objects that use parametric configuration options. For instance, location- and orientation-sensitive shading panels can be created that may change their inclination on the building according to specific, external criteria.

Accurate architectural documentation, construction details, element schedules, and cost-estimates may also be extracted from the design project at any stage of the design. This helps designers make well-informed design decisions and client presentations.
The ARCHICAD BIM project may also be shared with structural and MEP engineers, as well as energy consultants using the IFC and BCF protocols and OPEN BIM standards. A simplified building skin geometry may be extracted and forwarded to create the structural building scheme using TEKLA Structures. The completed structural model can be merged back into the architectural model for reference, clash detection with the MEP systems, and for further collaboration purposes.

The Rhinoceros model -- generated using the Grasshopper add-on -- may also be used for building energy analysis. Using the Ladybug and Honeybee Rhino add-ons, the design can be analyzed using Energy Plus. ARCHICAD also offers various energy evaluation functionalities out-of-the-box, while also providing various project export possibilities for other applications including PHPP, iSBEM, VIP-Energy, gbXML, as well as a dedicated "green" IFC translator.

"Today buildings can be enhanced with dynamic properties -- one might even say a "behavior"; -- the building skin may vary in real-time according to the changes of the environment. Designers have to define not only the shape of the buildings, but also control their behavior. Thanks to recent computer software innovations such behavior-control is much easier using algorithmic applications, enabling architects to use mathematical functions and open parameters for such control. These allow a very sophisticated, yet direct connection between the dynamic, environmental input and the complex, architectural design output. The person capable of handling both the shape of the building and its behavior is called a Computational Designer. His responsibility is not only to define the building shape, but also to manage interoperability, oversee standardization and ensure fabricability."

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11 Mario Sacco, Architect, ArchiRADAR, www.archiradar.it
The presented workflow offers architects the possibility to incorporate algorithmic design scenarios throughout the entire design workflow and use it not only to create astonishing forms, but also to develop an energy-conscious design that is responsive to its environment and micro-climate as well.

Figure 14: Structural design (TEKLA Structures) and model checking (Solibri Model Checker) © Michele Calvano and Mario Sacco, ArchiRADAR

Summary

Algorithmic design scenarios -- a process taken from Nature -- may be used by architects to generate beautiful building shapes using mathematical rules, parameters and constraints. In addition to creating impressive shapes, generative design may also provide invaluable help to design zero-energy buildings, using 100% renewable energy to meet end-user requirements throughout the life-cycle of the building.

Architectural design decisions made at the early design stages define about 80% of the energy performance of the future building. MEP systems are added at later design stages by consultants and engineers -- when the building volumes, functions, as well as the properties of materials, openings, etc. are all determined and confirmed. In practice, this means that conceptual architectural design does not only determine the shape of the future building project, but also its initial energy characteristics.

Algorithmic design may provide invaluable help to implement all passive solar design aspects: create buildings with optimal volume-surface ratio; reduce the length of sharp edges on the external building envelope to reduce heat-loss; determine solar gain based on transparent surfaces, their orientation and shading; consider the effect of macro- and micro-climates using various materials; perform dynamic energy calculations by analyzing the energy performance throughout the entire year.