BUILDING DESIGN AS AN INDIVIDUAL COMPROMISE BETWEEN QUALITIES AND COSTS
A general approach for automated building generation under permanent cost and quality control

BENJAMIN DILLENBURGER, MARKUS BRAACH, LUDGER HOVESTADT
Chair of CAAD, ETH Zurich, Switzerland

ABSTRACT: We introduce an evolutionary design approach for the automatic arrangement of a predefined space program on a given site. The design goal is to distribute floor spaces while ensuring the essential building performance and usage. The presented evolutionary strategy is applied to acquire optimal design solutions considering both environmental conditions and inner organization under diversified fitness functions. The evaluation process consists of the direct analysis of the spatial network and the physical factors in an adequate accuracy. The method provides a fast generation of qualified volumetric studies. The resulting buildings become a manifested compromise between qualities and cost.

KEYWORDS: Evolutionary strategy, multi-fitness criteria, dual graph representation, network analysis, building envelope


MOTS-CLÉS: Stratégie évolutive, fonction de fitness différencié, dual graph, analyse de réseau, enveloppe du bâtiment
1. INTRODUCTION

1.1. An economic view on building shapes

Building design can be seen as an individual compromise between quality and cost, a manifested cost-benefit analysis. Since the beginning of architectural theory, the economic aspect of architecture has been considered a main topic of the discipline. To construct a building always implies an effort that has to be worthwhile. So the difference between benefits and costs should be as high as possible. The Austrian architect Josef Frank (1931) describes architecture and design as a compromise between function, material, form, quality and costs. This latter definition provides the starting point for our approach.

While the building costs seem to be easily computable (for production and maintenance), the benefit of a building cannot be expressed precisely. Functionality can be theoretically measured as the appropriateness to a purpose. But the purpose of architecture is an open notion, depending on the physical, social, economic cultural and historical background, where it is used. Yet one can claim that some qualities are inevitable to provide a usable space, and can be precisely measured through geometric and topologic analyses. Several empirical studies have been conducted to assess the relationship between the geometric appearance of buildings and their function. Fuller (1963) sees in the Manhattan Grid a solution of conflict between lighting and heating. Nobbs (1937) claims that a maximum building depth is restricted by the need for natural illumination. Bon (1973) found a relationship between floor area and circulation length. Sullivan (1896) proclaims:

...These things, and such others as the arrangement of elevators, for example, have to do strictly with the economics of the building, and I assume them to have been fully considered and disposed of to the satisfaction of purely utilitarian and pecuniary demands...

Up to a certain level of detail and scale, these qualities can be evaluated regardless of material or construction. In our research, we combine these principle fitness criteria, and develop algorithms for their automatic calculation. Both the outer shape and the inner organization of buildings will be considered.

Steadman (2008) is right when he warns against a functional determinism, with the belief in only one optimal solution of an architectural task, predefined by its requirements. Usually for every design there are alternative arrangements. Every building represents a new, individual compromise. Hence in our approach we do not implement a static fitness function, but a parametric one: The desired mix of qualities can be individually adjusted. The results of our research demonstrate that even with a relatively small range of considered qualities a huge variety of complex forms can be generated.
1.2. Common architectonical problems

One crucial challenge of architecture is the conflict between building site and program. Intelligent building layout has to support its functionality within an environment. The confrontation of inner organization with outer factors is a key to realistic results. Our aim is to find a solution adapted to a special situation, rather than an ideal and universal building typology. Therefore we address two common architectural problems in our approach.

We choose two perspectives. The architects view: Given a specific building site, how could a spatial arrangement for a given program of rooms look? This is basically a simulation of an architectural competition. The developers view: How much floor area can be built on a given site while ensuring the essential qualities for the building’s functions? With what arrangement can one expect the highest return on investment? Solving these problems manually can be a difficult and time-consuming task, bearing the risks of mistakes and loss of precision.

1.3. Automated Spatial Synthesis

The idea of a machine as a creator is not new. With the invention of the computer, these machines seem to become more realistic. In the early seventies, in literature and art, software has been developed to simulate the work of an artist. By contrast, our approach does not attempt to substitute the architect for an author. We will concentrate on the generation of a pure functional object, which is to be the basis for further architectural development. Our goal is not to simulate the architect, but to assist him. We relieve him of the duty of functionality, so he can concentrate on more sophisticated parts of building design. William Mitchell (1977) points out the basic setup for an automated spatial synthesis:

*Given a data structure capable of representing a range of building designs find a state of the data structure (i.e., a particular design solution) such that specified objectives and/or constraints are complied with.*

2. A GENERAL APPROACH - THE BUILDING SYNTHESIZER

2.1. Artificial evolution

Evolution is a process where variants are produced through reproduction or replication out of a population as shown in Figure 1. Only some of these versions are selected for the next replication.
Artificial evolution is a domain of artificial life. Researchers use methods from artificial evolution as optimization tools, or more generally speaking, as design methods. Simulated evolution offers a general and flexible approach to solve complex optimizing tasks, where no specialized algorithms can be found (Holland 1975). Therefore, we have chosen this technique for the optimization part of our building synthesizer.

As Joedicke (1976) proposes, design can be seen as a process of producing and reducing variations. The evolutionary strategy follows the same scheme. When we delegate this task to the computer, we can obtain several benefits: One is of course the high calculation performance. Many additional variations can be generated and tested. The computer has no historical background. Without any experience and preconception, it starts working on his task (Dawkins 1986). In the best case, the offered solutions can be so exotic, that we could never have conceived them.

In building design, many problems can be found where a computer aided solution search can be helpful. From urban planning to furniture design, experiments with artificial evolution have been made (Bentley and Corne 2002; Eastman 1975). Jagielski and Gero (1997) present a promising approach for the space layout problem, but they only optimize the inner organization, evaluating the circulation costs. Until now, almost every research stayed an application-prototype and could not be applied in practical use.

As Steadman (2008) points out, there remain several research questions for the generation of architecture. The implementation of multiple fitness criteria including context, the definition of an appropriate representation for a general and neutral solution space, while ensuring the creation of workable and practical buildings. An efficient evaluation technique must be applied to allow the testing of a high number of generations.

Our approach, which we describe below, addresses these challenges. We introduce an evolutionary strategy that offers the generation of usable space for a predefined purpose. The space is arranged into a specified lot in three dimensions under adaptable, multiple fitness criteria.
2.2. Data structure

One possible way of representing the shape of objects in artificial evolution is to subdivide the space into cubic voxel. Structure and topology of the object need not be defined in advance. They evolve during the optimization process. No parametric shape has to be defined before.

We decided to use a discretization method based on the voxel model. Our data structure consists of points that are distributed on the building site. Unlike the voxel model we do not limit our structure to a regular, orthogonal and cubic grid (Figure 2). Hence we can diversify the possible solution space. The dual graph representation of the cells offers a direct and computationally cheap quality evaluation through graph algorithms and computational geometry. Therefore we implement the quad edge data structure (Figure 3) by Guibas and Stolfi (1985), which can simultaneously represent the graph and its dual.

Like in John Frazer’s (1995) “Universal State Space Modeler”, these data points can have different states (in our case: parts of the building program). They know their position in space and their adjacent points. This three-dimensional network of cells allows the description of the environmental context and the generated buildings as well.

**FIGURE 2. DIFFERENT DISCRETIZATIONS OF A SITE.**

**FIGURE 3. DUAL GRAPH REPRESENTATION AS QUAD EDGE DATA STRUCTURE.**

2.3. Search space and Genotype

The search space is the overall amount of the possible coded solutions. The data structure representing the potential building forms will always limit the endless
range of possible buildings. Our approach tries to use a data structure as abstract as possible to ensure a maximum freedom. We will not limit it to known architectural typologies, or to specialized geometries as rectangular rooms like in the approaches described by Flemming (1977) and Steadman (1983).

Still the search space has to be restricted to avoid an extensive variation of unusable buildings, enabling an efficient search. For the goal of a qualified mass distribution, each floor height is assumed equal. The cells are distributed on horizontal layers, which are stacked with equal distance. So each cell in the grid gets the same height. The resolution of the discretization must be adapted to adequate balance between the range of the search space, the accuracy and the calculation time. The algorithms for the evaluation stay the same. The organization of the search space offers two further options: An effective restriction is the limitation to a 2.5 dimensional arrangement of the building mass, where no overhangs and free flying building mass are allowed. This restriction leads to a much faster evolution process. If the context claims a uniform building height, the search space can also be adapted to two dimensions, with the same consequences.

The desired building mass is split into atomic building primitives, according to the resolution of the cell network. Depending on the resolution, one cell does not represent a single room, but an abstract part of it. These building primitives are distributed on the cells in three dimensions. This distribution represents the building code, the genotype of the architecture. Every cell is occupied by a cell-type with an individual configuration.

2.4. Variation and selection

The authors adopt an evolutionary strategy (Rechenberg 1973), which can be described as a genetic algorithm with a population size of 1. The evolutionary strategy will hardly reach the global maximum, but this is not our goal. Since the search space is ample, we still can expect to find an adequate solution, gaining a greater flexibility and speed with the evolutionary strategy.

The parent solution is replicated and mutated to become a child solution, from which the fitness is evaluated. If the child is better, it turns into the new parent and the old parent is discarded. Otherwise, a new child of the parent is created by another mutation. The mutation rate is adapted to the rate of successful new generations.

When there is a predefined program of rooms, we only mutate by swapping the content of the space cells. The overall area stays constant, only the arrangement of the space is changing. When we want to find the highest amount of usable space on the site, the variation is done through mutating the state of the cell (From empty to occupied or inverse)

The computer mutates the genotype until the building has the desired fitness. The size of the region that is mutated can change, to overcome some of the local fitness maxima (Figure 4).
2.5. Phenotype

The building itself is generated out of the distribution of the building primitives. The shape is smoothened, and the staircases are positioned.

Determining location of staircases in building volume is a challenging design issue. Usually, the building code limits the maximum distance (e.g., 25 meters in Germany) between each room and its closest staircase on each floor. A greedy algorithm is incorporated in order to decide the location of staircase in the building volume by scanning from topmost storey to ground level in a most effective manner as shown in Figure 5.

The upper-left image shows the first step to decide the first staircase. The algorithm starts at the topmost storey (4F) and scans the building floor by floor. The most effective position for the first staircase is chosen. It is the location with the highest number of cells accessible within the maximum distance. After placing the staircase, some cells are now accessed. For the remaining cells as shown in remaining two images, the process iterates until every cell has a staircase within the certain distance. This algorithm cannot ensure the optimal placement in other purposeful arrangements. However, it is appropriate for the architectural program of this study.

**FIGURE 4. MUTATION OF THE GENOTYPE.**

**FIGURE 5. VERTICAL SECTION VIEW OF THE DIFFERENT STEPS OF THE AUTOMATED STAIRCASE PLACEMENT (MAXIMUM ALLOWED DISTANCE TO STAIRCASE IS 2 UNITS. NUMBERS REPRESENT THE EXPECTED UNITS TO ACCESS).**
These simple formal rules can be extended to a more complex or specific building design. In Figure 6, you can see result of this transformation that is the phenotype, the instantiation of the building code in the environment. This phenotype still keeps the dual graph data structure. This offers a direct and fast evaluation. Our approach uses a very close relationship between genotype and phenotype. Thus we have permanent control over the floor area, and similar phenotypes belong to similar genotypes.

**Figure 6. Genotype and phenotype of a horizontal section.**

### 2.6. Evaluation

Former applications of evolutionary algorithm focus only on a simple fitness criterion. Elezkurtaj and Franck (2002) concentrate on the close packing of rooms and their spatial relationship. In Rosenman (1996) work, the considered fitness is the compactness of the room layout, and adjacencies between rooms on the house level, although they claim that other fitness criteria could be included. A more differentiated fitness function raises new challenges. Some qualities may be contradictory and lead to multi-goal conflicts. Still a multiple fitness analysis is inevitable for the generation of seriously workable solutions.

March and Steadman (1974) describe the relevance of graph theory in architecture. Hillier (1993, 1996) discloses in his research of space syntax the importance of the spatial network connectivity for architecture. Our approach combines network analyses and physical analyses like view, heating and solar exposure. Both structure and topology of the building are evolved and evaluated by the computer.

The key for the successful implementation of the evolutionary strategy is a fast analysis of the building performance. We decide not to evaluate the generation with external simulation software. As mentioned before, one of our main priorities is a fast evaluation process, which allows real time interactions. Conventional simulation software would calculate much too precisely, compared to the fuzziness of the generated buildings. The representation of the phenotypes as a dual graph offers a direct calculation of structural and topological qualities. The shortest paths between the cells are evaluated through algorithms from Floyd (1962) and Dijkstra (1959).
The evaluation of qualities is conducted by traversing cell by cell. The total fitness is the sum of the different qualities measured in each cell multiplied by their weight factors. We implement a communication model between the cells. Information can be transmitted through the network of cells. Each cell type has its own character of communication. It has different parameters for the emission, the demand, and the transmission of information (Table 1). This abstract model is a general method for the fast evaluation of qualities. It turned out that a set of less than 10 different qualities and their combination with the different room-types leads to a manifold range of building layouts.

**Table 1. Information Model.**

<table>
<thead>
<tr>
<th>Information</th>
<th>Permeability</th>
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<tbody>
<tr>
<td>Temperature</td>
<td>Isolation</td>
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<td>Light</td>
<td>Translucency</td>
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<tr>
<td>View</td>
<td>Transparency</td>
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<tr>
<td>Sound</td>
<td>Sound isolation</td>
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<tr>
<td>Water</td>
<td>Waterproof</td>
</tr>
<tr>
<td>Proximity</td>
<td>Circulation costs</td>
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<tr>
<td>Weight</td>
<td>Stability</td>
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<td>Depth</td>
<td>Space</td>
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<tr>
<td>Traffic</td>
<td>Accessibility</td>
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3. SOFTWARE IMPLEMENTATION

3.1. Software architecture

The building synthesizer consists of two modules that can be used independently. The generator designs buildings, and the evaluator analyses the qualities of the building. It is also possible to use both modules independently and to test a handmade building design with the evaluation module. These two modules can interact in a feedback loop, to optimize the design as shown in Figure 7.

**Figure 7. System Architecture of the Building Synthesizer.**

3.2. Input

The starting point for the applet is a differentiated specification of the environment. One possible user input is the site to work on. It can be described in
different layers: geometry with topography, the building-regulations, the existing environment and infrastructure. This layer structure is an open list that can be extended for special cases. Vector- and bitmap inputs are both possible (Figure 8).

**FIGURE 8. INFORMATION LAYERS OF THE SITE: TOPOGRAPHY, BUILDING LAW, PHASE OF CONSTRUCTION, INFRASTRUCTURE, FOREST AND EXISTING BUILDINGS.**

The user can individually adjust the needs of each room Figure 9 illustrates the second required input, which is the requested space plan with the different demands of the diverse functions. These can be topologic (adjacency matrix), geometric (proportions) and physical (illumination, quietness, etc.)

**FIGURE 9. EXEMPLARY DESCRIPTION MATRIX FOR THE BUILDING PROGRAM.**
The user of the software can adjust the weight of the different qualities per slider in real time (Figure 10). He decides which compromise the computer should try to find.

**FIGURE 10. SCREENSHOT OF THE GRAPHICAL USER INTERFACE**

3.3. Output

Every building generation is rendered in three dimensions. The results of the evaluation of each quality can be projected on the building geometry to visualize the performance. The generated results can be exported as a 3D model for common CAD software, together with the precise tables of the analyses (Figure 11).

**FIGURE 11. VISUALIZATION OF DIFFERENT ANALYSES: STRUCTURE, FUNCTIONS, LIGHTING, DISTANCE TO ENTRY, BETWEENNESS AND CENTRALITY.**
4. RESULT

The software has been successfully used for the design of an apartment building. The computer managed to arrange more than a hundred different apartments together according to their individual demands. Another application was a design study for a new office building. The main aspects were the reduction of circulation costs for a better internal communication of the employees while ensuring enough illumination for the workspaces. Figure 12 depicts the multiple layouts, which the computer proposed. All of them are reflecting the different settings of the quality mixer.

**FIGURE 12. DIFFERENT GENERATED VARIATIONS OF AN OFFICE BUILDING.**

5. DISCUSSION

Some of the generated morphologies clearly express what qualities were important for their evolution. This is the case when the weighting was radically adjusted and the fitness function simple. If multiple, contradicting criteria
where evaluated, the result becomes more complex: a human architect would have solved such a task by simplification, the computer maintains the complexity and generates an individual compromise that yields to unexpected new arrangements. Especially the ratio between natural lighting, connectivity and the façade area of the building seems to have a great impact on its shape. We call the results statistic design (Braach and Fritz 2007), objects between a diagram and architecture. Neither aesthetic criteria nor symbolic purpose were formulated. The buildings are generated from scratch, without any cultural background or knowledge. Their design represents a pure response to function (Alexander 1974). It is remarkable that still some of them are similar to well known architectural typologies, they probably would pass the “Turing test”. With the design of the solution space, the authors influence the results. Nevertheless the ratio of authorship decreases from conventional design over parametric design to the design through artificial evolution. The results are intended to be a starting point for further architectural refinement. Still we do not consider the solutions to be generic but highly specific.

6. FUTURE WORK

Automated building design is ongoing research topic. New room-types can be introduced, and different formal styles will be tested. An interesting challenge will be to increase the level of details and to test the solutions in a finer scale, from single rooms to building elements. Some improvements can be made in the mutation strategy. The impact on building design of the ratio between natural lighting, connectivity and the facade area can be subject to further research.

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