Integrated Design
A Generative Multi-Performative Design Approach

by

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Abstract:

There are building systems, called "modularized", in which the component systems (for structure, lighting, etc) can be analyzed and synthesized independently since their performance and design do not interact or affect one another. There are other building systems, called "coupled", in which the component systems do interact and influence one another. The thesis acknowledges that in a building there are both sub-systems that act independently and others that interact. While many design processes have been proposed for dealing with discrete sub-systems, there is no systematic study for building sub-systems that interrelate. This thesis examines a different design approach called *integrated*. The term "integrated" has a dual utilization in this study. The first use refers to the integration of form and building performance. The second use refers to the integration of interrelated and diverse building performances involving multiple disciplines. The integrated design approach analyzes and evaluates several interrelated design systems involving different disciplines in the early design phase. The goal of the approach is the generation of design alternatives guided simultaneously by two basic objectives: the aspiration for form exploration and the satisfaction of the performances of interrelated systems. After defining a framework for an integrated design approach, which includes inter-disciplinary collaboration, unified design, optimization, simulation, and other formal and digital techniques, the approach will be demonstrated in a case study. The objective of the case study is to demonstrate that the integrated design approach has validity and can be realized, in this case, for the generation of high-rise buildings guided by structural, lighting, zoning codes, and aesthetic criteria.

Thesis Supervisor: Terry Knight
Title: Professor of Design and Computation

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1. Introduction

In general, two dominant design paradigms govern current digital design efforts in architecture: the Generative Design paradigm and the Performative Design paradigm. Generative design can be broadly defined as an algorithmic or rule-based process through which various potential design solutions can be created. Generative design systems, such as cellular automata, L-systems, shape grammars etc, are the primary design tools. The dominant aspiration for generative design is form exploration. On the other hand, Performative Design can be broadly defined as a design paradigm in which the dominant intention is meeting building requirements or else building performances, such as functional, environmental, safety, structural, financial etc. In Performative Design, a building form is evaluated against performance criteria and modified after it is created using traditional methods. The primary design tools in this case are optimization and simulation algorithms.

Only recently, has a third design paradigm started to emerge: Generative Performative Design. By its name it is clear that this paradigm is a combination of the two aforementioned ones. Indeed, in Generative Performative Design both form and performances guide the generation of designs by using, as design tools, generative systems, simulation techniques and optimization algorithms. However, examining thoroughly these studies, the conclusion that can be reached is that most of these are constructed in such a way that satisfies the performances for just one building discipline.

Integrated Design approach fills this gap by the introduction of more than one building performance from different disciplines. This feature converts Generative Performative Design to Integrated Design as a Generative Multi-Performative Design approach. Integrated Design is governed by two principal components: the integration of form and performance and the integration of multiple building systems. The relation between form and building performance is manifold. Indeed, it has been a core subject throughout the history of architectural theory and practice. The discussion lies in the fact that architecture is a combination of art and science. Consequently, a design should meet both aesthetic and functional requirements. Within this scope, the term "integrated" is introduced. Redefining form not as the geometric representation of a material object alone, but as a multitude of effects and behaviors, the dualism of form and function is transformed to a synergy aspiring to integral design solutions.

At the same time, the term "integrated" has a second use throughout the thesis; it designates an alternative framework in which multiple building performances can be considered. In general, there have been two primary categories of building systems: "modularized" and "coupled". Modularized sub-systems refer to discrete building sub-systems whose existence and performance do not influence one another, so they can be analyzed and synthesized independently. Coupled sub-systems, on the other hand, refer to building sub-systems all of which are tightly linked together. They interact and influence one another and that is why they are solved simultaneously. Coupled sub-systems are not usually identified in an architectural project, while modularized sub-systems are.

This thesis acknowledges that in a building there are both sub-systems that act independently and others that interact. While there are many design processes that have been proposed for dealing with discrete sub-systems, there is no systematic study for building sub-systems that interrelate. This thesis will propose an alternative design approach to deal with more than one building performance that will interact with others. In higher detail, integrated design describes the framework of simultaneous analysis, evaluation, and generation of interrelated building systems, which belong to different disciplines, at the early phase of the design process in order to satisfy both form exploration and performance efficiency.

The potential benefits from the utilization of the integrated design approach can be many, such as the increase in the number of examined design scenarios and alternatives, the improvement of the overall design understanding, promotion of multi-disciplinary collaboration, reduction of the design cycle. Last but not least, through the use of a generative multi-performative procedure, new levels of complexity might be explored and new unexpected aesthetics might emerge. The potential occurrence of these benefits should not lead to the conclusion that this approach has no difficulties or weaknesses. Indeed, there is a set of prerequisites that should be met in order for the integrated design approached to be used. These prerequisites demand changes not only in architectural practice and computational technology but also, and most importantly, in the way architects have been taught to perceive design.

This thesis is divided in three main parts. The first examines the most dominant design paradigms that exist today so as to understand where integrated design can be introduced and which needs it tries to address. The second part analyzes the basic framework of Integrated Design, some of the potential benefits of the approach, as well as conditions to be met in

order to facilitate or make possible the approach. The third part demonstrates the validity of Integrated Design. Through a proof-of concept study, or case study, it is examined how a computational model could be defined that takes into account a number of interrelated performances and how the conflict or synergy of these forces could be visualized through form. In higher detail, the case study demonstrates whether Integrated Design can be utilized, in this case, for the generation of high-rise buildings guided by structural, lighting, zoning codes, and aesthetic criteria.

2. Definitions

2.1. Generative Design

2.1.1. Definition of Generative Design

Generative design can be broadly defined as an algorithmic or rule-based process through which various potential design solutions can be created. The rules of a generative design process may include parameters or variables and being applied in a systematic way to a starting condition or configuration to generate a range of design possibilities.

2.1.2. Generative Design Systems

The rules of generative systems can be defined in different ways, for example with verbal grammars, diagrams, sets of geometrical transformations or scripts. Generative systems have different degrees of control, ranging from automated to step-by-step manually controlled. Constructing and validating generative systems becomes a major task of the design process since they implicitly govern the resolution of form exploration, and consequently the strain of the alternative results.

Based on the potential representations of the design solutions, generative systems can be categorized into three broad groups. The first category is *analogue systems*. In this category some properties in the systems are used to represent other, analogous properties of the designed object. Representative examples of analogue systems are mechanical and electrical systems. *Iconic systems*, the second category, create alternative design solutions by assigning operations, such as addition and subtraction, and transformations, such as move, scale, rotation and reflection, to the parts that are described. The third category is *symbolic systems*. They use symbols, such as words, numbers and mathematical formulas, to represent the possible outputs. (Mitchell, 1977)

Generative systems have played an important role in philosophy, literature and music. The history of generative systems is summarized by William Mitchell (1977), who maps out a line from Aristotle to Lull. In architecture the systematic use of generative systems goes back to Leonardo da Vinci and most recently to Durand. In his study *Précis des Lecons d'Architecture* (1803), Durand proposed innovative ways to generate plans and elevations by re-assembling parts of a structure, such as columns, walls etc.
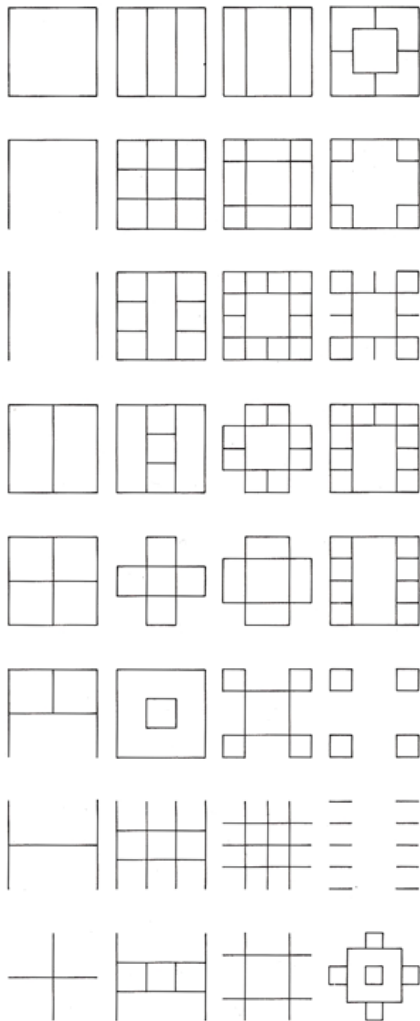
Sample of Durand's generative pattern studies in *Précis des Lecons d'Architecture*. Image: (Mitchell, 1977).

Form has been a central focus in the theories and practice of architecture throughout history. In the last few decades, however, form exploration and form innovation comprise the initial and basic objective of many architects. Due to this fact a plethora of generative systems has been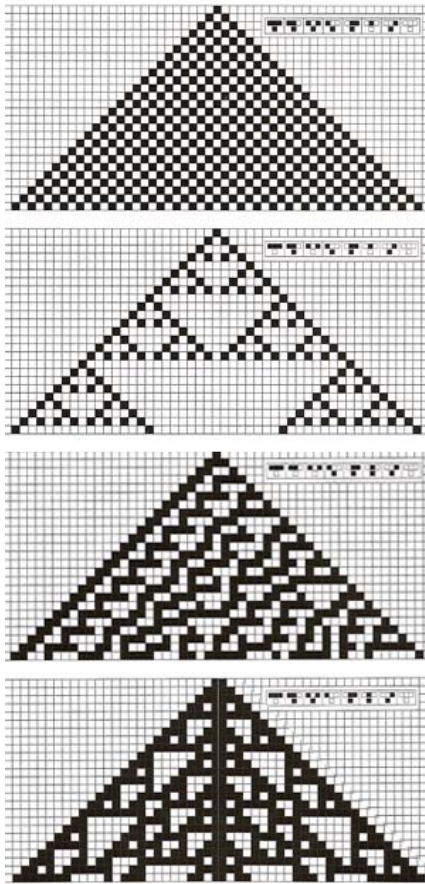 recently borrowed from other disciplines, such as biology and mathematics, and has been introduced to architectural practice and design experimental works as form generation tools. Among them are cellular automata, L-systems, Fractals, Voronoi diagrams, Shape Grammars and Genetic Algorithms [GA]. In architecture GAs operate in two ways: as optimization tools and as form-generation tools. In the first way GAs address well-defined building problems, such as structural, mechanical, and thermal and lighting performance. In the second way GAs are used under the scope of the concept of *Emergence*. While GAs will be investigated further on a following section, all the other generative systems are analyzed below.

Cellular Automata
John Von Neumann built an abstract model of self-reproduction in the late 1940s to simulate biological growth. This system is known as Cellular Automata [CA]. Cellular Automata are discrete models consisting of an array of cells, each of which can be in one of a finite number of possible states. Each cell is updated synchronously according to local interaction rule that takes into account the states of the neighboring cells. Architects use CA due to their ability to generate patterns. Their application ranges from ornamentation to automated volumetric building generation. Ingeborg M Rocker and his design team at Studio Rocker applied a CA to generate forms in building scale, while Michael Batty utilized them to create neighborhoods of different land uses in an urban scale. (Wolfram, 2002)

L-Systems
Aristid Lindenmayer devised Lindenmayer-systems, also known as L-systems, in 1968 as a method to simulate the growth of plants. L-systems consist of four elements: a starting configuration or initial string, a set of rules, constraints, and variables. The basic concept behind L-systems is writing and rewriting the code by replacing the letters that comprise the initial string by others based on the prescribed rules applied in parallel. The new string is subject to the graphical commands that are pre-selected. L-systems grow by repeating this process for several iterations. The fact that through a few simple rules complicated forms can emerge makes L-systems a powerful tool for designers. Among others, Karl S. Chu and the Emergent Design Group utilized L-systems as a form generation tool for the projects X Phylum and Genr8 respectively. (Lindenmayer and Prusinkiewicz, 1990)

Patterns generated by various Cellular Automata rules. Image: (AD, Vol. 76, No. 4, pp. 37).

Voronoi Diagrams

Voronoi diagrams were considered as early as 1644 by René Descartes but are named after the Russian mathematician Georgy Fedoseevich Voronoi who defined and studied the general n-dimensional case in 1907. Voronoi Diagrams are a class of patterns called Dirichlet tessellations. A Voronoi diagram is a way of decomposing a space into regions. All of the Voronoi regions are convex polygons. Each polygon contains exactly one generating point and every point in a given polygon is closer to its generating point than to any other. Voronoi diagrams are used widely in biology, computer graphics, geophysics, anthropology, and urban planning. In architecture, Voronoi diagrams are used both in two-dimensional and three-dimensional compositions. For example, Benjamin Aranda and Chris Lasch have used this system to create an organizational template assembling project called Grotto, which will be examined further in the next section. (Aurenhammer. and Klein, 2000)

Fractals

Benoit B. Mandelbrot originated the term Fractal in 1975 to define the mathematical rules that govern natural objects such as coastlines, clouds, and snow flakes. Fractals are broadly geometrical shapes that can be subdivided into parts and their geometric characteristic is self-similarity i.e. each of the parts are similar, reduced copies of the whole. To produce a Fractal one should define the initiator which is the starting shape and rules whichreplace each copy of the initiator with a smaller copy or set of copies. Representative examples of this process are: Sierpinski gasket, Koch curve, and Cantor set. Fractals are used in African, European and Indian Architecture especially for the generation of temples and monuments. On the other hand, Greg Lynn based the initial formulation of the Cardiff Bay Opera House on Fractal organization. (Addison, 1997).

Shape Grammars

In 1971, George Stiny and James Gips introduced Shape Grammars as the first design-oriented generative system. Shape Grammars is a rule-based method which generates designs by performing visual computations with shapes in two steps: recognition of a particular shape and its possible replacement. A Shape Grammar consists of a set of rules which are applied recursively starting with the initial shape. Rules specify the particular shape to be replaced and the manner in which it is replaced. Underlying the rules are spatial transformations -i.e. translation (move), scale, rotation, and reflection- that permit one shape to be part of another. With a finite number of rules shape grammars generate an indefinite number of designs. A distinctive feature of shape grammars is

that rules can recognize and be applied to emergent shapes, that is, shapes that are not predefined as part of the grammar. The power of Shape Grammars also lies in the fact that they can be used both as analysis tools, decomposing complex shapes into simple entities, and as synthesis tools, generating complicated forms from simple shapes. Jonathan Cagan has generated real product designs using shape grammars with customized output programs. (Gips and Stiny, 1972)

2.1.3. Generative Design Examples

Many recent projects have used generative algorithms and most of them have usually combined various generative systems. Two representative examples of these projects are examined bellow. The first, Experience Music Project designed by Gehry, second, Grotto project designed by Aranda / Lasch, uses Voronoi diagrams as a composition tool.

Experience Music Project, Gehry Partners, Seattle, 2000
The project is a multi-use facility that hosts a variety of programs surrounding the theme of music. Shape Grammars were utilized to rationalize the highly curved surfaces of the building. The design surface was initially decomposed to a rectangular grating to which the grammars' operations are to be performed. The grammar was constructed in such a way to define the regions of the surface whose digression from a plane was within a predetermined tolerance. This simple and straight forward algorithm could be modified in a variety of ways,
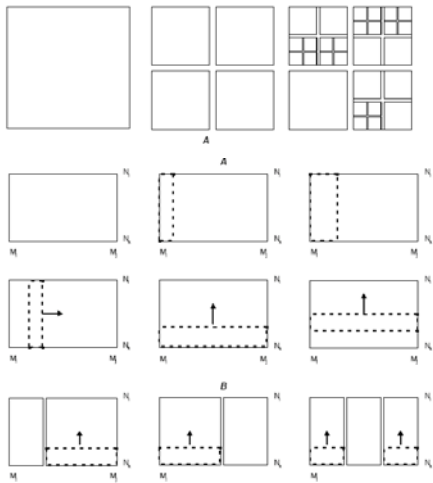
Top: Sample of Shape Grammars subdivision rules. Bottom: Representative results from the subdivided surfaces. Image: (Shelden, 2002).
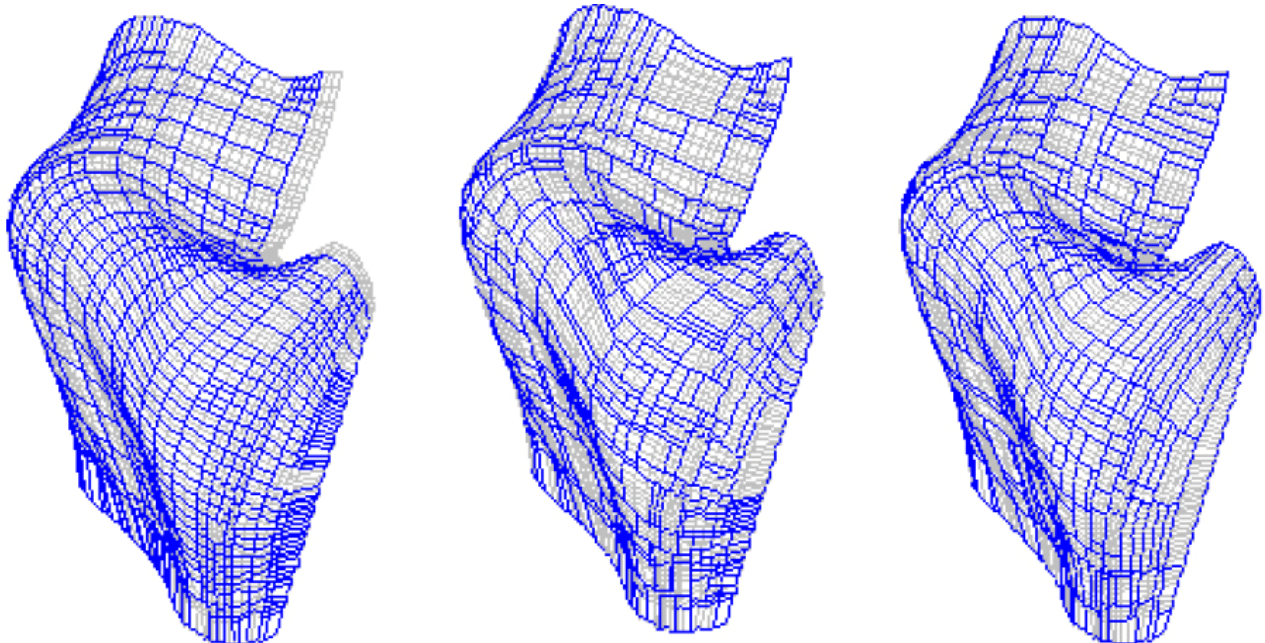
generating a plethora of possible solutions. For example instead of splitting the region in the middle the algorithm could divide it in three or four parts. During contract document preparation, the subdivision approach was modified again. The fabricator imposed additional constraints, minimizing the size of a panel sheet and the area of panels. The subdivision grammar re-ran producing an acceptable panel size. Figure shows the results as they appeared on the design development package of the project. These sequential studies demonstrate the power of Shape Grammars to address certain constructability issues on surfaces and consequently influence the qualities of a design. (Shelden, 2002)

Grotto, Aranda / Lasch in collaboration with Daniel Bosia

The Grotto project is a proposal for a summer pavilion inspired by English gardens of the eighteenth-century. Benjamin Aranda and Chris Lasch envisioned the project as a courtyard installation which bears a resemblance to a natural cave. Since the structural module of a grotto is the boulder, the architects utilized four different boulders which fitted together generate a three-dimensional pattern which never repeats itself in the same way twice. The way that those four modules are fitted together was governed by a combination of generative systems, such as Voronoi Diagrams and Danzer tiling, implemented by the Advanced Geometric Unit at Arup. Architects gave names for the four boulders based on their geometrical attributes, since each of the four modules behaves differently. To construct the project, the architects cut the boulders out of foam and assembled them with steel reinforcement between connecting faces. Plug and Eraser boulders, i.e. the names that designers gave to two of the four modules, create a stable ring pattern and represent the basic structural unit. Since the four boulders were defined as building elements that create the closed space, the open space, which is used for the functional needs of the pavilion, was generated by excavating space of the non-repetitive modules. (Aranda and Lasch, 2006)
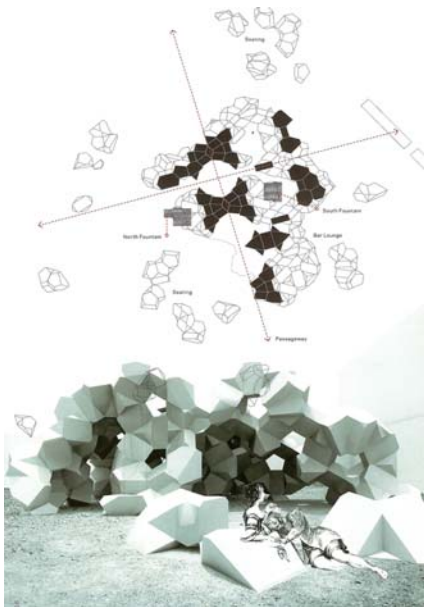
Top: Plan and 3d model of the Grotto project. Bottom: 2d Voronoi study. Image: (Aranda and Lasch, 2006).
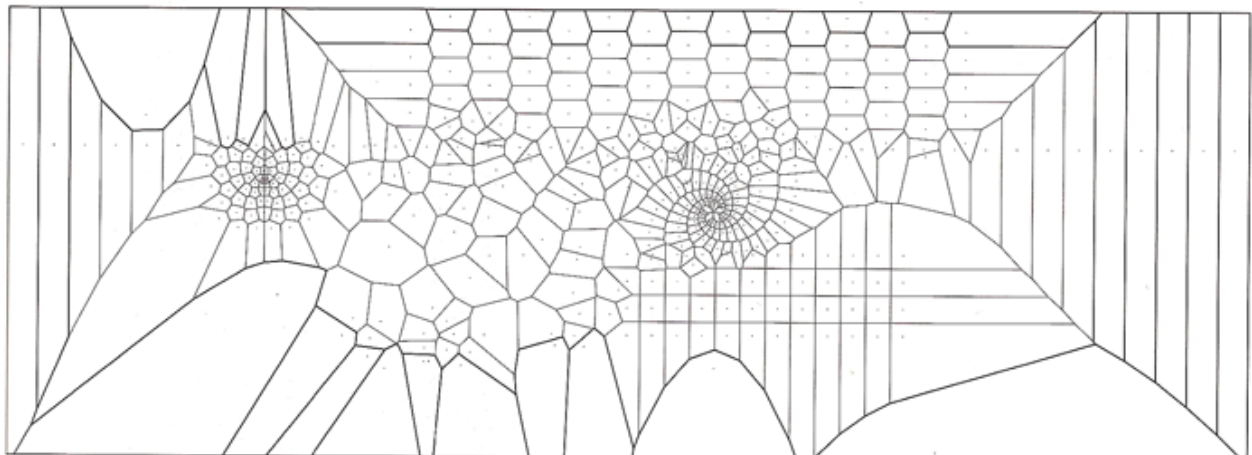
2.2. Performative Design

2.2.1. Definition of Building Performance

The notion of performance has been a central subject of contemporary theory and practice of architecture. Architects have started to realize that building performance and building behavior can be a crucial input in the design process and in form exploration and not merely act as compulsive function applied later to a form. There is, however, an indistinct picture about what building performance is. According to the American Institute of Architects (AIA) the basic aim of building performance is:

"To ensure individual effectiveness over time through functional and environmental quality in buildings, e.g. thermal, indoor-air, acoustical and visual quality,[…] to ensure organizational effectiveness over time through the integrity of buildings, e.g. flexibility, durability, and structural and fire safety,[…] to ensure societal effectiveness over time through equitable resource utilization and integration with the surrounding built environment, e.g. materials, land, water, energy, waste, and infrastructure." (Bullen, 2008)

2.2.2. Definition of Performative Design

If building performance is defined within such an extensive context, then performative design is defined as a design paradigm which involves multiple realms, from social and cultural to technical and financial. In performative design there is a shift from a merely aesthetic approach to a more multi-level approach towards the behavior of the building. Consequently, a building is modulated mostly by how it performs rather how it appears. That is because the performance guides govern the design process. Indeed, the designer in order to specify the desired performance has to first determine the performance variables, and constraints and then specify the performance criteria. Undoubtedly, the selection of the variables, constraints, and objectives along with the determination of their values modifies not only the desirable performance of a building but also the appearance of it.

Need for Sustainability
Mistakenly, many people equate Performative Design with Sustainable Design or "Green Architecture". The major difference between the two is that Sustainable Design focuses only on the "green" performance of a building trying to minimize its impact on the environment, while Performative Design is a holistic way of looking at the behavior of a building. Besides their differences, their similarity, which is the need for energy conservation, is the motivating force that propagates the notion

Dwellings in Cappadocia, Turkey. Image: (Lechner, 2001).

BUILDINGS 35%

INDUSTRY 35%

TRANSPORTATION 30%
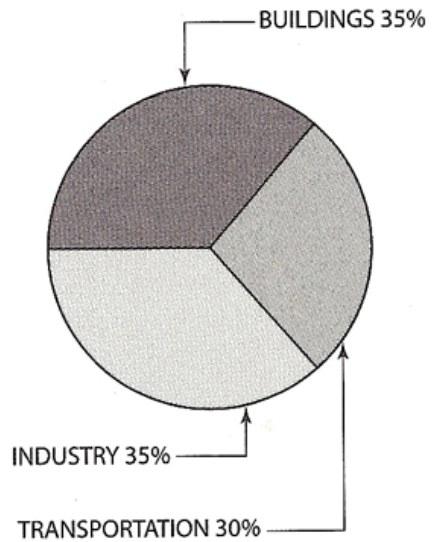
Energy consumption of the United States.
Image: (Lechner, 2001).

of Performative Design worldwide, not as another architectural trend but as a necessity.

In the past due to the lack of technological means vernacular architecture was directly bonded with building performance and passive systems, i.e. free-energy methods for heat transfer and storage. With the advent of active systems, artificial lighting, air-conditioning and other building technologies, architecture started to secede from building performance and focus merely on formal exploration. This shift had a profound reverberation on energy consumption and the planet's eco-system. The construction and operation of buildings consume fifty percent of energy resources worldwide, while transportation consumes the thirty percent and manufacturing the remaining twenty percent, making the building industry "the least sustainable industry in the world." (Edwards and Hyett, 2001)

However, the real problem is not the energy consumption within the buildings but the consumption of non-renewable forms of energy, and consequently the emission of environmentally damaging by-products, such as carbon dioxide. The challenge is, therefore, to reduce energy consumption and at the same time to utilize renewable forms of energy that do not have adverse consequences. Based on these promises, new mechanical systems that supply air-conditioning and heating, lighting systems and other building technologies are designed. Many architects also design buildings that generate their own renewable energy.

2.2.3. Design Tools

While generative design uses generative algorithms as design tools, performative design uses optimization and simulations techniques to formulate the design problems as described following sections.

Optimization
Optimization is a problem-solving method that searches for the best (optimal) way to satisfy a prescribed need within several constraints using the available means. Optimization is broadly applied in engineering realms since the world "optimize" contained in the term optimization is embodied on the philosophy of engineering. Indeed the fundamental intention of an engineer is to find ways to improve a design so as to satisfy the original need, within the available means. The phase of design optimization is the phase where the designer selects the "best" alternative solution. Approaching building as a design problem and the design process as a way to solve this problem inevitably introduces the notion of optimization in architecture.

Performance Space
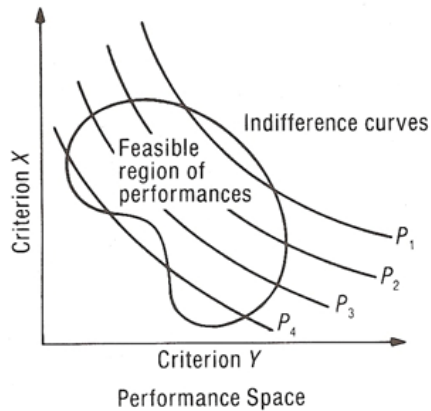
2d representation of feasible solutions. Image: (Gero & Radford, 1980).

Due to Computer-Aided Design [CAD], Computer-Aided Engineering [CAE], Computer-Aided Manufacturing [CAM], and optimization software, designers can approach and solve very complex problems. To do so the key point is the good formulation of the design problems and consequently the formulation of the four elements that a design problem consists of: the design variables, the objective functions, the parameters, and the constraints. Design variables can be any quantity represented by any number under the absolute control of the designer. For example for a building envelope variables could be the height, the width and the length of the building. The set of variables describe all the possible design alternatives.

Design variables are quantities or mathematical expressions that form the design space and are controlled by the designers.

$$x = \begin{bmatrix} x1 \\ x2 \\ x3 \\ x4 \\ ... \\ xn \end{bmatrix} = \begin{bmatrix} aspect\_ratio[-] \\ transmit\_power[W] \\ \#of\_apertures[-] \\ orbital\_altitude[km] \\ ... \\ control\_gain[V/V] \end{bmatrix}$$

Design objectives are what designers intend to attain, for example in optimization objectives are the functions that designers try to maximize or optimize. The objective is expressed in terms of the design variables. Often the objective is a scalar function; however, in real systems there are multiple objectives that often conflict. (Lecture notes of MIT class, ESD.77J Multidisciplinary System Design, instructors: Prof. de Weck and Prof. Willcox)

$$J = \begin{bmatrix} J1 \\ J2 \\ J3 \\ J4 \\ ... \\ Jz \end{bmatrix} = \begin{bmatrix} cost[\$] \\ range[km] \\ weight[kg] \\ datarate[bps] \\ ... \\ ROI[\%] \end{bmatrix}, x \rightarrow J(x)$$

Design criteria are the explicit functions that a solution must satisfy in order to achieve the prescribed design objectives.

Design variables are quantities or mathematical expressions that form the design space and are controlled by the designers.

$$x = \begin{bmatrix} x1 \\ x2 \\ x3 \\ x4 \\ ... \\ xn \end{bmatrix} = \begin{bmatrix} aspect\_ratio[-] \\ transmit\_power[W] \\ \#of\_apertures[-] \\ orbital\_altitude[km] \\ ... \\ control\_gain[V/V] \end{bmatrix}$$

Parameters are quantities that affect the design objectives but are considered fixed so they cannot be changed by the designers. Sometimes parameters can be turned into design variables to increase the design space and other times parameters are former design variables which were found not to affect any of the objectives or excluded because their optimal level was predetermined. *Constraints* act as boundaries of the design space and typically occur due to finiteness of resources or technological limitations of some design variables. Constraints can be divided into inequality constraints and equality constraints as shown below.

Graph of a single objective function. Image: (Gero & Radford, 1980).

Inequality constraints: $g_j(x) \leq 0, j = 1, 2, ..., m_1$

Equality constraints: $h_k(x) = 0, k = 1, 2, ..., m_2$

It might be difficult for the designer to recognize whether a condition is a constraint or an objective. For this reason designers sometimes revise the initial formulation in order to fully understand the design space. To put it simply, objectives are what we are trying to achieve, design variables are what we can change, and constraints are what we cannot violate.

One of the earliest applications of optimization techniques was the "Building Optimization Program" utilized by the architectural firm Skidmore, Owings & Merrill (SOM) at the late 1960s. The optimization software was based on the idea that the design of tall office buildings was specified by strict constraints, such as the lot size, the building regulations, the programs, and cost restrictions. Once the computer was fed with the relevant information, it could calculate all the possible configurations of a building, computing the floor heights, the rentable floor areas, the sizes of structural elements, and the production cost.
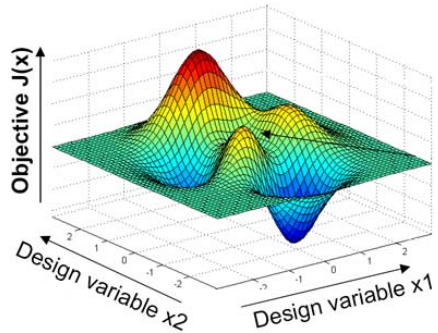
3d graph of an optimization problem. Image: (Lecture notes of MIT class, ESD.77J Multidisciplinary System Design).

Single and Multi- Objective Optimization
When there is a single objective to be minimized or maximized then the optimization model is scalar, and the problem is called a single-objective optimization problem.

$$min\ J(x)$$
$$s.t. \quad g(x) \leq 0$$
$$h(x) = 0$$
$$x_i^t \leq x_i \leq x_i^u \qquad i = 1,...,n$$

If the problem has more than one function as an objective then the optimization model will have a vector objective rather than a scalar one, and it is called multi-objective optimization problem.

Most architecture design problems, as most real world problems, are multi-objective in nature. Several methods exist for converting a multi-objective problem into a substitute problem that has a scalar objective and can be solved with the usual single objective optimization method. The simplest one is to assign weights to each objective. To find the overall solution one should multiply each objective by its corresponding weight and then add all the objectives. This method is rather subjective since the decisions that are taken to find the optimal solution to the substitute problems are based on the designer's judgment. This lies in the fact that design preferences are rarely known precisely from the very early of the design phase, so preference values are adjusted gradually and trade-offs become more evident.

The best algorithm
To run an optimization method one should not only know how to define the variables, objectives, parameters and constraints but also how to select the search algorithm among a plethora of algorithms that are suitable for optimization. The selection of an algorithm is based on the number of design variables, their type, i.e. whether they are real or integer, continuous or discrete, the linearity and smoothness of the objective function, whether there are equality or inequality constraints, the number of the objectives etc. Apart from these conditions, however, as most of the seasoned users would argue "the best algorithm is the one you understand best". That is because the effectiveness of an algorithm is influenced both by the underlying theory of the algorithm and its implementation.

Due to the nature of design problems, which will be further examined in the next chapter, designers usually utilize a particular class of optimization algorithms called heuristic algorithms. Heuristic algorithms follow a simple set of rules to return within a minimal computing time an acceptable and

approximated solution of a design problem. The advantage of heuristic algorithms is that they are efficient and can be used for large scale optimization problems which cannot be solved to optimality by standard optimization algorithms. The disadvantage is that heuristic algorithms do not guarantee the "best" solution. Three representative examples of heuristic algorithms are: Simulated Annealing [SA], Tabu Search [TA], and Genetic Algorithms [GA]. Genetic Algorithms will be analyzed further not only because they are used both as a form generation tool and as an optimization tool but also because they are used in the case studies that are presented in this thesis to demonstrate the possibility of implementation of Integrated Design.

Genetic Algorithms
The concept of Genetic Algorithms [GA] was introduced by Holland in the 1970s and since then they have been used as adaptive heuristic search methods for solving optimization problems simulating biological evolution. Genetic Algorithms transform a set of individual objects that represent an initial population into a new generation using the Darwinian principle of reproduction and survival of the fittest and analogs of naturally occurring genetic operations. In GA terminology, the initial population called the genotype or chromosome is controlled by the rules and the settings embodied in the genes. Before utilizing the GA, the designer maps the points of search with the artificial chromosomes. The mapping function is called encoding and the physical expression of the genotype is called phenotype. The GA process is directed by four basic operations: the creation of the population, selection, crossover, and mutation.

The population of chromosomes represents the possible solutions of the problem and is randomly generated. Typical population size ranges from 30 to 200. Generally the initial population needs to be large enough to allow a wealth of genetic information to be included in the process. However, the implications of using large populations are both large inertia in search progression and high computing time. Micro-GA answer to problem by using small populations, encouraging early convergence, and maintaining the best chromosome from the previous generation; a selection called elitism.

An individual of the population is probabilistically selected based on its fitness function, defined by the designer that determines how "good" a solution is. In other words, the fitness of an individual determines the probability of its survival to the next generation. There are different selection procedures in a GA, such as proportional selection, ranking, and tournament
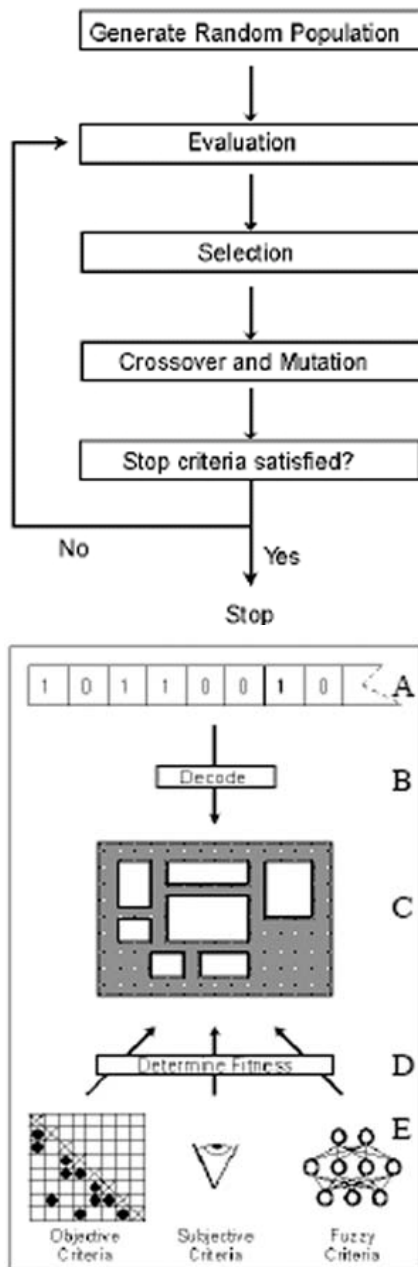
Top: Flow chart for the GA Process. Bottom: Evaluation function in GA. Image: (Acadia Proceedings, Daru , 1997, pp144).

selection procedure. The selected individuals are ranked by their fitness and copied to the next generation.

The genetic operation of crossover is performed to create the new generation of chromosomes. It allows new individuals (offspring) to be created by the combination of individuals (parents) that were selected based on their fitness. Each offspring contains some genetic material from each of its parents. After many iterations of the crossover operation, genes of good chromosomes prevail and appear more frequently, eventually leading to good design solutions. There are various types of crossover but the most frequently used are: the one-point crossover, in which the parents are cut at a specific point and the head of the first is pasted to the tail of the second or vice versa; and the two-point crossover, in which a part from one of the parents is obtained and exchanged with the part that lies in the same location of the other parent.

Before re-applying selection to the new population, the mutation function takes place. Mutation is a random event, occurring with a user-defined probability to only some of the new offspring, altering some characteristics of chromosomes. Mutation plays a critical role in a GA. While through crossover the offspring are getting more and more alike, mutation reintroduces genetic diversity back into the population and assists the search escape from local optima. Typically the mutation rate is very small and therefore, the new offspring produced by mutation will not be very different from the original one.

Genetic Algorithms differ from traditional search optimization methods since they: search a population of points in parallel and not only a single point, use probabilistic transition rules and not deterministic ones, require little information about the design problem, can operate on various representations, and are very robust. They are efficient when the search space is large and complex, no mathematical analysis is available and the traditional methods have failed. However, as with all heuristic algorithms, GA have no clear termination criteria and they do not guarantee the optimum solution.

Genetic algorithms have been used in architecture in various realms. The most successful applications of GA are related to energy consumption and structural analysis. In the first case there are many studies that tried to optimize the size and control of Heating, Ventilating and Air Conditioning [HVAC] systems, such as the study of Wright in 1996, Huang in1997 or Caldas 2001. In the second case GA have been used for the optimization of trusses, beams, columns, and other structural
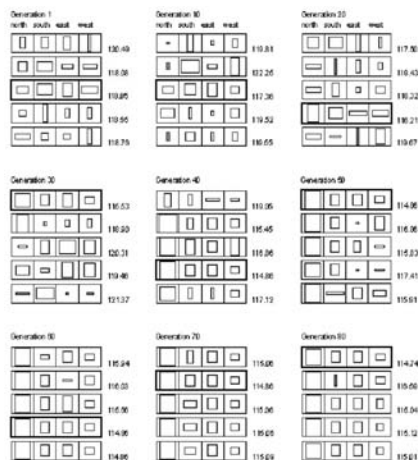
Generations of window orientation and size of buildings through the use of GA. Image: (Caldas, 2001).

elements in many studies, among others the work of Camp in 1998, Wang in 1996, or Shea 2000.
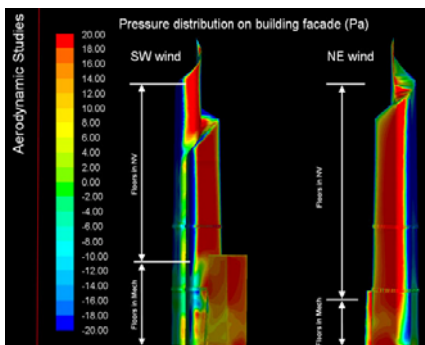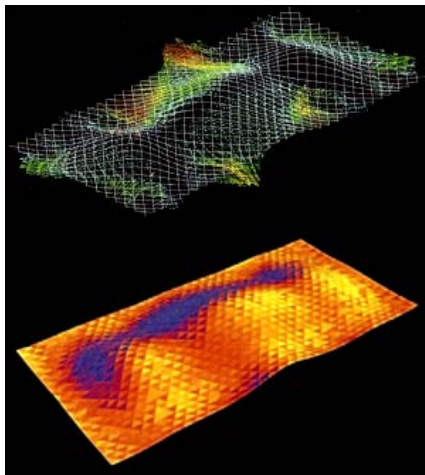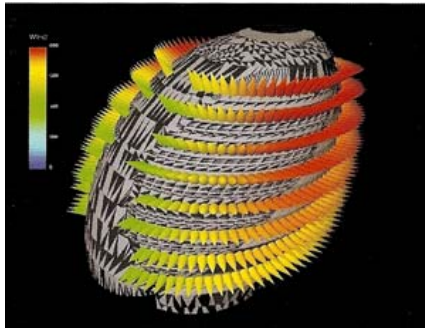
Simulation

The term simulation is used in many contexts. Throughout this thesis simulation will be used to denote a modeling technique which can be used to predict the behavior of a system through the abstract representation of basic components of the system without embodying the entirety of it. In order to utilize simulation, the designer has to describe the system's physical behavior in mathematical formulas, including all the necessary variables and constraints that govern the system. The power of simulation techniques and software lies in the fact that by modifying the values of the design variables the designer can observe the impact of the changes on the system's performance. Their weakness is that they work under a trial and error process. That means that the designer, in order to get any feedback, must first have a solution so the design process involves repeated postulations, evaluations and modifications to obtain the desired result.

Despite its disadvantages, simulation has played a significant role in computation. In particular, in performative design, simulation techniques feed the design process helping designers to obtain, justify, and confirm through representations the achievement of the desired solution. However, the success of this process depends on the ability of the designer to define the design problem correctly, to formulate a useful hypothesis and most importantly to interpreter the alternative output. To do so the designer must be an expert in design, engineering, construction, mathematics, physics etc since the simulation draws its resources from many disciplines. Probably, something like that might be difficult to achieve by just one person, but that will be analyzed further in the third chapter of this thesis. The new advanced simulation environments, however, expedite to a great extent the aforementioned difficulties while at the same time allow the representation and evaluation not only of very complex geometrical forms but also the simultaneous calculations of multi-performances.

Simulation Environments

The history of simulation environments for building performance goes only a few decades back, yet their impact on the way that the buildings are analyzed, designed and constructed is great. Many applications have been developed that simulate and evaluate different building performances, such as structural, lighting, thermal flows etc and utilize different simulation algorithms. Advances in building simulation environments have been focused in two areas: how they are structured and which functions they support. Indeed, developers upgrade simulation

Top: Solar Diagram for London City Hall. Image: (Performative Architecture, pp 211.) Middle: Structural and Solar simulation analysis for Smithsonian Institute Courtyard Enclosure. Image: (AD, Vol76, No 2). Bottom: Pressure distribution on the Bishopsgate Tower façade. Image: (International Journal of Architectural Computing, Vol. 05, No. 01, pp. 66).

algorithms, used to predict building performance, in order to achieve efficiency of representations and prediction validation.

It is difficult to categorize simulation programs since many of them have multiple features. Below, however, three representative examples of structural, lighting, and building energy simulation environments are briefly mentioned. ANSYS Structural delivers qualified and reliable structural simulation results through the use of linear and nonlinear algorithms. Also, the user can easily simulate large-scale, complex structures or intricate components. Ecotect is a tool for lighting, acoustics and energy analysis. The ability of the user to model and script is very promising for the further development of an environment that integrates the analysis with synthesis. Given the hourly weather data of a site, the description of the building and its HVAC equipment, DOE-2 simulates the hourly consumption and cost of a building. Through output, a designer can assign the values of the building variables that improve energy efficiency, while retaining thermal comfort and cost-effectiveness.

2.2.4. Performative Design Examples

There are many projects that exemplify the principles of performative design. Two of those will be analyzed below. The first is the New York Times Building in New York by Renzo Piano Building Workshop completed in 2007 and the second is the British Museum Great Court in London by Foster and Partners in 2000. The first is cited mostly because of its sustainable design and the second due to its optimized structural design.

New York Times Building, Renzo Piano, New York, 2007
The fifty-two-story transparent glass tower accommodates the New York Times headquarters. The double curtain wall increases energy efficiency while the atrium located on the five-story base of the tower creates an open urban space and at the same time increases the natural air ventilation of the building. Piano's main challenge of the project, regarding energy consumption, was to reduce the heat gains during the summer and spring months. Instead of using small windows or coated glass, the architect proposed a double-skin curtain wall of low-e glass with ceramic rods that acts as a sun screen and the use of internal automated blinds that decrease the reflected glare. An advanced dimmable lighting system with motion sensors decreases the real energy consumption to 70%. The under floor air distribution system that is utilized retains free air cooling and heating and 100% outside air ventilation. The complemented power of the site is generated by a1.4 megawatt gas-burning

plant. While the utility costs are reduced significantly, no renewable-energy sources are used on the site. (Jones, 2008)

British Museum Great Court, Foster and Partners, London, 2000

This project is about the reinvention of the Great Court. Foster, through the use of an undulating glazed roof covering a space of 92x73 meters, converted the courtyard at the centre of the British Museum into the largest enclosed public space in Europe. The roof supports the frames of glass panels that are designed so as to maximize daylight and decrease summer solar gain. Since the space that should be covered is asymmetric, the formation of the geometry of the roof was a very difficult and complicated process. Firstly the designers and engineers created a starting grid based on which they specified the initial positions of the nodes on the curly surface. Then they displaced each interior node after checking that the new node remained on the surface. The displacement was computed by the weighted average of the coordinates of the four surrounding nodes. This relaxation process was repeated until the final geometry of the roof was settled. The result was an undulating minimal steel latticework that supports 3,312 unique triangular glass panels that have different sizes and shapes. (Glynn, 2004)

Top: Aspect of the glazed roof. Bottom: Original, relaxed, and finalized roof grid. Image: Chris Williams, (staff.bath.ac.uk/abscjkw/Organic).
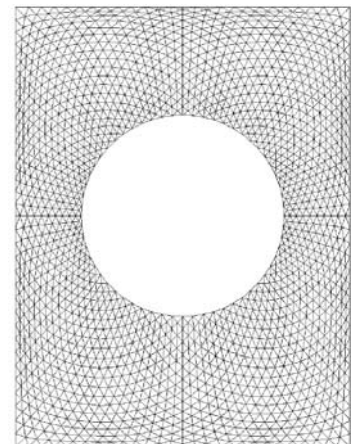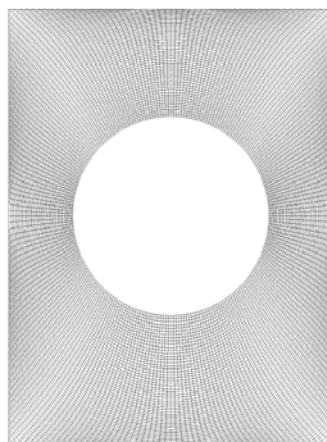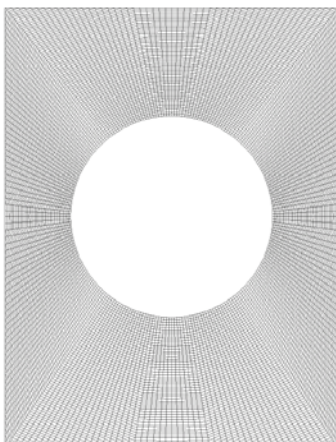
2.3. Generative Performative Design

2.3.1. Definition of Generative Performative Design

Generative Design is an approach in which aesthetic criteria supersede all others. On the other hand, in Performative Design performance variables and criteria govern the design process and consequently the design solution. Generative Performative Design is a paradigm which combines on a certain level the two aforementioned design approaches. Moving beyond form generation alone, Generative Performative Design includes performance models, simulation techniques and optimization algorithms. Indeed, the designer creates an evolving algorithm which encodes a generative algorithm and includes performance feedback. This way the computer is used to automatically generate and evaluate possible configurations, and present the designer with optimal or acceptable and approximated solutions for the problem under study.

2.3.2. Generative Performative Design Examples

In the case of Generative Performative Design paradigm not many studies have been implemented yet. However, two representative examples will be analyzed below. It is worth mentioning that these examples are not buildings; they are software applications, design tools that are tested later on design projects. The first example is the Generative Design System implemented by Luisa Caldas in 2001 and the second is the EifForm developed by Kristina Shea in 2000.
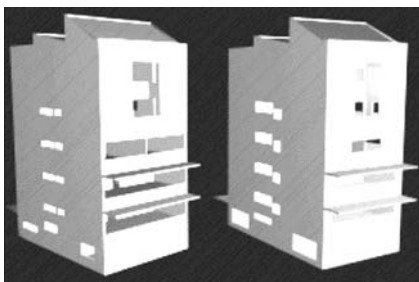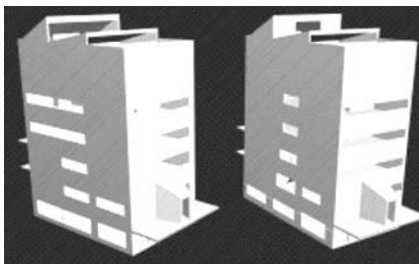
Top row: Siza's solution. Bottom: GDS solutions. Image: (Caldas, 2001).

Generative Design System, Luisa Caldas, 2001
The Generative Design System [GDS] is an evolutionary optimization software developed by Luisa Caldas at MIT, Cambridge in 2001. Generative Design System generates energy-efficient novel building envelopes optimizing lighting and thermal performances. The software combines a search optimization algorithm, Genetic Algorithms [GA], and a building energy simulation environment, DOE-2. While in EifForm the generation of form was driven by a specific generative system, SG, in this case the design rules do not follow a predefined algorithm. The designer encodes her/his design intentions and GDS generates alternatives that meet both the performative objectives of daylight and thermal. The Generative Design System was tested within the framework of Alvaro Siza's School of Architecture at Oporto, Portugal. Results from the test ranged from ones similar to Siza's solutions to some radical alternatives from the existing design. (Caldas, 2001)

EifForm, Kristina Shea, 2000

EifForm is a stochastic optimization software developed by Professor Kristina Shea at Cambridge University, Great Britain in 2000. EifForm generates the overall form of a structure and its assemblies (lattice elements and joints) optimizing performances such as structural efficiency, assemblies size, saving of materials and aesthetics. EifForm combines a generative algorithm, Shape Grammar [SG], and a heuristic optimization algorithm, Simulated Annealing [SA]. The whole process can be defined by the term Shape Annealing that first Mitchell and Cagan introduced in 1983. The software, through the rules predefined by the SG, generates the spatial transformation of the lattice structure and measures their performance and through SA chooses the alternative that is nearest to the optimal solution. EifForm can generate innovative designs that are rational and well adapted to their purpose. The Hylomorphic project created as part of the exhibition "The Gen[H]ome Project:: Genetics and Domesticity" was located in the MAK Center for Art and Architecture in Los Angeles on March 2006. The Hylomorphic project is a temporary lightweight canopy and was implemented by EifForm. (Shea, et al. 2003)

EifForm is one of very few examples of Generative Performative Design in which Generative Design systems are integrated with more that one performance, in the case of EifForm, structure and aesthetics. As such it could be perceived as a precedent of Integrated Design, which is thoroughly examined in the following chapter.
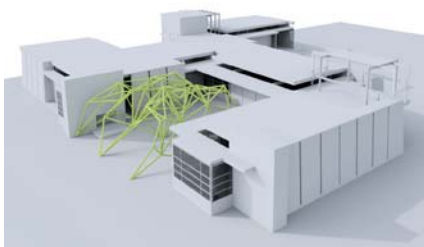
Top: Model of the building of MAK Center of Art and Architecture and canopy structure. Right: Representative iterations of EifForm. Image: (Shea, 2006).
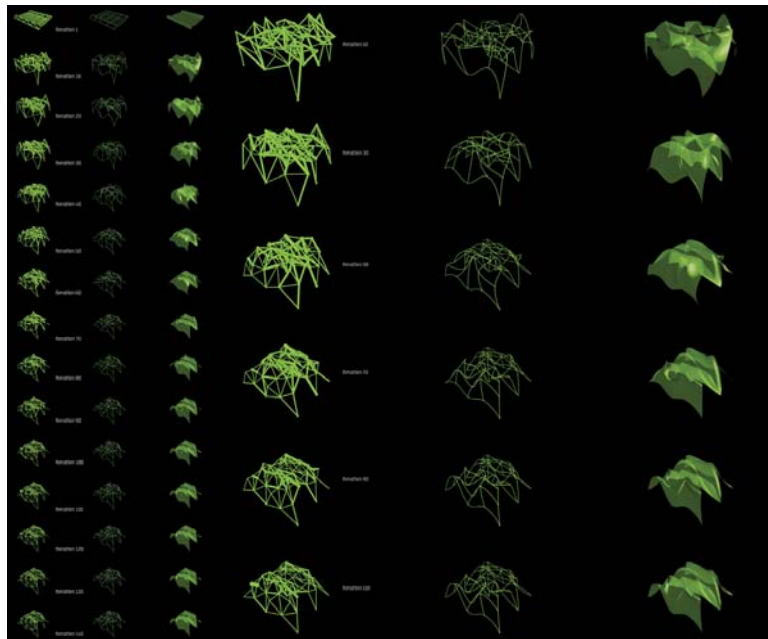
3. Integrated Design: A Generative Multi-Performance Design Approach

3.1. Definition of Integrated Design

In general terms, Generative Performative Design emerged by the combination of the principles of Generative Design and Performative Design. Examining thoroughly Generative Performative Design demonstrators, the conclusion that can be made is that most of these are constructed in such a way to satisfy performances from one building area. Integrated Design approach fills this gap by the introduction of more than one building performance from different disciplines. This feature converts Generative Performative Design to Integrated Design as a Generative Multi-Performative Design approach. The two principal components of Generative Multi-Performative Design are: the integration of form and performance and the integration of multiple building systems. Before further defining and analyzing "Integrated Design", a detailed examination of these two components will introduce the framework of Integrated Design approach.

3.1.1. Integration of Form and Performance

The relation between form and building performance is manifold. Indeed, it has been a core subject throughout the history of architectural theory and practice. A representative example is the well-known phrase: "form follows function". The whole discussion lies in the fact that architecture is a combination of art and science, form and performance. Consequently, a design should meet both aesthetic and functional requirements.

Indeed, design is not only comprised of geometrical and spatial problems. Design problems should not merely satisfy designers' form aspirations. They cannot be viewed only as systems of representations outlined in composition and experienced in perception. At the same time, design problems are not merely engineering problems. They cannot be expressed only through mathematical equations and solved by search techniques. They should not be seen as nothing but a system of components governed by physics and realized by construction. If the focus is merely on the artistic or the scientific aspect of architecture, on form expression or on building performance then design loses its integrity. If the emphasis is on form innovation and complexity disregarding building requirements, then design loses its feasibility.

Even though Christopher Alexander in his book Notes on the Synthesis of Form (1964) does not refer to performance but to context, i.e., everything that makes demands on the form, the relation he proposes between form and context could also describe the relation of form and performance. According to Alexander (1964): *"Every design problem begins with an effort to achieve fitness between two entities: the form in question and its context. The form is the solution to the problem; the context defines the problem.* This statement points out that the relation between form and performance is not competitive; is not a duality. On the contrary, it is cooperative and mutual.

Within this scope, the term "integrated" is introduced. Redefining form not as the geometric representation of a material object alone, but as a multitude of effects and behaviors, the dualism of form and function is transformed to a synergy that aspires integral design solutions. Introducing building requirements at the early phase of the design process and using them along with spatial relations as guides for form exploration combining search methods with design algorithms, architects will get various possible satisfactory solutions that improve the functionality and quality of the design.

3.1.2. Integration of Multi-Building Systems

At the same time, the term "integrated" has a second use throughout the thesis; it designates an alternative framework in which multiple building performances can be considered. There have been two primary ways to perceive and deal with complex multiple performance requirements, in general. The first way is to perceive that a problem consists of discrete sub-systems whose existence and performance does not influence the rest sub-problems. These sub-systems are called *modularized*. The independent solution of modularized sub-systems leads eventually to the solution of the overall problem. The second way also is to perceive that a problem consists of sub-problems that all of them are tightly linked together. They interact and influence one another that is why they are solved simultaneously. These sub-systems are called *coupled*. Such coupled sub-systems are usually met in industries like automobile, aerospace and naval where all sub-systems are tightly joined and exist to support a main function. In architecture coupled sub-systems are not usually identified, while modularized sub-systems are.
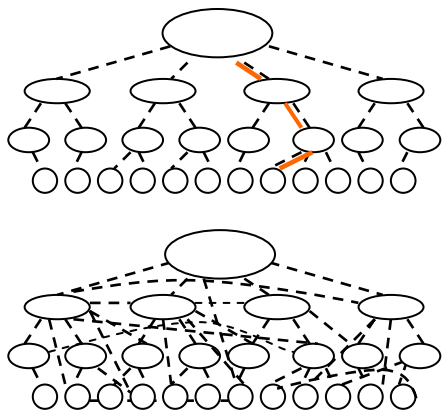
Graphs of modularized and coupled systems.

Indeed, many architects perceive a building as a system which is sub-divided into modularized sub-systems each of them perform a single principal function, such as spatial, acoustic, lighting, structural etc. Due to this fact, each sub-system is analyzed, evaluated, and synthesized independently in a sequential process. To put it simply in this case architects assume that the performance of one sub-system has no effect on the performances of the other subsystems. For example, in a tall building the participants in the design process may individualize the slabs, the structural system and the curtain wall, each of which represents a different performance and a discipline. Based on this resolution, the architect will study the design of the floor plans satisfying both functional and aesthetic criteria, then the structural engineer will select the structural system maximizing its stiffness and minimizing the weight and cost of the material, and then the lighting designer will propose the design of the curtain wall maximizing solar gains during the winter months and minimizing energy consumption.

While the concept of modularized sub-systems has been adopted by many designers for a long time questions emerge from its practice in architecture. The most crucial one is the relation between the building sub-systems. Are they really independent? Does not their design and performance have any impact on the design and behavior of other elements, and consequently on the overall appearance and performance of the building? The answer is neither easy nor unique. That is why there is a debate on the subject.

3.1.3. Integrated Design Approach

Architecture is not a monolithic unity but constitutes multiple and diverse components that operate at different scales and levels. That is why the thesis acknowledges that both independent and interrelated sub-systems co-exist in a building. Many design processes have been proposed for dealing with discrete sub-systems; the thesis will propose an alternative design approach to deal with more than one building performance that will interact with others. In higher detail, the thesis examines a different design approach that simultaneously analyzes, evaluates, and generates interrelated building systems, which belong to different disciplines, in order to satisfy both form exploration and performance efficiency. The thesis shifts from an independent and largely mono-functional design approach to a more interactive and multi-performative one.

It is worth mentioning at this point that an integrated design approach is not an optimization method. On the contrary, the research has been built upon the notion of "alternative" rather
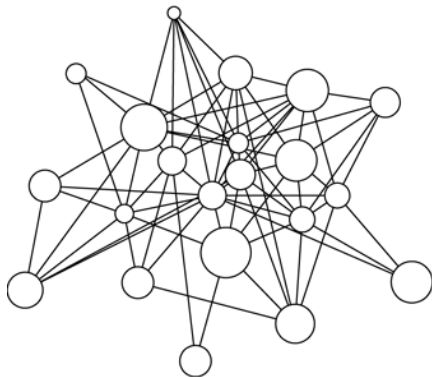
Bubble diagram of interrelated performances.

than "optimal." That is because the term optimum, either referring in a process or a building, is vague in design. Also, the end product of the proposed approach is not a single building. Actually it is not even a building. Through the utilization of this approach several potential design solutions emerge. They are digital visualizations of primitive design "ideas" that embody a higher level of intelligence combining both efficiency and form exploration. However, they should be used as basis for further investigation and elaboration in the next steps of design process.

Also, no specific and detailed processes, algorithms or steps are proposed for the utilization of integrated design approach. That means if someone wants to follow this approach he is free to select the process, determine design data, select the design tools, and implement the computation model that will perform the calculations and generations under subjective judgment. These actions do not influence the framework or the efficiency of integrated design because the end product of integrated design is a broad design approach and not a design software, an algorithm, or a strict process that requires a finite sequence of steps to be completed.

Setting the basic framework of the integrated design approach, this chapter will build up step by step the whole context and scope of the approach. Many questions emerge especially about the practicability of this approach. Examining thoroughly the approach of Integrated Design, the potential benefits of the approach, as well as conditions to be met in order to facilitate or make possible the approach, the thesis will try to answer most of the emerging questions and fill in the puzzle of the integrated design approach.

3.2. Potential Benefits of Integrated Design Approach

The potential benefits from the utilization of Integrated Design approach can be many. Indeed, a significant advantage is for example the increase in the number of examined design scenarios and alternatives. In practice, designers and engineers faced with time and budget constraints often generate and test relatively few options for a design problem. Another potential benefit is the improvement of the overall design understanding. In practice, the specialization of participants makes them missing the whole picture of the project and the whole design process time-consuming, something that leads to gross errors in transmitting and interpreting information. Also, the reduction of design cycle is another potential advantage of the utilization of Integrated Design. Indeed, the simultaneous integration of

multiple performances leads to the reduction of back and forth steps are reduced and consequently to the overall decrement of the design circle. The final result of these benefits, undoubtedly, is the reduction of the overall cost. Last but not least, through the use of a generative multi-performative procedure, new levels of complexity might be explored and new unexpected aesthetics might emerge.

All these potential benefits act as motivators for the adoption of integrated design, without leading to the conclusion that this approach has no difficulties or weaknesses. Indeed, the difficulties of the process need to be addressed in order for this design approach to be followed. These prerequisites demand changes not only in the architectural practice and computational technology but also, and most importantly, on the way architects have been taught to perceive design.

3.3. Prerequisites for the Utilization of Integrated Design Approach

3.3.1. Multi-Disciplinary Collaboration

Undoubtedly, the design and construction of a building is a multi-disciplinary and inter-disciplinary situation. While this is a self-evident precondition in theory, it is not applied in practice. The way an organizational chart of architectural and engineering firms is structured does not promote the communication and collaboration of employees. Each individual focuses merely on the specific area of the building industry that she/he works on without paying any attention to the rest of the scales and areas of a project. The quantity and diversity of supporting participants involved in the design phase in particular, is another factor that leads to the lack of collaboration.
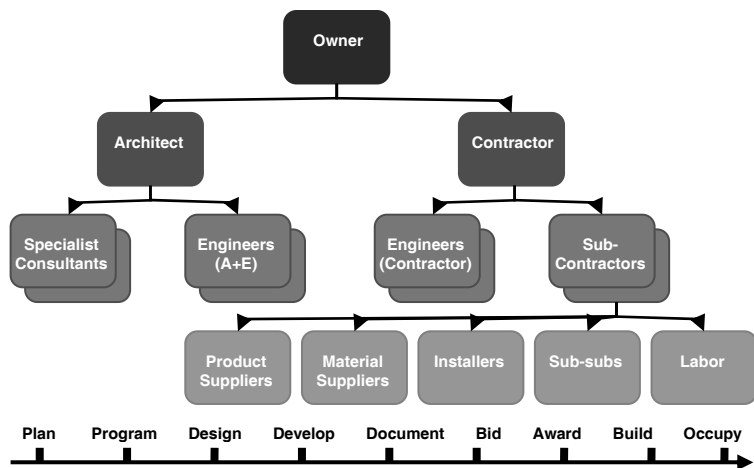
Conventional organizational chart is structured hierarchically according to disciplines and time.

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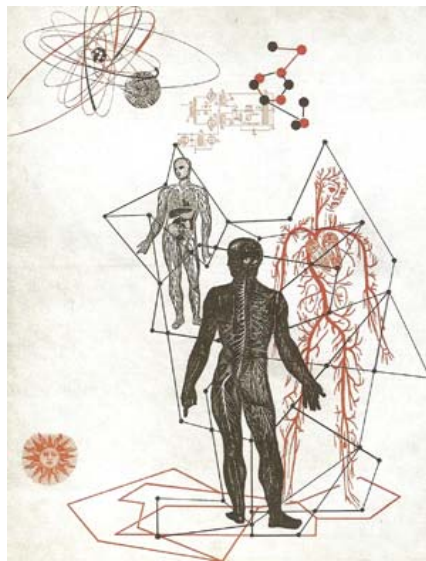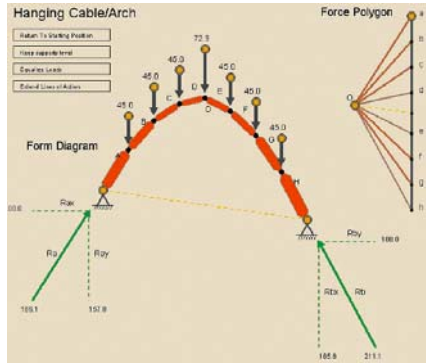
Top: Active statics diagrams. Image: Screenshot Active Statics, (http://acg.media.mit.edu/people/simong/statics/data/index.html). Bottom: Illustration from Jon Entenza, What is a House? Image: (Arts and Architecture, July 1994).

Two major teams can be distinguished broadly within the design phase: engineers and architects. The first studies the natural sciences which are concerned with how things are, while the latter studies architecture which is interested in how things ought to be (Simon, 1970). Consequently, their tasks and points of view are different, if not conflicting. Engineers solve deterministic problems, trying, for example, to maximize structural efficiency while minimizing the quantity of materials. On the other hand, architects design with multiple, complex and conflicting networks of requirements and even though their goals might be objective many of the design problems and their evaluation criteria are ill-defined and subjective respectively. Based on their field of study, supportive participants have been trained to observe, perceive, and interpret things under a specific scope. Inevitably, that has a direct impact on the comprehension of the nature, the definition of inputs, and evaluation of possible solutions of a design problem. Besides the many differences that exist between architectural and engineering approaches to design, there is a strong need for bridging them.

The fact that Integrated Design approach is based on the integration of both building performance satisfaction and building form exploration makes multi-disciplinary communication a dominant prerequisite for its utilization. A collaboration that will promote sharing of knowledge, conceptual brainstorming, multiple goals, creative negotiations, and performative feedbacks, will be necessary. An environment in which participants in the design phase work at the same level of importance, are interested in each other's problems, and answer each other's questions and uncertainties will aid multi-disciplinary collaboration. Such an environment will permit many multi-disciplinary, and maybe conflicting, performances to be examined and faced in greater detail at the early design phase and not when the design solution is solidified.

3.3.2. Early Integration

Generally, the sooner you solve a problem the better it is. In an integrated design approach in particular, the early introduction and analysis of variables, objectives, and constraints of interrelated and multi-disciplinary performances is a necessity. Indeed, although the design phase itself represents only five per cent of the overall construction costs of a project, the decisions made at the very early design stages often have the greatest impact not only on the overall building performance but also on the overall cost.

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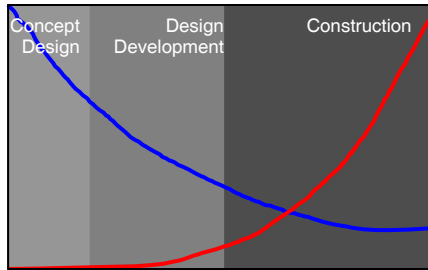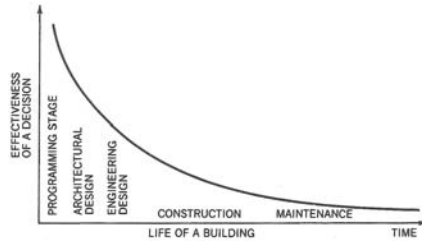
Potential Effect on Building Performances
Implementation Cost

Top: Graph of design decision effect along building cycle. Image: (Lechner, 2001). Middle: Cost and effect graph during design process.
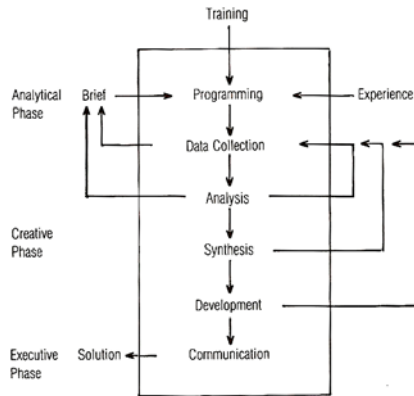
Archer's graph of design process. Image: (Rowe, 1987).

That might rest on the fact that many of the involved performances most likely will conflict at some point. So, if participants deal with these conflicts soon, they can solve the design problems more easily and perhaps the alternative solutions will be also more efficient than when facing the conflicts later. Alexander (1964) states about that: "The later in the process conflicting diagrams have to be integrated, the more difficult the integration is. Naturally, then, since the conflicts have to be resolved sooner or later, we should like to meet them as early in the process of realization as we can, while our ideas are still flexible."

Undoubtedly, it is impossible to exhaustively list all the sets of requirements at the very early stages of the design phase, since many of them occur not only during the design phase but also during the construction phase or even after the implementation of the project. However, there are ways to face this "natural" difficulty of design problems. For example, the system that participants will build could be a real time system in which the interface between user and machine is continuous. In such a way, the user could modify the design problem, by adding, removing or changing data, throughout the design phase.

3.3.3. Identification and Operation of Design Sub-Systems

After the 1940s, many studies have been done in the field of design theory. In these studies, design has been perceived as a goal-oriented or a problem-solving activity. These systematic design methods tried to reduce the amount of errors, trade-offs and implementation time, while obtaining more innovative and advanced designs. Representative examples are the design methods and models of Morris Asimow (1962), Christopher Jones (1962), Bruce Archer (1963), Herbert Simon (1967), Horst Rittel (1972), Donald Schön (1983) and Konstantinos Papamichael (1991).

Most of the other systematic design processes share a common ground, such as the number of design stages. Indeed, in general, the basic design phases described in most of the aforementioned design methods are the *analysis*, the *synthesis*, and the *evaluation* of the design problem. In detail, during the first phase designers collect and classify the data relevant to the design problems, then they formulate the design alternatives, and finally they appraise the outputs by using some criteria. The three basic stages of analysis, synthesis and evaluation are used as references throughout the thesis more as a common, easily-applied and broad design strategy rather than a norm. That means that participants, in order to utilize Integrated

Design, can replace them by other design sub-processes or routines if they want.

What, however, is considered as another prerequisite for the utilization of integrated design approach, is operation of design sub-systems. In it the evaluation and synthesis of interrelated sub-systems should be done in a holistic and synergetic way. In more detail, while the analysis of a very complex inter-disciplinary problem is usually done through its decomposition into smaller problems, the next phases should be more unified and synergetic so as to activate the "integrated" aspect.

A fourth prerequisite is the perception and identification of sub-systems. Unconsciously, designers have learned to identify sub-systems by a very explicit way, equalizing each of them with a single-function, however in reality a sub-system have multi-functions. For example, the separation of structural and façade systems, which is usually done in practice, does not follow always physical separation. Particularly in this instance, the identification of the two obvious systems might lead to losing a potential observation of co-related performances, which in turn could result in a loss of innovative formal representations. A very common example is the oblique columns that could also function/act as external shading devices. By thinking about the performances beyond their affiliated systems, designers might invent new building systems that satisfy many needs simultaneously through an unexpected form. A system is not merely comprised of physical materials and visual objects; it can be a force or energy.

Various visualization of tectonic sub-systems. Image: (Reiser, 2006).

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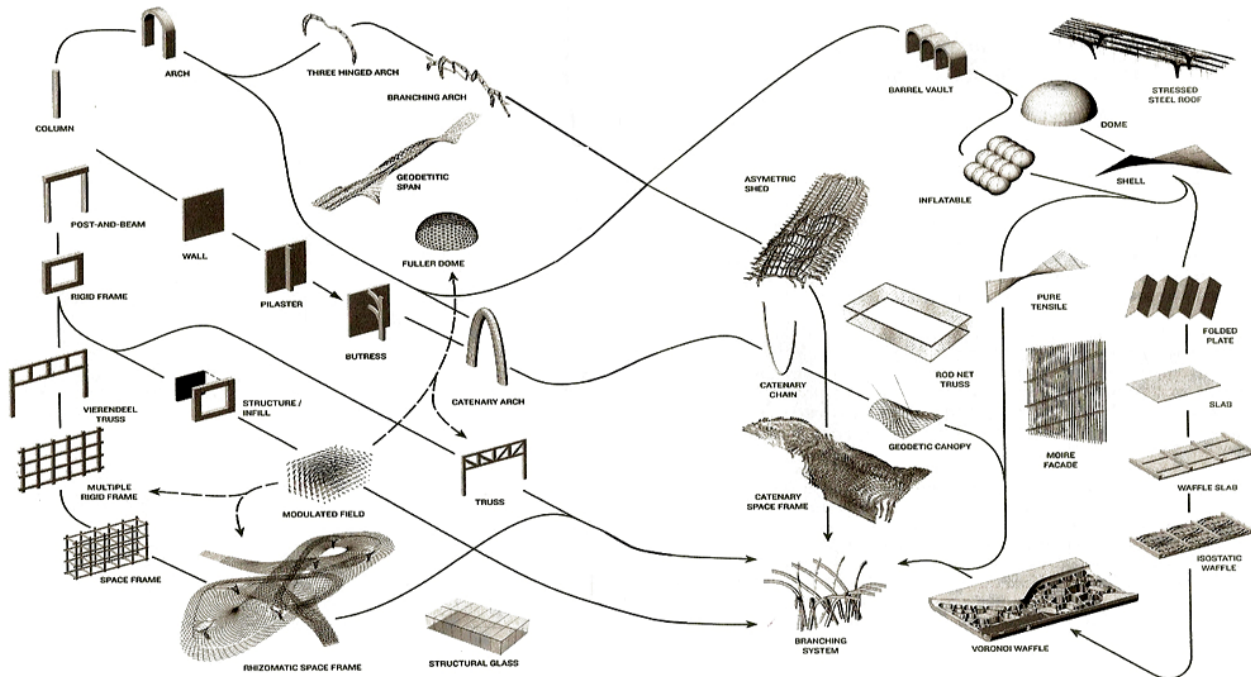
3.3.4. Real-time Interaction

While early integration is a prerequisite, it is acknowledged that it is impossible for all the sets of requirements to be exhaustively listed at the very early stages of the design phase, since design problems emerge continuously and some features of them may never be fully covered. This mainly rests on the fact that in a design problem both deterministic, objective, quantitative sub-problems and non-deterministic, subjective, and qualitative sub-problems co-exist. In the recent literature on problem-solving design processes the terms of well-defined and ill-defined are used to describe the dual nature of design problems. Among others theorists, Newell, Shaw, and Simon (1967) and Rittel (1972) opposed well-defined problems to ill-defined ones. In general terms, they defined the first as problems that have prescribed goals, definite formulation, and can be solved by provision of appropriate means. On the other hand, they defined ill-defined problems as open-ended problems, which do not have a rigorous and stable formulation and consequently they have different potential solutions, no stopping rule, and are not by default correct or incorrect. Given the fact that many of design problems are ill-defined, designers who approach integrated design should better avoid static formulations of the design problems and prefer more dynamic ones which will be open to future modifications of the system.

Also designers should know the basic principles of simplification, since it is an integral part of Integrated Design. Generally, designers tend to analyze an abstraction of a real system and not the real system itself. In particular, in the proposed approach in which designers have to deal with many interrelated performances and a huge number of complicated and conflicting relations among them, the simplification of a design system is a prerequisite. Certainly, simplification is a very helpful tool towards the solution of a complex design problem. However, it might lead to undesirable results, turning a simplified system of a problem to a reductive one. An abstractive model is the approximate representation of complex functions of real world systems. To put it simply, a simplified model keeps all the information of the physical system that has a crucial influence on the performance of the model. At the same time, it omits data that neither affect the performance of the system nor the performances of interrelated systems. A reductive system, on the other hand, is a system that has been simplified to such an extent that it loses part of the significant functions and relations that it should carry. The results generated by a reductive system are not that meaningful since they do not depict reality. To articulate, formulate and simplify a design problem and its sub-problems, static formulation should be avoided while more dynamic formulations should be

promoted that will be open to future modifications throughout the design process.

3.3.5. Design Multi-Tools

While in the second chapter various design tools and techniques were analyzed, in this section more advanced optimization and simulation methods will be examined. These try to meet the increased needs that arise from the simultaneous analysis of many interrelated performances among multiple disciplines, such as the multi-physics simulation environments and multi-disciplinary optimization techniques.

Multi-Disciplinary Optimization

Multi-disciplinary Design Optimization [MDO] is a methodology for the design of engineering systems that searches for optimal solutions for complex and interacting problems among various disciplines. (Lecture notes of MIT class, ESD.77J Multidisciplinary System Design, instructors: Prof. de Weck and Prof. Willcox) Industries from the field of engineering that use MDO are: aircraft, spacecraft, and automobile. The utilization of MDO methods in the case of an integrated design approach is ideal, due to the structure of the method and the common field of study. Indeed, like many design problems, multidisciplinary optimization problems consist of more than one traditional disciplinary area expressed by governing equations from various fields, such as physical, economic, social etc.
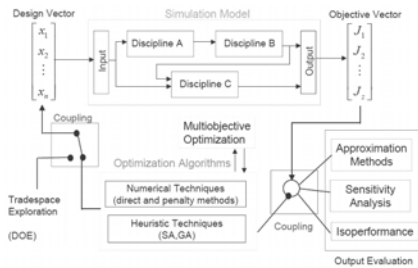
Graph of MDO process. Image: (Lecture notes of MIT class, ESD.77J Multidisciplinary System Design).

Briefly, MDO mathematically traces a path in a predefined design space from an initial design towards improved designs, according to the objective criteria, by operating simultaneously on a large number of variables, constraints, and objective functions. Undoubtedly, it is about a feature that is beyond the power and perception of the human mind. Probably that is why MDO is such a powerful design tool. In general terms, the typical process that is followed in a MDO system is first the designation of all the requirements of the system, then the definition of variables, objectives and constraints, and next the formulation of equations that govern the system. Next is the integration of the model into an overall system simulation, benchmarking of the model, formal optimization to find the objective function, and finally a post-optimality analysis to explore the possible tradeoffs.

Certainly, MDO is a rather complicated method; however, the potential benefits of its utilization are many. Among others, it is the huge quantity and variety of data that can be handled, the reduction of design time, and the fact that it is a highly scientific procedure not biased by intuition. Yet, a designer has to face a

number of possible disadvantages most of them related to the number of design variables. Indeed, the increase of design variables leads to rapid growth of numerical problems and computational time and memory. Other weaknesses are the limited operation of MDO on discontinuous functions and its limitation to the range of applicability of analysis programs.

In the building industry and particularly during the design phase, MDO methods cannot be utilized within the overall range of a design problem due to the nature of design problems. However, MDO can be a very helpful tool for the designers, since it performs calculations exploiting potential relationships and combinations that surpass designers' abilities to thoroughly comprehend and predict them. On the other hand, designers should be aware that MDO is not a stand-alone, automated design tool. It can be a very valuable design tool only when it is combined with substantial human interaction and complemented with other design tools, such as multi-physics simulation software.

Multi-Physics Simulation Environments
The need of simultaneous analysis and prediction of many interrelated performances from different disciplines demands more advanced simulation tools which will implement these operations within one environment. Multi-physics simulation environments respond to this need incorporating performance evaluation from diverse disciplines. Multi-physics simulation environments permit a more realistic representation of building behavior during the action of various and simultaneous phenomena, such as earthquake and wind loads, fluid flow, sound waves etc.

A representative example of a multi-physics simulation environment is the ANSYS multi-physics system which integrates structural, thermal, computational fluid dynamics, acoustic and electromagnetic simulation analysis and evaluation in a unified environment. Using it, users construct a single model for performing all the analyses and calculations of various performances, avoiding the numerous exports and imports of files between the various simulations and design software.

A Unified Design Multi-Tool
Methods to perform integrated analysis have been developed, such as the MDO and multi-physics simulation. However there are still many gaps in the full support of Integrated Design. The most fundamental ones are: first, the integration of the three basic digital tools: design, optimization, and simulation software, second, the usage of optimization and simulation tools during the synthesis phase, and third is the accommodation of

generative process within these three different digital environments.

In practice, the design loop for the use of various digital tools can be outlined as follows: designers develop the design model using design software packages, such as AutoCAD, 3dMax, Rhino, Maya or even more advanced ones like Revit, Digital Project and Generative Components. Then engineers create the analysis and behavior prediction model using simulation software, then they create the decision model in Excel, Matlab, etc creating their own evaluation and weighting code, and finally they create the optimization model. This process is followed for many iterations, and when a satisfactory solution emerges, based on the subjective judgment of the designer, the process is over. Due to the lack of integration between the various involved digital tools, the process requires the construction of many representation models, each of them having its own unique format, which in analytical tools is often non-graphical. Likewise, the results have a specific format that is not always supported by all involved means and therefore the outputs are not easily redirected back into the overall design process.

The fact that many architects are trying to create their own design tools that have a better connectivity between the three basic digital tools, justifies the need of integrated digital multi-tools. On the other hand, only recently have been several methods been developed which couple optimizer and simulation models by accommodating the necessary equations and algorithms. This shift has started to make "technically" possible the development of frameworks that can achieve design analysis integration based on semantic representations which support object and data interaction.

At the same time, there are advanced tools that perform very sophisticated processes simulating complex physical phenomena and finding the optimal solutions to complicated and multi-level problems. These tools merely feed the analysis phase by simulating and optimizing a static design solution without strongly affecting the stage of synthesis. Recently, a shift has been noticed towards the utilization of these tools as both analysis and synthesis tools. This shift is directly related to the utilization of optimization and simulation tools for the generation and modification of the digital prototype. In order for this to happen, generative algorithms must be implemented within the simulation and optimization environments, since these environments do not currently provide generative capabilities. Even if this development is achieved, another condition must still be satisfied to fully meet the computational needs of an integrated design approach.

Description	Decisions	Objectives
Simulation		
Generation		
	Optimization	

Categories of CAD models according to description, decision, and objective stages. Image: (Gero & Radford, 1980)

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Indeed, even if simulation and optimization tools are used for design synthesis as well, the potential solutions will be governed merely by building performance criteria. Consequently, there will be no room for geometric relations and aesthetic criteria. This will lead to a loss which will alter the nature of architecture. Undeniably, treating buildings as efficient, yet, soulless objects will lead to the equating of design with the natural sciences. Calculating physical equations omitting any level of creativity and originality is not a design activity. The point is not to create merely feasible buildings. The point is to help the designer to exploit design possibilities, following a new path towards generated analysis and synthesis that surpasses designers' limited calculating ability and creativity.

In order for an integrated generation to be achieved, the integration of design tools with simulation and evaluation tools and the exploration of generative capabilities of digital design tools are needed. Indeed, current digital design tools, apart from the fact that they are not connected sufficiently with analysis tools, do not efficiently support the development of generative systems. Thus, they limit the range of alternative solutions to a minimum and their quality to static. In an integrated design approach, in particular, design tools that will generate alternative design solutions based on spatial, aesthetic, and building performance criteria are needed. The ideal scenario will be the development of a unified environment in which the three basic digital tools will be used both for analysis and synthesis phase integrating generative, optimization and simulation algorithms.

3.3.6. Alternative Design Solutions

Evaluation of Design Solutions
As in all problem-solving activities, as well as in design, at the end of each search procedure there must be an evaluation phase. During the evaluation phase the potential solutions will be compared with the prescribed evaluation criterion, i.e., the desired performance standards defined by the designer, and will be sorted by ranking. The phase of evaluation is very significant in design, since the number of potential design solutions might be inexhaustible. At the same time the nature of design problems make evaluation phase a really hard case. Indeed, if there is no rigorous idea about what a design problem is and how it could be solved, a discrete evaluation criterion is rather impossible. Also, whereas quantitative criteria can often be easily specified and measured, qualitative criteria cannot. Moreover, some qualitative design criteria cannot be determined at all, deeming judgment as impossible.

For example consider aesthetics: can aesthetics be coded and consequently evaluated? If the answer is positive, how can this be achieved? There are studies that have tried to include aesthetic criteria among other performance criteria. If the aesthetic evaluation is done manually -i.e., after the completion of an automated evaluation phase some of the potential solutions are selected based on subjective nondeterministic aesthetic criteria of the designer, it is easy, since no specific designation of aesthetics is needed. However, there are proposals that handle aesthetic evaluation automatically. For example, in the case of EifForm aesthetic criteria are extracted and calculated by the geometric principles of the project, i.e., symmetry, analogies etc. Undoubtedly, one can argue that symmetry and "good" analogies is not the only criterion of aesthetics. Indeed, the difficulty in coding and evaluating aesthetics lies upon its complicated, manifold and subjective aspects. At this point the case of compromises arises and will be examined below.

Weighted Multi-Criteria
Given the fact that a building has to meet various and diverse requirements, the subjects of conflicts will arise sooner or later. In the case of Integrated Design the conflicts arise earlier making the beginning of the design process more difficult. That is because, first, the criteria are no longer single-objective but multi-objective, and second, the performances are interrelated so the evaluation criteria are more likely to conflict. Due to the features of design criteria, the relative importance of the criteria is not well-specifiable. Consequently, the designer should balance each "best-possible" performance of each building requirement and the overall building performance. To put it simply, the design is a continuous compromise between what is desirable and what is possible. In order for participants to deal with such a crucial problem, a common process followed by other engineering fields is the assignment of weight values on different objectives and criteria.

However, weighting building performances is not an easy and straightforward activity. Indeed, while the identification of a building requirement is rather objective, the assignment of weights for objective criteria is a rather subjective activity. Thus weighting performances creates continuous disagreements among the participants throughout the design process. There are many examples of conflicting objective criteria. For example, the view criterion might be important for the architect while the orientation criterion might be significant for the daylight designer. If the "good" view is west oriented then there will be a conflict between the two requirements and consequently on the weights they will assign to the view and orientation criteria.

Since the design criteria are many and some of those are nondeterministic, subjective, and conflictive, the possibility of change should be open throughout the design phase. Especially when some criteria are not met, the modification of design variables and design objectives is required. Trying to improve performance according to one or more performance variables may result in upgrading, improving or degrading performance with respect to one or more of the other performance variables. *Upgrading* a performance criterion means to include new performance variables that affects the criterion. *Improving* a criterion means that a solution has been found but it can be enhanced. Finally, *degrading* a criterion means that the criterion does not meet the desired standards and might never do so (Papamichael, et al. 1993). It is worth mentioned at this point that adjusting the weights of criteria does not necessarily lead to average solutions. After many modifications, the final weights of design criteria are those that evaluate the final alternative solutions.

Set of Satisfying Design Solutions
Undoubtedly, if someone had to choose between a good and a best solution she/he would select the best one. However, in real life such choices rarely happen since it is very difficult to find the optimal solution for a large number of diverse, interrelated and complicate problems. Especially in design, where many of design problems are nondeterministic and ill-defined, design solutions are rarely perfect and almost never found without sacrificing any requirement. To put it is simply, design almost invariably involves compromises and there are no almost optimal solutions that will simultaneously meet all building requirements.

Answering to this feature of design, Simon (1957) introduces the term of "satisficing" to describe the range of acceptable solutions which even though not optimal, still satisfy the multi-objective criteria. "Satisficing" are middling solutions that perform reasonably well with respect to several criteria and acceptably with respect to some others. Among others, Alexander (1964) corresponded to the notion of "satisficing" design solution stating that: "for most requirements it is important only to satisfy them at a level which suffices to prevent misfit between the performances, and to do this in the least arbitrary manner possible."

The fact that a design is not an optimization problem does not lead to the conclusion that optimization techniques and methods cannot be used during the design process. While for optimal alternatives optimization methods can be used, such as linear and dynamic programming, for "satisficing" solutions heuristic

algorithms, such as Genetic Algorithms and Searching Annealing, can be utilized. Heuristic algorithms, as discussed in the previous chapter, return acceptable and approximate solutions and are ideal for large scale optimization problems, which cannot be solved by standard optimization algorithms. In this case designers through the computational design process identify possible solutions for a problem and select the most suitable one, based on their subjective judgment.

The problem of finding optimal solutions for multi-criteria problems is not faced only in design. Many other engineering fields share this difficulty. For example, the MDO method most of the time is not used to find the truly optimal but rather to find an improved or even a feasible design. A common method used to deal with this aspect of multi-criteria problems is the reduction of at least one objective criterion without any other being augmented. With this method the solutions are decreased to an achievable sub-set called *Pareto set* comprised of *Pareto points*. According to Papalambros and Wilde (2000) "in multi-criteria minimization a point in the design space is a Pareto (optimal) point if no feasible point exists that would reduce one criterion without increasing the value of one or more of the other criteria.

Pareto set of solutions in multi-criteria problems is the nearest equivalent to the optimal solution of single-criterion problems. Any of the Pareto points may be a potential 'good" solution; defining "good" based on each designer's judgment on the relative importance of performances. There are four different ways to generate Pareto sets: the constraint method, the weighting method, the Pareto optimal dynamic programming, and the noninferior set estimator (John Gero and Antony Radford, 1988).

The first two methods will be examined more since they are commonly used in design. The basic concept behind the *constraint method* is to turn an n-objective problem to single-objective, by keeping one primary objective and converting the remaining n-1 objectives to constraints. In simple terms, the *weighting method* converts a multi-criteria problem to a scalar optimization problem by assigning weight values to each objective. To determine the weight values, the designer tests different set of weights until he finds the adequate representation of the Pareto set. Then, the overall objective function of the multi-criteria problem is calculated as the sum of the weighted objectives.

Multi-Objective = Objective1 (weight) + Objective 2 (weight) + ...
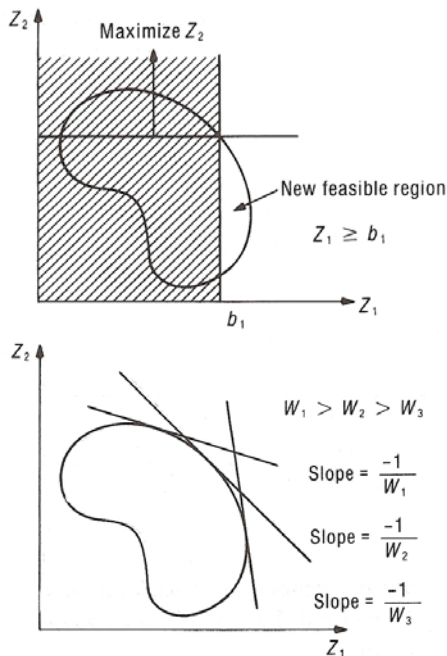
Top: Graph of constraint method. Bottom: Concept of weighting method. Images: (Gero & Radford, 1980).

The *noninferior set estimation method* is an extension of the weighting method that adopts the already known Pareto points and then uses weights to investigate the rest of the Pareto set. Finally, *Pareto optimal dynamic programming* is similar in concept to conventional dynamic programming, which however is a rather complicated process and cannot be explained in few sentences. The selection of the Pareto method is the last activity, before the final selection of outputs. It is also the last prerequisite for the utilization of integrated design approach.

3.4. The role of the architect

The word architect derives from the Greek word *αρχιτέκτον* comprised of the words *αρχή* that means chief and *τέκτον* that means builder. That is why in general terms an architect is a person who translates a client's requirements into a built artifact. Throughout the history of architecture, the role of architects has been manifold, ranging from designing structures, estimating costs, assembling components and materials, to managing the construction process. Undoubtedly, since the twentieth century architecture has been identified with the construction of a building. However, many things have changed since then: the invention of advanced materials and technologies, the increasing level of complexity involved in most building projects, and the quantity of information widespread to many disciplines etc. All these changes have led to the proliferation of specialization. Since the integrated design approach is focused merely on the design phase, omitting other phases such as the construction, occupancy, and maintenance, the examination of the role of the architect here will be limited on this phase.

In general, an architect's contribution to the building industry extends far beyond form creation and aesthetics. It can influence the perception, safety, performance and value of a building. In practice, a simplistic view of the role of the architect during design phase is: the generation of alternative architectural approaches, the creation of drawings and physical models, and the validation of the design against client requirements, state regulations, cost budget, and assumptions. While by definition an architect should act as a coordinator of participants involved in the design phase, such as structural, mechanical and electric engineers, in practice this is not always applied. Indeed, most of the time an architect is the first and the last link in the design chain, without participating in the in-between phases.

At this point it is worth mentioning that the integrated design approach is not a process that could be utilized and realized merely by a single person; it is almost impossible and risky.

Given the fact that the design approach is comprised of a number of sub-tasks that require diverse skills and knowledge for their implementation, an individual architect or engineer cannot thoroughly comprehend, predict and perform all these multi-disciplinary tasks. Taking multi-disciplinary collaboration as a given, the architect should be the person who is actively present and guides the overall computational process.
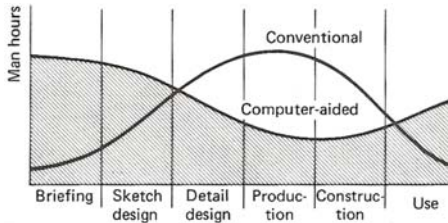
On the other hand, the fact that the process is implemented in computers does not lead to the conclusion that it is a button-pushing process or that the architect is merely a feeder of data. Any computational design process does not make a designer superfluous because of a machine performing calculations. On the contrary, the machine by itself cannot do anything without human interaction. However, the increased complexity and quantity of information embodied in recent projects impose tasks that surpass a person's cognition, computational ability, and creativity. That is why the introduction of computers is justified. In Integrated Design approach human strengths, such as creativity, intuition, decision-making ability etc, is united with computer strengths, such as speed of calculations, memory storage, objectivity, alternative combinations etc. However, the human mind will always be the key component and the driving force in a successful design process.

This statement finds some opponents. Some argue that the introduction of digital means in design process has downgraded the role of the architect, as Manuel DeLanda states, to the "equivalent of a racehorse breeder" and "judge of aesthetic fitness" (2002). This thesis counters on both these characterizations. An increasing number of architects have recently started to gain a design computational background. It gives them the opportunity to implement generative systems, utilize optimization and simulation algorithms, script their own code in design environments etc. Undoubtedly, all these operations do not downgrade a designer to a form breeder or a judge of aesthetics. These operations require a sophisticated treatment of design, which definitely differs from the traditional one, but that does not make it useless or inferior.

On the other hand, the majority of architects do not have the skills to adopt integrated design approach or any other computational activity. However, Integrated Design approach does not merely refer to participants in the design phase who have a computational background. The point is not whether an architect knows how to script or structure a system. The point is that architects should re-define their coordinated role within the design phase. It is crucial for an architect to comprehend the overall design problem, to identify the requirements, to define

CAD effect on design effort. Image: (Mitchell, 1977)

the variables and the constraints of sub-problems, to assign weights on objective criteria etc. All these operations and decisions are evidence that the role of the architect within the context of proposed approach is central, significant, and far beyond the role of forms breeder.

Given the fact that many design problems defy deterministic description and offer an inexhaustible set of alternative solutions, indeed, the end of the process cannot be finite, rigorous or identifiable. The outcome of the process, as Schön (1987) argues "is objective, in the sense that one can discover error in it, but it still remains personal." It is objective since many sub-processes describe physical phenomena that are defined by physical equations. It is subjective because the vague nature of many design problems forces designer's judgment to prevail throughout the design phase. The set of outputs might not fully satisfy the designer, yet, it will be the most satisfying among the rest solutions. Lack of time, money, and information are often fundamental factors towards a rushed end of the design phase. However, the integration of objectivity and subjectivity within the realm of design is probably what makes architecture a combination of art and science.

4. An Integrated Design Paradigm: Case Study

Daylight Simulation of a control floor.

4.1. Background Work: Preliminary Case Study

The preliminary case study is actually an example of the Generative Performative Design paradigm. Indeed, the design objective is the generation of alternative design solutions that satisfy prescribed daylight requirements combining generative and optimization algorithms. However, the primary aim of this preliminary case study was the familiarization with the design processes of the Generative Performative Design paradigm and the exploration of various design, optimization and simulation methods and techniques. Most importantly, this preliminary case study was the path through which some questions could be addressed, such as what is the relation between form and performance, how these are interrelated, what is the role of the architect in this process etc. This preliminary case study represents the starting point towards the exploration of the Integrated Design approach and the basis for the implementation of the following case study.

In general terms, a design algorithm creates the initial population and Genetic Algorithms evolve the population, both implemented in Rhino Script. For the determination of fitness function three daylight principles are used: Daylight Autonomy [DA], Useful Daylight Index [UDI], and Daylight Factor [DF] (Reinhart et.al., 2006). Daylight Autonomy is a dynamic metric that determines the percentage of time over the year when a minimum illuminance threshold is met by daylight alone. Useful Daylight illuminance is a dynamic metric that determines the percentage of time over the year when daylight levels are 'useful' for the occupant, that is, neither too dark nor too bright. Daylight Factor is a static metric which determines the ratio of the internal illuminance at a point in a building to the un-shaded, external horizontal illuminance under a CIE overcast sky. Simulations take place in Ecotect and Daysim. The ranking of each member of the population is calculated by a ranking algorithm implemented in MS Excel.

The design algorithm creates the initial population of the selected building type, skyscrapers, dictating by constraints such as the core area, the total height, and the upper and lower boundary of the transformations that may occur. Each building consists of six elliptical control floors that represent the ground floor, the 20th, the 40th, the 60th, the 80th, and the 100th floor. Each control floor of each building can be either rotated,
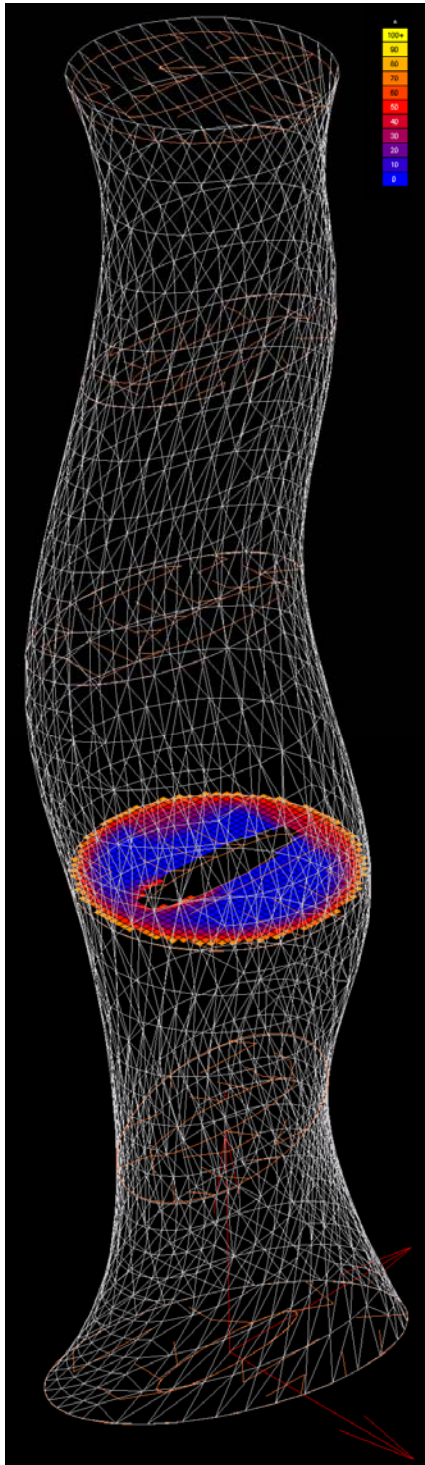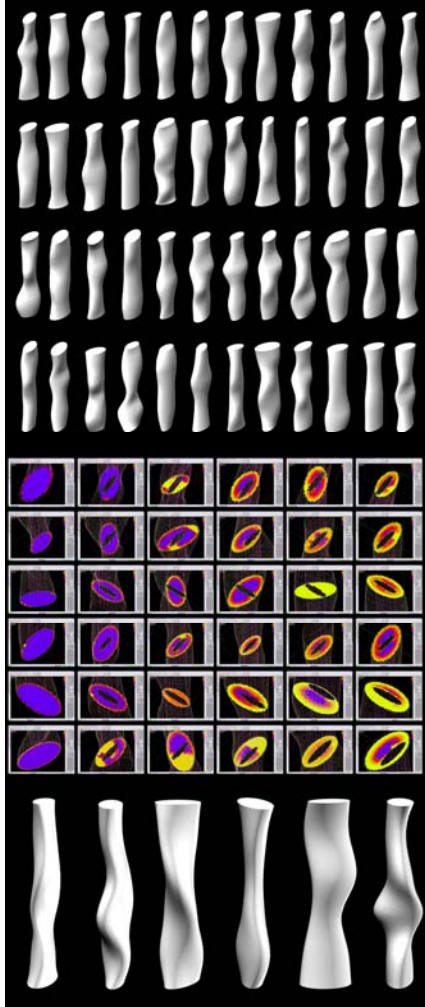
Outline of the followed process: initial population, simulation analysis, offspring

or/and moved, or/and scaled within a defined range per transformation. These floors are called "control floors" firstly because all the possible spatial transformations are applied on them and secondly because all the simulations are performed on them. Finally, the envelope of buildings is defined by "lofting" each set of six control floors.

After the creation of the initial population and the ranking by fitness, a crossover function is applied. Crossover pairs follow the sequence: the first best with the last, the first best with the second best etc. Each offspring is the combination of the fittest control floors from each of the parents. A mutation function is applied randomly on the new generations and alters the shape of a control floor from elliptical to a cyclical one. After the crossover and mutation functions are implemented, the code redesigns the offspring population.

While the design and optimization was automated, the simulation needed to be performed manually. This inhibitory factor required a large amount of time which inevitably led to the limitation of iterations. However, the emerged design solutions had an improved daylight performance compared to the initial population. Most importantly, this case study modulated the path towards the following case study, whose difficulty increased rapidly by the introduction of multiple interrelated building performances from different disciplines.

4.2. Case Study Approach

To demonstrate that the integrated design approach has validity and can be realized, a proof-of-concept study, or case study was developed. The basic aim of the case study is to examine how a computational model could be defined to take into account a number of interrelated performances that influence one another and all together the overall behavior of a building, and how the conflict or synergy of these forces could be visualized through form. More specifically, the computational model generates high-rise buildings guided by zoning, structural, solar, and aesthetic criteria. In order to perform the necessary generative, optimization, and simulation algorithms I developed a model that involves Rhino, Excel, and Ecotect environments. However, the model is very much an early prototype. The goal is neither the specific generated buildings that will emerge nor the satisfaction of the specific objectives that were selected but to see generally how form and multiple performances might be handled simultaneously.

An important note, the case study violates, unavoidably, a dominant prerequisite of integrated design approach: it is implemented by a single person. Indeed, an integrated design approach should not be utilized and realized merely by a single person; it is almost impossible and risky. Given the fact that the design approach is comprised of a number of sub-tasks that require diverse skills and knowledge for their implementation, an individual architect or engineer cannot thoroughly comprehend, predict and perform all these multi-disciplinary tasks. That does not lead to the conclusion that the followed process, the selected attributes, the calculations, the results etc are vague or meaningless. However, it leads to a given: reality is very complex and most of the building performances consist of complicated and manifold relations and restrictions. If this case study wanted to present a product that would directly accommodate the increased demands of reality, it should have addressed all aspects of each building performance. But that was not the intention.

Also, this justifies why simplifications and idealizations are used especially for the determination of performance design objectives and criteria. In zoning, the restriction of total allowable built area and the lot coverage acted as design objectives. The buildings should satisfy the regulation of maximum lot coverage and the closer to the total allowable built area their total floor area is the better fitness they have. In structural performance, the basic objective is the minimization of weight of the selected material that will lead to the minimization of cost. However, in order to ensure the stiffness of structure to the gravity and lateral wind loads, the total stress of any column at any level should not exceed the allowable stress of the material, steel. After the satisfaction of this criterion, the less the weight of the material, the better the fitness of the building is. Finally, in solar performance the objective is the maximization of daylight penetration in the interior space and the maximization of solar exposure. As for the aesthetic, it is inevitably involved in the creation of the design algorithm, as it will be described in the next sections, and the final selection of the design solution.

There are two primary reasons that these performances were selected among other building performances. The first is that all of them have a great impact on the overall performance of a building. Especially the last two have a significant impact on the energy and cost savings as well as on the occupants' safety and comfort. The second reason is that all of them, probably more than any other building performance, have a continuous interaction with the built form: they influence the modulation of form and form influences their behavior. The observation of this relation is very interesting. Especially in this case where this

relation is trying to be defined and satisfied as a bidirectional relation. That is to say, that the modulation of form and the accommodation of performances are integrated.

The building type of the examined population of design solutions is high-rise building. This building type was not selected randomly. Skyscrapers are tightly bound with zoning, structural, and solar performances and the developments of skyscrapers would not have been achieved without the inventions and advances in these performances. In high-rise buildings, the meaning of integrated design approach could be represented in a better way than any other building type because in this case the need for integration among various interrelated building systems is of special importance. In addition, the inherent monumentality of skyscrapers resulting from their scale, makes their architectural expression very significant in any urban context. Based on this building type, a very dense urban environment was selected in order to create a rather intriguing scenario for the case study by stretching solar and zoning performances. Indeed, the selected lot is located in downtown Manhattan, New York, between Pine, Wall, Front, and Pearl streets. The variety of heights of the surrounding buildings and the high density of the area put an extra degree of difficulty on the design alternatives to satisfy the objectives of the performances, which will be analyzed in detail below.
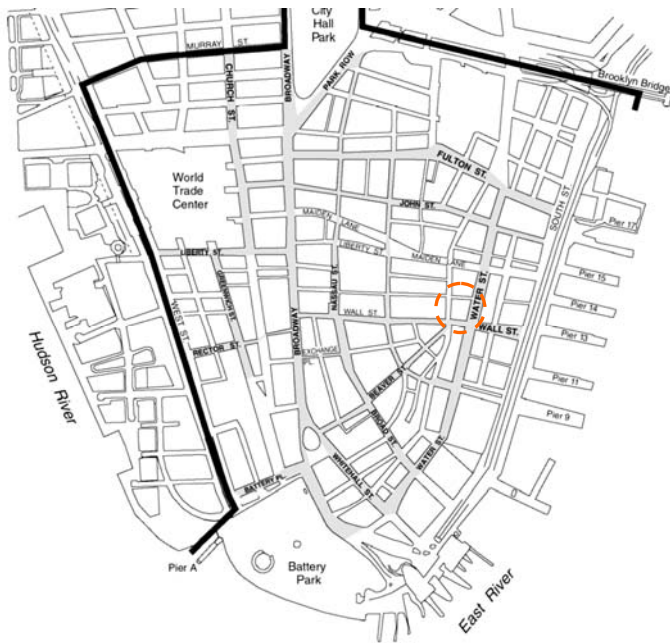
Map and perspective view of the selected lot. Images: (NYC Department of City Planning, Web version of the New York City Zoning Resolution) and (Google Earth).

4.3. Performances

While structural and solar performances are usually understood as building behaviors, zoning is perceived as requirement. However, given the fact that *performance* is defined as a term that includes all requirements and properties of a building, zoning is also perceived as a performance, yet maintaining all the characteristics that a set of strict regulations has.
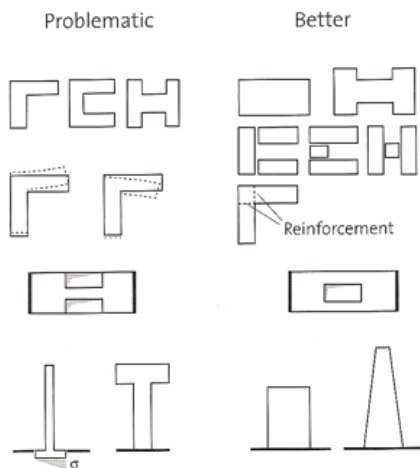
4.3.1. Zoning

In general terms, zoning codes shape a city's urban figure, since they determine the use and the size of a building as well as the density of the city's neighborhoods. Zoning, as a term referring to a set of land-use regulations, is used in various areas worldwide, including United Kingdom, Australia, and North America. In the United States in particular, the first zoning regulations were adopted by New York City and they became the blueprint for zoning in the rest of the country. Indeed, in 1916 the first zoning resolution was legislated. It is worth mentioning that the impetus for the first regulations was the construction of the Equitable Building, completed in 1915. (NYC Department of City Planning, NYC Zoning) That is because the seven-acre shadow of the building led to loss of daylight penetration and air ventilation of surrounding buildings. After New York City, many other cities developed a set of zoning codes based on their local needs. Since the late 1920s, new and more complex regulations were developed in each city. For example in New York City, the second legislation of zoning codes was done in 1961 and in the past ten years new additions have been included that deal with mixed uses, neighborhood transformations, emerging design trends etc.

The primarily effects of Zoning Codes on a building are on its use and its envelope. That is because, firstly, zoning includes regulations that determine the acceptable activities, such as residential, commercial, and industrial, for particular sections of a city. (NYC Department of City Planning, Glossary) Secondly, zoning determines the total floor area of a building by multiplying the area of zoning lot with the *floor area ration* (FAR). Floor area ratio is a constant number, such as 10, 15, 18 etc, that differs from building to building and section to section. Zoning Codes also define the *lot coverage*, which is the total amount of a lot that a building can cover, and the *setback*, which determines the distance between a building and the lot lines. The setback requirements are those that ensure the adequate levels of daylight and air is provided on the surrounding buildings. All these regulations undoubtedly affect the overall envelope of a building.

Given the location, the site of the case study is part of the Special Lower Manhattan District. The special regulations of the district and particularly of the site are set forth in Article IX, Chapter 1. (NYC Department of City Planning, Web version of Zoning Resolution) Within the framework of LM zoning codes the building shape is also influenced by its type. In the case of a tower in particular there are two basic categories of it: the *tower-on-a-base* and the *basic tower*. In the tower-on-a-base case the lot coverage regulations play a vital role in the formulation of a building. Indeed, between zero and a maximum of forty five meters there must be a contextual base that will cover the whole lot and extend continuously along the lot line. Between twenty six and a maximum of ninety one meters the lot coverage should not exceed sixty five per cent of the lot area of the zoning lot. Finally, above a height of ninety one meters the maximum lot coverage is fifty per cent. On the other hand, the basic tower rules generally permit the tower portion of a building to cover no more than forty per cent of the area of the zoning lot, or up to fifty per cent on lots smaller than 1.858 square meters. (NYC Department of City Planning, Glossary)

For simplification reasons the basic tower was selected. Based on this selection, the location and the size of the site, the following zoning regulations are applied to the building: FAR is eighteen so the total maximum floor area of the building should not exceed thirty six thousand four hundred fifty square meters, lot coverage should not exceed forty per cent of the site area, the height should not exceed two hundred meters, and the tower portion of a building must be set back at least three meters from a wide street and at least five meters from a narrow street. All these regulations will be used for the determination of design variables, constraints, and criteria, among others, to define the design space of the case study.

4.3.2. Structural

Structure is one of the fundamental factors that influence the shape and the behavior of a building, especially if it is a skyscraper. This rests on the fact that most high-rise structures tend to be relatively tall and slender so the key element is their height. The height plays a vital role in the modulation of the shape, the selection of the structural system, and the material of the structure. Finally, the height of a skyscraper affects the loads, both horizontal and vertical, that the structure bears. Indeed, like every building, skyscrapers have to resist the primary loads of gravity and lateral forces in order to be stable and stiff. Also the good understanding and analysis of gravity and lateral forces will lead to the selection of the most appropriate structure system.

Effective and non effective building plan and section for structural performance. Image: (Eisele & Kloft, 2002).

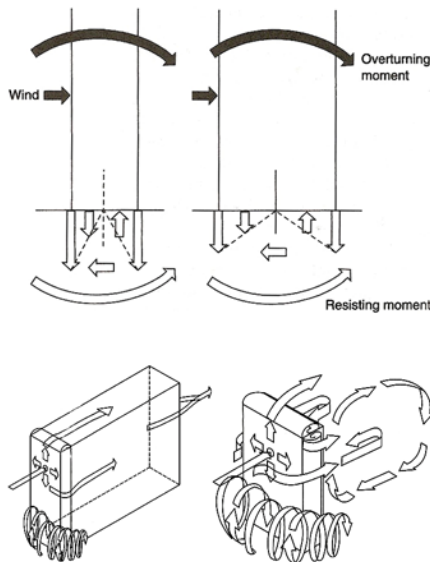Structure loads are distinguished as static and dynamic loads. *Static forces* are applied slowly on the structure and have a steady state, while *dynamic forces* are applied suddenly and do not have a stable state since their magnitude, location, and direction change quickly (Schodek & Bechthold, 2007). Static forces are distinguished as *dead loads* that are fixed, such as the weight of the structure and the weight of fixed building elements, and *live loads* that are movable, such as the weight of the occupants and the weight of environmental elements like snow is. Within this scope, an engineer focuses on the satisfaction of two primary objectives – the stiffness primarily for static loads and the damping for dynamic loads.

Gravity loads are related to the calculation of dead loads based on the unit weight of the selected material and the volume of the structure. The weight of a structure increases linearly in relation with height. So, it is the weight of the vertical structural elements, such as columns, that affect the gravity loads. That is because the weight of these vertical elements increases linearly, while the weight of the vertical elements, such as floors, remains constant. On the other hand, dynamic forces are distinguished as *impact loads* and *continuous loads*. The first are discrete forces, such as a blast, while the second are oscillating forces, such as inertial forces and wind forces.

The calculation of wind forces is much more complicated than the gravity ones, and from a certain height above ground they act as a form-determining factor of a skyscraper. When wind acts on a structure then *lateral wind loads* produce at a point on the structure an overturning moment, which must be balanced by the structure. The wider the building, the higher is the resistance to turning moments. By deforming the plan configuration of the building, the overall stiffness and its ability to carry lateral wind loads can be increased. To put it simply, when a building is very slender, very high forces are developed in the vertical structural members to provide the internal resisting moment. While, when the building has a wider base or generally has less slender proportions, it needs smaller forces to provide the same internal resisting moment. Increasing the slenderness, i.e., the building height-to-width ratio, and height of a structure "the importance of lateral force action rises in a much faster nonlinear fashion as compared to the gravity loads and becomes dominant" (Schueller, 1977).

Apart from the magnitude and direction of gravity and lateral wind forces, the overall geometry of a building influences the selection of a structure system. Indeed, many structure systems have been developed specifically for skyscrapers such as: bearing wall structure, core structures, suspension building,


Top: Wind forces acting against a narrow and wide face of a building. Image: (Schodek & Bechthold, 2007). Bottom: Wind flow patterns against a narrow and a wide façade. Image: (Eisele & Kloft, 2002).

skeleton structures, braced frame structures, trussed frame structures, mega structures, and hybrid structures etc. The impetus for the invention of a new structure system is the increase of the height of the structure and the decrease of the weight of the material. Representative example of this is the creation of the diagrid system that has been broadly used in many hyper-tall skyscrapers recently. The primary characteristic that makes this system so effective for very high structures is that it has its major lateral load resisting system at the perimeter of the building.

Undoubtedly, the fully analysis of gravity and lateral wind forces and optimization of the volume and the structural system of a skyscraper require the calculation of complex physical equations in structural finite element analysis simulation software. However, this case study will focus on the analytical examination and calculation of two simple but still significant considerations: failure stress of columns and weight of the structure. The structure will consist of a central core and a set of slant columns located on the perimeter. For simplification reasons, the building structure will be idealized in order for the total stress to be calculated, as the sum of gravity and later wind stress. The total stress at any column at any level should not exceed the steel failure stress, which is about 20ksi. The buildings whose column stress exceeds this number are not allowed to pass to the next generation. The buildings that satisfy this condition should meet the next criterion, which is the minimization of material. In this case, the buildings that weigh less, so the material that is used is less and consequently the cost decreases, have a better structural performance.
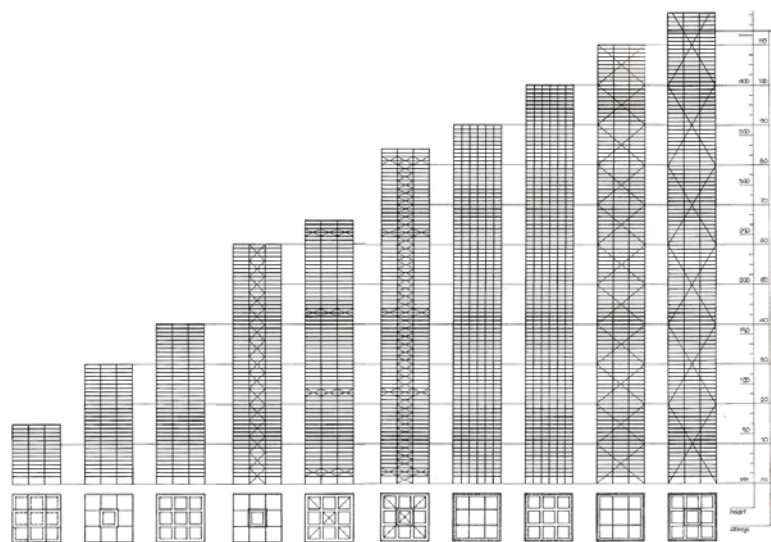

Representative structure systems used for various building heights. Image: (Engel, 2007).

4.3.3. Solar

In general terms, there are three tiers towards the accomplishment of environmental design: the basic building design strategies, the passive systems, and the mechanical systems. In the case study, the analysis of solar performance will focus on the first tier. The first tier is the minimization of solar gains during the summer, the maximization of solar gains during the winter, and the efficient use of daylight. Making early design decisions based on these three aspects has a significant impact, among others, on the reduction of energy consumption. The case study will focus on the last objective, analyzing the effects of daylight in buildings, occupants, and environment, and then how daylight influences the modulation of the shape of a building.

Throughout history daylight has been a dominant factor for architecture and the formulation of building shape. From ancient Greek and Roman architecture to modern and, most recently, green or sustainable architecture, daylight has modulated building forms and design strategies. Le Corbusier underlined the vital role of daylight in architecture stating: "Architecture is the masterly, correct and magnificent play of volumes brought together in light. [...] The history of architecture is the history of the struggle for light." (Le Corbusier, 1989). Undoubtedly, the invention of artificial light and the introduction of fluorescent lamps in the buildings supplanted daylight at a great extent. Fortunately, the last decades, architects and clients have started to re-recognize the positive effects of natural lighting.

Indeed, solar performance influences not only the building but also the environment and the occupants. By increasing the efficient use of daylight and the illuminance levels in a building, the use of mechanical and active systems, such as air-conditioners, decreases and consequently the energy and financial savings could be considerable. Of equal importance is the contribution of natural light to human comfort through its effects on mood, motivation, behavior, and well-being. Many studies have justified that humans' stress and discomfort is reduced in a naturally lit environment (IEA/SHC, Task 21, 2000). In addition, natural light also provides an almost "perfect white light" that increases the visual quality of the space and consequently the visual performance of occupants. For example, people's aesthetic judgments are determined primarily by the perceived brightness and color of the overall space. However, natural light is not without its issues, such as direct glare, visual contrast, and overheating. There are many ways, advanced or not, to deal with these undesirable effects of daylight today. For example, the glare issues can be addressed by avoiding direct sunlight on the field of view of building
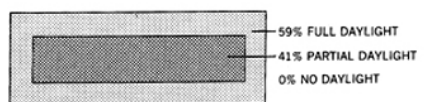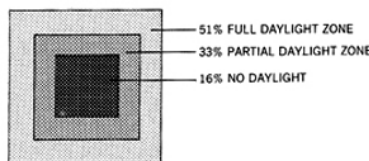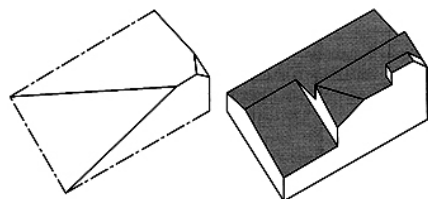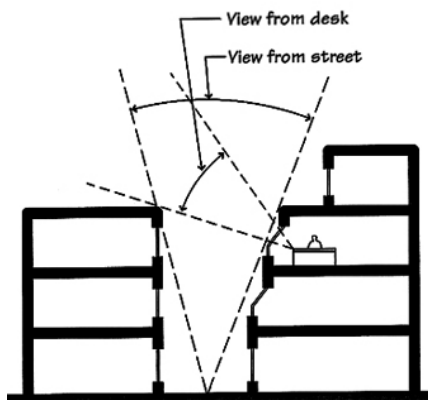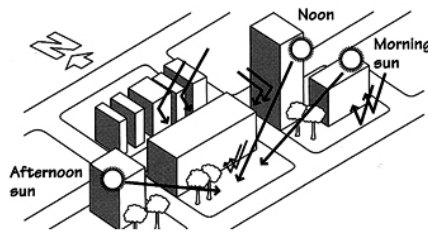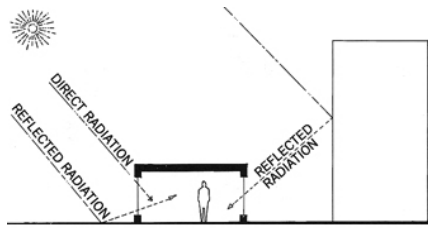
Solar effects on urban scale and building envelope, plan, and section. Images: (Eisele & Kloft, 2002), (Lechner, 2001), and (Egan & Olgyay, 2001).

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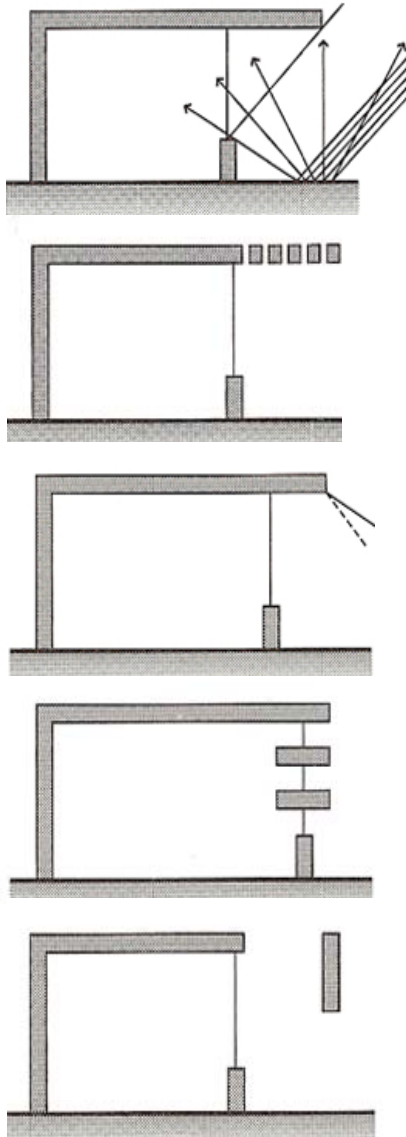
Shading design strategies. Image: (Egan & Olgyay, 2001).

occupants while protecting them from disturbing reflections. Overheating problems can be avoided by using exterior shading devices, such as overhangs and vertical fins, filtering solar radiation.

On the other hand, there are many other design strategies to increase the illuminance levels of an interior space by modifying the building shape. Indeed, the increase of daylight penetration, which is a primary objective for solar performance, can be addressed by ensuring a favorable relationship between the volume and the surface area. That means that primary design decisions such as the building orientation, the building portions and the building form play a crucial role on solar performance. For example, the narrower a building is, the higher the daylight penetration. Undoubtedly, the climate conditions, the location and the size of the lot, as well as the obstructions to the sun and sky from the surrounding buildings have a significant impact on the solar performance and the selection of daylight design strategy. Indeed, apart the determination of the geometry of the building and the color of finishes, the use of secondary spaces, such as atria and courtyards, represents another strategy. The use of atria increases the illuminance levels of interior spaces. Other, more detailed strategies are also used that relate to the size and orientation of apertures, the selection of fixed and movable shading devices, and the selection of glazing types, such as clear, low-transmission, coated, and dynamic glazing.

Since integrated design focuses on the early design phase, the daylight design strategy that is selected is related to the geometric modulation of the building. The buildings that have minimum depth allow more daylight to penetrate in the interior. At the same time, based on the spatial configuration of the surface of a building the solar radiation that it receives may increase or decrease, and consequently increase or decrease the solar exposure of the building. The maximization of daylight penetration and the maximization of solar exposure modulate the objectives of solar performance.

4.3.4. Performances and Form

From the above analysis it is obvious that there is a direct relation between each of the three performances and building form. Indeed, it is a bidirectional relation where each performance in order to be satisfied modulates the form and simultaneously the form can affect, positively or negatively, each of these performances. The interesting part is that each of the selected performances influences form in a different if not opposite way. To put it simply, the idealized or optimum form for zoning, structural, and wind performance differs. For the zoning codes that rule the lot there is no predetermined ideal form
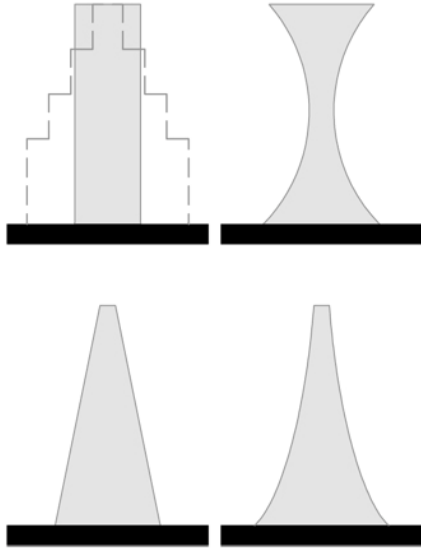
Simplified "ideal" forms for zoning, solar, structural, and wind performance.

since there are no physical equations that govern it. However, the limited lot coverage, forty per cent, along with the maximum total floor area drive to a rather vertical form that covers forty per cent of the lot area.

On the other hand, structural performance has ideal form. Actually in this case there are two slightly, yet significantly, different ideal forms, the first corresponding to the gravity loads and the other to lateral wind loads. While in the first the oblique walls are linear, in the second they are curved. Finally, the ideal form for solar performance and particularly for solar exposure differs based on the orientation, the climate, and the context. Testing three primitive solids on the latitude of New York yet with no context the form that has the higher solar exposure is the one that is getting thinner on higher floors. It is worth underlining that the simplified "ideal" form of solar performance is the same with the optimum form for structure. However, testing primitive solids located on the specific lot and adjusted by surrounding buildings, and then the form that received more solar radiation is the one that is curved in the middle.

The three idealized forms that correspond to each selected performance are known after the analysis is performed independently for each performance. The independent analysis and synthesis of each of the building performance is a norm in practice. Sometimes the analysis and synthesis is further subdivided to smaller building subsystems. For example, engineers usually examine and optimize the volume of a building and then based on the optimized volume they select and optimize the structural system. In this study those two actions will be performed simultaneously. That means that instead of being read and synthesized as two separate building systems, form and structure, they will be synthesized together at the same time. Also, while in the aforementioned structural strategy the form is optimized merely for the structural performance in this study the form will emerge as an integration of three performances, which might conflict. While there are very interesting and sophisticated structural studies that have thoroughly examined the optimal volume of a skyscraper, the optimal structure systems, and the combination of those, in this case study it will be intriguing to examine how three different performances influence the modulation of a skyscraper in an alternative way: less static and independent.

Indeed, what will happen if the performances will be synthesized together? What will be the end product? Will it be the geometric average of the three idealized forms or will one of these prevail? The answers to these questions are not easy. However it will be very helpful if the designer before starting any calculation has

some ideas not about what the visual product could be but the underlying relations among the performances. It will be very helpful mostly because in this way the architect could test the feasibility of the designs; the designer could justify if the results make sense or not, at least in terms of the physics. These three performances are interrelated, conflicting or coinciding. Increasing the value of one, the values of the others are affected. These relations between the performances will play a crucial role in assigning weights for the evaluation criteria, which will be analyzed in the following section.

4.4. Process

4.4.1. Design Algorithm

In order to streamline the process of designing buildings, a design algorithm implemented in VBScript for Rhino was used. The user inputs the main characteristics of a site – length and width – and the general geometry of the building – height, floor shape, and core. Then the script produces a random population of buildings based on these characteristics and by applying randomly various spatial transformations. Finally, the user defines whether the building will have outside columns or not, whether these columns will create a grid or not, as well as the size of the population to be generated.
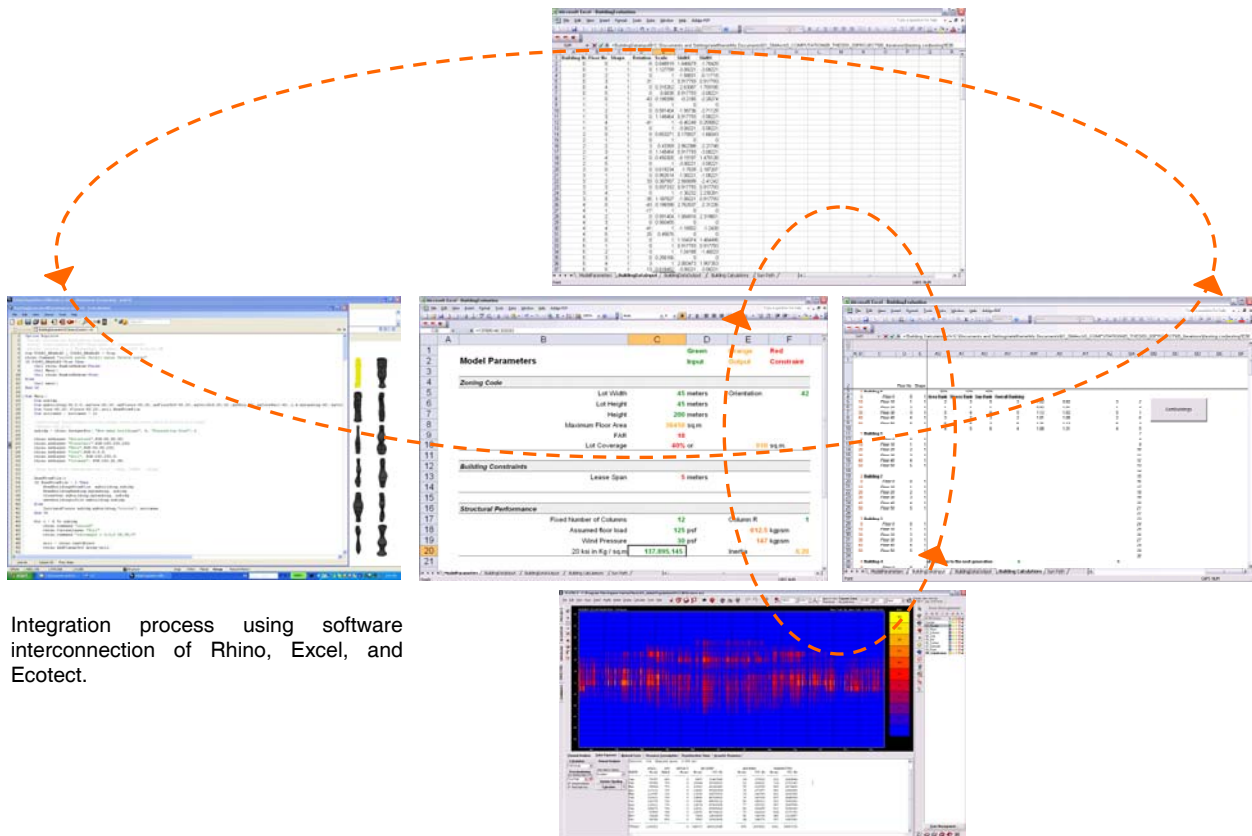
Integration process using software interconnection of Rhino, Excel, and Ecotect.
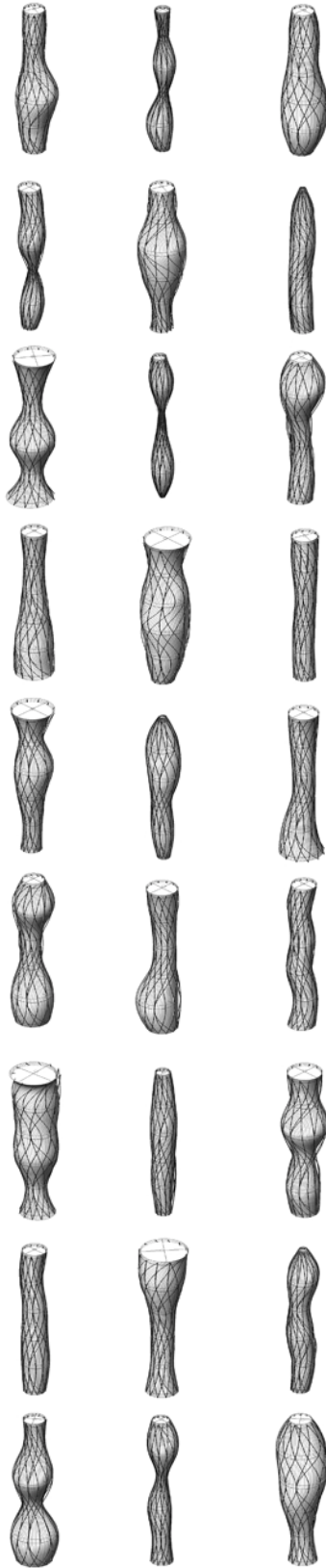
Sample of initial population.

In this case the buildings created are generally cylindrical. Their form undergoes alterations dictated by constraints such as the perimeter and the area of the core, the total height, the maximum and minimum perimeter of floors, and the upper and lower boundary of the transformations that may occur. These transformations (rotation, move, and scale) are assigned probabilistically to each of the six control floors, one every forty meters of height. These control floors also define the form of the building, since a building is a "loft" of the six control floors. The script that creates the buildings also creates an output file with the geometric properties of each building, such as floor radius, shift, scale and rotation that is to be used in fitness calculations as explained below.

4.4.2. Evaluation Algorithms

When Rhino produces the population of buildings, these building get evaluated based on three performances simultaneously. For each one a specific calculation takes place, to measure the performance of the building under consideration.

Starting with the zoning performance, the evaluation algorithm takes into consideration the total floor area and the lot coverage. Zoning performance is measured with the use of Excel Spreadsheets. The spreadsheet calculates the total area of the building based on the output of the script that generates the populations. Lot coverage is also calculated using the same spreadsheet. The buildings should satisfy the regulation of maximum lot coverage and maximum allowable total floor area. The buildings that do not satisfy both restrictions do not pass to the next generation, while the buildings that do are ranked based on their total floor area. The closer to the total allowable built area their total floor area is, the better fitness they have.

In structural performance, the total stress of any column at any level and the total weight of a building are measured. Stress is evaluated on the basis of column stress, given that the material for the columns is steel. Two causes of stress are measured; loads including structure, dead and live loads, and lateral wind load. The first is measured by calculating the weight of the building and dividing by the number of columns. The second measures the force of the wind in the projection of the building's façade, assuming a constant force by the wind. MS Excel is used for stress calculations. Column stress is basically dependant on the area of the floors, the height and the width of the building. The larger the floor area, the greater the weight it has. Also the width is larger resulting in higher lateral wind forces. Given the material of the columns, the buildings are forced to satisfy the stress constraint so that columns do not collapse. Buildings that do satisfy this are ranked depending on
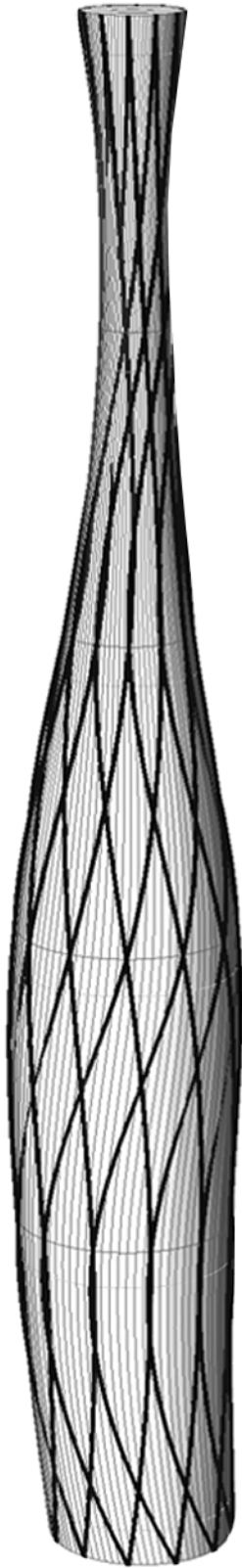
the ratio of total weight to total volume of the building. The lower the ratio the better the fitness a building has.

Finally, the lighting performance of a building is constrained by the depth of each floor. That is to say the distance between the core and the façade should not exceed a number of meters, in this case fifteen meters, so as to ensure adequate light penetration to each floor. For the buildings that satisfy this criterion, solar exposure is evaluated using simulation software Ecotect. In it, the incident solar radiation that the surface of a building is receiving throughout the year is measured. The fact that the shades and abstractions of surrounding buildings are included in the simulations offers a very close to reality snapshot of what is to be expected. Simplistically it is assumed that the higher the solar exposure, the higher the daylight performance potential of the building. Each of the buildings of the populations is saved in a file that can be read by Ecotect. Within Ecotect the building is placed in a digital model of its physical premises. A script written in Lua – the scripting language embedded in Ecotect – performs the Solar Exposure calculations for this building in Wh/m^2. More complicated and detailed calculations can be performed in smaller scale – for example within each of the floors. For all calculations, simplifications have been made, as the purpose of this study is to demonstrate the ability of combining those performances, rather than to propose a certain methodology of detailed building optimization.

4.4.3. Design Generation

For the evolution of generations the concept of Genetic Algorithms is used. That is because, Genetic Algorithms, as a
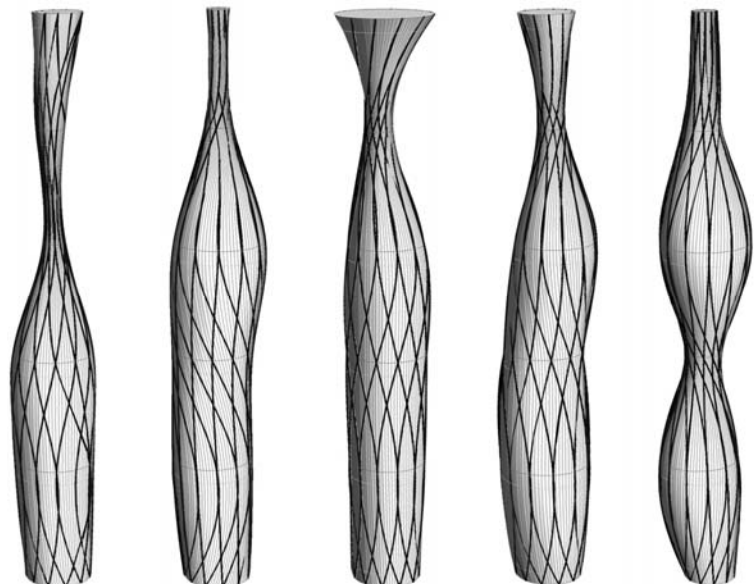

Top: Alternative design output for weight values of 0.5 for zoning, 0.1 for structural, and 0.4 for solar. Right: Sequential generations from right to left.
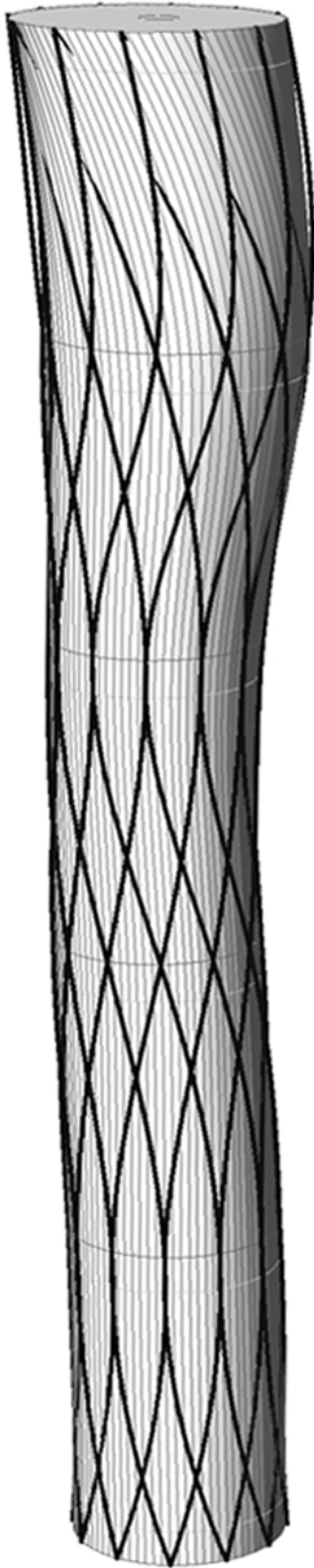
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Heuristic Algorithmic method, follow a simple set of rules to return within a minimal computing time an acceptable and approximated solution of a design problem. The outcome of the evaluation algorithms is used to rank the buildings from best to worse. Ranking is based on the fitness of each building in each of the performances, as described above. To do that, all three rankings are fed into an excel spreadsheet that assigns weights to each and calculates the overall fitness of the building under consideration. The weighted ranking is used to sort the buildings by fitness. When this process is completed, the script that created the initial population is run with parameters that allow for it to "read" the sorted building set. This input is used for the function of crossover and mutation. In this case, crossover happens by exchanging floors between building pairs and mutation alters the scale of a random floor. When the population undergoes this process, offspring are created. This newly created generation, is again going through evaluation, being measured for fitness, ranked and fed back to the script that again creates a new generation. The process is over when the participants involved in the design phase judge that the latest design solutions satisfy both aesthetic and performative criteria and then the phase of final selection takes place.

4.4.4. Observed Results

For each performance, of course, the ranking of a single building might end up being different. The selection of these weights plays a significant role in determining the characteristics of the final ranking. Indeed, by increasing the weight of zoning, the floor area of the building will be increased, which leads to the increase of weight of the material and consequently the

Top: Alternative design output for weight values of 0.3 for zoning, 0.3 for structural, and 0.3 for solar. Right: Sequential generations from right to left.

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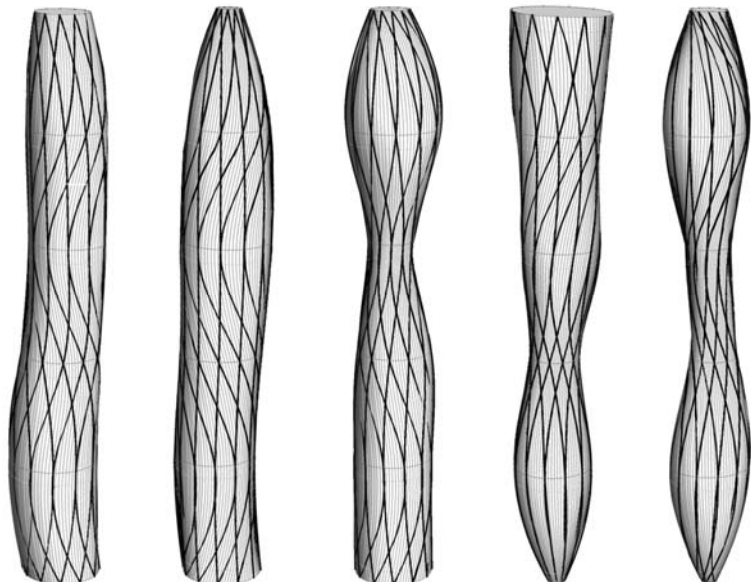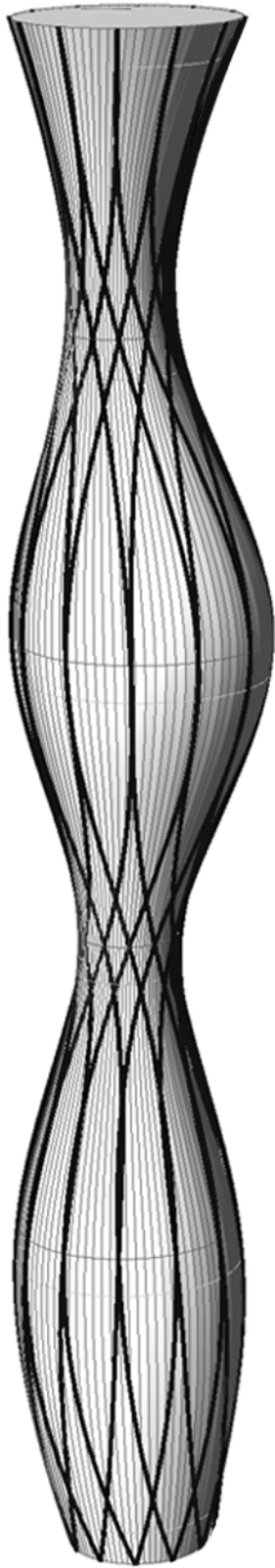
decrease of column stress. That means that a satisfying zoning fitness equals an unsatisfying structure fitness. At the same time, the increased zoning weight increases the floor area which is directly related to the increase of floor depth and consequently the decrease of daylight penetration. Decreasing daylight penetration leads to the decrease of illuminance level in the interior spaces. On the other hand, the increase or decrease of the weight of the material and structure has no implication on daylight. While weight is not related to daylight that does not mean that the structural performance is not linked with the solar. Not only it is related, due to the lateral wind forces, but also it seems to conflict. This conflict is obvious if the two idealized forms of wind and solar performance are compared. The first gets narrower in height while the latter gets wider.

Some possible solutions are shown representing various generations whose difference lies in the modification of weights. Indeed, the point of the experiment was to observe how modifying the assignments of weights and thus the relation between the selected interrelated performances could be mirrored on the form. Three different weight sets were assigned (the sum of which has be one or one hundred if it is assigned as a percentage): the first set was 0.33 for zoning, 0.33 for structure, and 0.33 for solar, the second was 0.5 for zoning, 0.1 for structure, and 0.4 for solar and the third was 0.15 for zoning, 0.15 for structure, and 0.7 for solar. Undoubtedly, some of these weights do not follow a logical thought. For example the last set would never be selected by architects in real life, since the relative importance of the performances is not mirrored in the assigned weights. Yet, stretching the weights will give a clearer idea how they affect the form within a few generations.
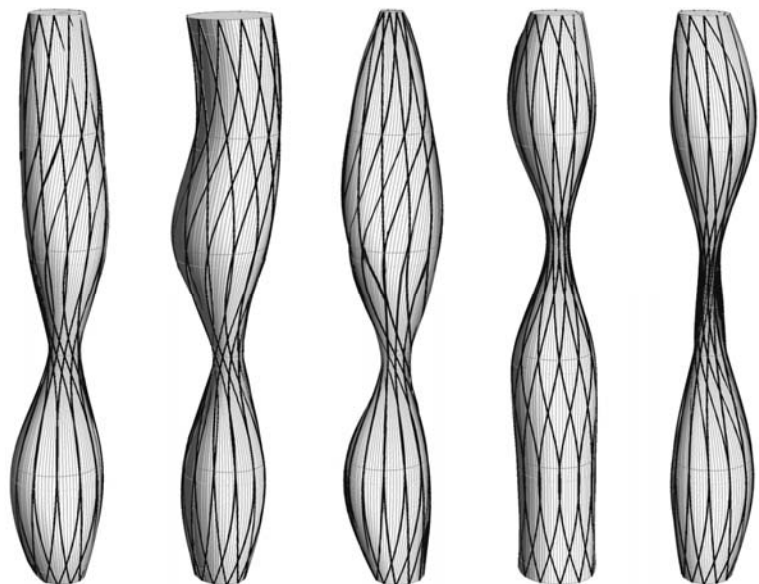

Top: Alternative design output for weight values of 0.15 for zoning, 0.15 for structural, and 0.7 for solar. Right: Sequential generations from right to left.

4.5. Reflections on the Integrated Design paradigm

A significant reflection on the Integrated Design paradigm is related to the assigned weights. Indeed, in the previous chapter it was mentioned that most of the weights of criteria are assigned based on the subjective judgment of the architect. After the completion of the case study it is concluded that this statement is true if and only if the criteria have firstly met all the strict regulations and safety rules. This prerequisite is grounded on the fact that some building performances represent restrictions while others represent needs. The first are strict and have to be met while the latter are open to interpretations and subjective judgments of the designer. Indeed, it is pointless to find a satisfying solution to a building in which the stress of columns exceeds the allowable one and consequently it will yield under the pressure of applied forces.

Zoning codes have the same characteristic. There are very strict state rules that every building has to fully satisfy. For example, let's assume that there are two buildings that have the same fitness. The first has more solar exposure, less consumption of material, and exceeds the maximum total floor area. The second has less solar exposure, consumes more material, and does not exceed the maximum total floor area. Both are satisfying in terms of their fitness. Moreover, the first one seems to have a better total performance, still it does not prevail on the evolutionary generation since it does not fully satisfy the zoning regulations.

A way to deal with performances that have this feature is the introduction of a "pass or fail" routine before the weighting. This routine will check whether a building satisfies the conditions defined by the relative regulations, safety rules etc. If the building will not fulfill the conditions, it "fails" and its fitness score is null. If the building satisfies the conditions, it "passes" to the next step, which is the weighting routine. After that, the designer is free to determine the weights of criteria based on subjective judgment even though the best way is to modify them until a weight is found that better satisfies the objectives. Usually, the weight of a criterion represents the importance of the respective objective. Even though not all performances are of equal importance, the decision of which performance is more significant than the others or which has the greater impact on the overall building performance is rather subjective. Since the relative importance and implication of a performance towards the others cannot easily be predicted from the very beginning, modifying the weights of criteria throughout the evaluation phase is a way to address this difficulty. This way is used in the case study as well.

Finally, the last observation is about the construction of the possible model. Before starting the case study a fully automated model was perceived as the best way for an Integrated Design paradigm to be implemented: a model in which the interface and modification would focus on the potential results. After the completion of the case study it was much appreciated that the way the model was created offers the participants the opportunity to observe at any generation how the selected performances interacted and consequently to have a better understanding of the underlying physical relations. That makes participants feel more secure because they can justify whether the results had any sense or not, and consequently that they have the control of the tool.

5. Epilogue

Summarizing, integrated design is a different design approach that analyzes and evaluates simultaneously more than one interrelated performance from multiple disciplines, such as civil, mechanical, and electrical engineering etc. The goal of the approach is the generation of design alternatives guided simultaneously by two basic objectives: the aspiration for form exploration and the satisfaction of the performances of interrelated systems. In order for integrated design to be utilized there are a series of prerequisites that must be satisfied. The most important ones are multi-disciplinary collaboration, the introduction of the integrated design approach at the very early of the design phase, the development of a unified, if possible, digital environment in which generative design, simulation and optimization techniques can be applied, and finally the development of a real time computational system which will boost the continuous interface between the user and the machine throughout the design phase.

Apart from the basic framework of the integrated design approach and the outline of its sub-routines, there are not any particular restrictions or specific ways that someone should follow to utilize the proposed design approach. The integrated design paradigm is not a methodology, an algorithm, or software that requires a finite sequence of steps to be completed. On the contrary, it is a different approach to design. Which particular way the sub-routines will be implemented, which optimization technique and which design environment will be used, whether architects have the background to structure the computational system or not etc does not really matter since it does not really influence the concept underlying integrated design.

However, as every action is followed by a reaction, the integrated design approach has several implications for architectural practice, design, architects, and buildings. The most significant change that the approach "imposes" in architectural practice is the prerequisite of multi-disciplinary collaboration. This change has a direct effect on the organizational chart of most of the big corporative architectural firms. Most of these diagrams follow a sequential flow of work, while the integrated design approach requires a more circular and interrelated flow of work and data. Undoubtedly, the need of multi-disciplinary communication is not accomplished merely by the transfer of data. It requires a lively collaboration by a sharing of knowledge, problems, ideas, experience etc among the participants. Of course, such communication presupposes a more flexible work environment that will boost the collaboration. In reality, there are firms in which architects, engineers, and

consultants do not even work on the same floor. Under these circumstances a multi-disciplinary communication cannot easily be achieved, yet it is not unattainable. Indeed, as with all new things an acclimatization period, during which things may get worse before getting better, and most importantly a willingness towards the potential change are key elements for modifying stabilized conditions of architectural practice.

Additionally, the potential benefits of the usage of integrated design approach might act as allurements for architectural firms. The increase of examined design alternatives, the reduction of errors, and the reduction of implementation time are some of the possible advantages of the approach that might convince the partners of a big architectural firm to make some radical changes on their organizational chart. As for the smaller architectural offices, their size supports and promotes anyway multi-disciplinary communication and vivid collaboration. Inevitably, regardless of the size of an architectural firm the utilization of an integrated design approach implies the redefinition of architectural services since it presupposes the rethinking of dogmatic architecture. To put it simply the proposed approach perceives design from multiple and diverse view points. The result should not be a segmental view but rather a holistic one. Certainly, this shift will have a direct effect on the way participants comprehend a building. Indeed, even though architects should have by definition a co-ordinated role in the design chain, architectural education, most of the time, forces them to another direction. Students of architectural schools are taught to perceive a building as a set of building systems, whose identification is derived from the primary discipline and performance that they service. This definition and identification bounds the perceptual ability and creativity of architects and certainly limits the design which should be unbounded. By designing a column and equating it with civil engineering and stability, it will always remain a column formally represented differently every time.

Architects might achieve the beloved innovation, if they work more with performances than their obvious and dogmatic visual representatives. Merely formal exploration has been always, more or less, on architect's core of interest. Especially in the last few decades, some architects have shifted towards other disciplines, such as biology, trying to find their lost inspiration. The point is not that these architects have shifted to other disciplines. On the contrary, throughout the history architects have borrowed elements from other disciplines. The point is that today architects treat these elements superficially. Consequently their artifacts do not interfere with other disciplines, as they state, but mimic irrelevant pictures from

other disciplines. For example, if someone copies the representation of a bacterium from a biology book and pastes it on an AutoCAD file, the 3D representation of it might be "interesting" or "innovative", yet it does not simulate natural growth or any other sonorous expressions, as s/he might argue.

The Integrated design approach gives participants the opportunity to learn alternative things about many aspects of the design, to discover the outputs that will emerge by an alternative activity. However, this approach requires time, especially in the beginning. Given the fact that many requirements are analyzed and evaluated together and then these requirements in conjunction with special relations drive the generation of design solution, the process requires many modifications. Actually the whole process lasts as long as design process lasts, since it is an open process which ends when the participants are satisfied with the results. The overall time of the process might be less compared to a traditional process that is segmented into smaller independent sub-procedures. On the other hand, if someone considers that the participants should work many times together and be present in most of the operations then they realize that this approach might be rather expensive for the companies. However, it is really difficult to estimate the cost of the proposed approach since it has not been applied yet, so one cannot really be sure, not for the potential advantages and disadvantages, but the real ones.

As for the buildings, one could argue that the end products are more feasible and perform better than the buildings emerging from another design paradigm, due to the simultaneous calculation of multi-performances. However, this argument will not be adopted. That is because, the feasibility and overall performance of the emergent potential solutions depend on many factors, such as identification of the design problems, selection of design variables, and most importantly the compromises made throughout the process. If someone utilizes the integrated design approach, this does lead by default to the most satisfying -according both to appearance and performance- building.

After all, it could be concluded that generally in an integrated design approach participants are in a continuous negotiation and confrontation for the determination of what is objective versus what is subjective, what is well-defined versus what is ill-defined, what is automated versus what is manual, what is a restriction versus what is a need, what is conflicting versus what is coexisting etc. However, such negotiations are an integral part of design and that is what makes design such an intriguing and creative activity.

Further Work
While Integrated Design can be utilized with the involvement of different design, optimization, and simulation software, as was demonstrated in the case study, the implementation of a unified design environment could be a further area of study towards streamlining the Integrated Design process. This design multi-tool will allow the integration of generative, optimization, and simulation algorithms involved both in analysis and synthesis phase.

Another area of study for Integrated Design is a thorough investigation and distinction between the various building sub-systems. In it, one can examine a "sensor" that will identify modularized and interrelated sub-systems, point out if their parts are related, and how this relation affects the overall building performance and form. This study could lead to an expanding utilization of Integrated Design in other design phases, where the detail and complexity introduced require a thorough investigation of design objectives, variables, constraints, and criteria.

Appendix

Samples of the Code of the Design Algorithm implemented in VBScript in Rhino.

```vbscript
Option Explicit
'Script written by Eleftheria Fasoulaki
'Script copyrighted by MIT Department of Architecture
'Script version 2.1.1 Wednesday, January, 2008 4:23:03 PM
Dim VIDEO_ENABLED : VIDEO_ENABLED = True
rhino.Command "unlock enter SelAll enter Delete enter"
If VIDEO_ENABLED=True Then
        Call rhino.EnableRedraw(False)
        Call Main()
        Call rhino.EnableRedraw(True)
Else
        Call main()
End If
Sub Main()
        Dim nobldg
        Dim
mybuilding(60,6,6),myCore(60,10),myFloors(60,10),myFloorSrf(60,10),myCeilSrf(60,10),mySkin(60),myCoreWall(60),
i,k,myranking(60),myColumns(60,10,20)
        Dim Core(60,10),Floors(60,10),soil,ReadFromFile
        Dim ncolumns : ncolumns = 12
        'mybuilding (buildingno,floorno,shape,rotation,scale,shiftX,shiftY,dcolumns)
        'design the plot
        nobldg = rhino.IntegerBox( "How many buildings", 6, "Population Size")-1
        rhino.AddLayer "Structure",RGB(90,90,90)
        rhino.AddLayer "FloorCeil",RGB(200,200,200)
        rhino.AddLayer "Skin",RGB(50,50,255)
        rhino.AddLayer "Core",RGB(0,0,0)
        rhino.AddLayer "Soil", RGB(250,250,0)
        rhino.AddLayer "Columns", RGB(193,92,99)
        'Read from File (ReadFromFile): 1 - TRUE, OTHER - FALSE
        ReadFromFile=1
        If ReadFromFile = 1 Then
                ReadBuildingsFromFile  mybuilding,nobldg
                ReadBuildingRanking myranking, nobldg
                CrossOver mybuilding,myranking, nobldg
                savebuildingtofile mybuilding,nobldg
        Else
                InitiateFloors nobldg,mybuilding,"circle", ncolumns
        End If
        For i = 0 To nobldg
                rhino.command "unlock"
                rhino.CurrentLayer "Soil"
                rhino.command "rectangle c 0,0,0 58,58,0"
                soil = rhino.LastObject
                rhino.AddPlanarSrf array(soil)
                drawBuilding
i,mybuilding,myFloors,myCore,myFloorSrf,myCeilSrf,mySkin,myCoreWall,myColumns,ncolumns
                drawColumns i,myColumns, 2
                rhino.MoveObjects Rhino.AllObjects,array(0,0),array(0,200)
                rhino.LockObjects rhino.AllObjects
        Next
        'construction of initial population
        rhino.UnlockObjects rhino.AllObjects
End Sub
        'Adding the core loft surface to the CORE layer
        rhino.CurrentLayer "Core"
```

```
Sub ReadBuildingRanking(ByRef myRanking(),nobldg)
        Dim objFSO, objFile, strFileName, strLine,attribute,flr,bldg,rnk
        Const ForReading = 1
        strFileName = Rhino.OpenFileName("Open Ranking File...", "Comma Separated Values (*.csv)|*.csv||")
        If IsNull(strFileName) Then Exit Sub
        mheight=flr*40+k*5+0.1-0.1
        moveto = array(shiftX,shiftY,mheight)
        Dim phi : phi = activevol * pi() / 6
        colcX = cos(phi)*(fcorner*scale+(Rcolumn/2))
        colcY = sin(phi)*(fcorner*scale+(Rcolumn/2))
        coloX = cos(phi)*(fcorner*scale+(Rcolumn))
        coloY = sin(phi)*(fcorner*scale+(Rcolumn))
        'rhino.Print("polygon   N   "+   CStr(nos)   +   "  c  "+CStr(colcX)+","+CStr(colcY)+","+CStr(mheight)+"
"+CStr(coloX)+","+CStr(coloY)+","+CStr(mheight))
        myColumns     =     rhino.command("polygon      N"+      CStr(nos)     +      "      c
"+CStr(colcX)+","+CStr(colcY)+","+CStr(mheight)+" "+CStr(coloX)+","+CStr(coloY)+","+CStr(mheight),False)
        LastColumnObj = Rhino.LastObject
        myColumns = LastColumnObj
        rhino.MoveObject LastColumnObj,array(0,0),array(shiftX,shiftY)
        rhino.RotateObject LastColumnObj, array(0,0,0),mrotation
        '         rhino.print "Created floor "+CStr(flr) +" column "+CStr(activevol)
        'no need for floor or ceiling for the columns.
        myColumnsFloor=0
End Function
Sub drawColumns (bldg, ByRef myColumns, gridType)
        'gridType defines diagonal grid versus vertical columns
        Dim bc,fc, dcolumn(60,6),cc,cl,cr,dcolumnl(6),dcolumnr(6),dc,mc(6)
        bc=bldg
        If gridType = 1 Then
                For cc = 0 To 11
                        For dc =0 To 5
                                dcolumn(bc,dc) = mycolumns(bc,dc,cc)
                                mc(dc) = CStr(dcolumn(bc,dc))
                        Next
                        rhino.AddLoftSrf array(mc(0),mc(1),mc(2),mc(3),mc(4),mc(5)),,,2
                Next
        ElseIf gridType =2 Then
                For cc = 0 To 11
                        If cc =0 Then
                                cl = 10
                                cr =1
                        ElseIf cc = 11 Then
                                cl =10
                                cr = 0
                        Else cl = cc-1
                                cr=cr+1
                        End If
                        'rhino.print "ColumnN : "+ CStr(cc)+ " ColumnL: "+CStr(cl)+ "ColumnR: "+CStr(cr)
                        dcolumnr(0)=myColumns(bc,0,cc)
                        'rhino.print "ColumnN : "+ CStr(cc)+ " ColumnL: "+CStr(cl)+ "ColumnR: "+CStr(cr)
                        dcolumnr(1)=myColumns(bc,1,cr)
                        'rhino.print "ColumnN : "+ CStr(cc)+ " ColumnL: "+CStr(cl)+ "ColumnR: "+CStr(cr)
                        dcolumnr(2)=myColumns(bc,2,cc)
                        'rhino.print "ColumnN : "+ CStr(cc)+ " ColumnL: "+CStr(cl)+ "ColumnR: "+CStr(cr)
                        dcolumnr(3)=myColumns(bc,3,cl)
                        rhino.AddLoftSrf
array(dcolumnr(0),dcolumnr(1),dcolumnr(2),dcolumnr(3),dcolumnr(4),dcolumnr(5)),,,2
                        rhino.AddLoftSrf
array(dcolumnl(0),dcolumnl(1),dcolumnl(2),dcolumnl(3),dcolumnl(4),dcolumnl(5)),,,2
                Next
        End If
End Sub
```

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